EVALUATING AND MAPPING THE FERTILITY OF SOILS OF THE ISLAND OF MAUI

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I. INTRODUCTION

Although a considerable effort has been expended over the past one-half century investigating soil fertility in the tropics, comprehensive statements cannot be made about the fertilizer requirements of important tropical crops. Factors that make the problem difficult include: soil variability, plant species and cultivar differences, management variables, constraints on production, weather variables, economic considerations, logistics of fertilizer supply and product disposal, labor availability, farmer acceptance of new ideas and techniques, and individual goals and pride of accomplishment.

An approach that can help solve problems related to soil fertility is to make an extensive survey of the fertility of soils. Information on soil resources is needed for areas ranging in size from individual farms to continents. To be most effective, the information must be organized and presented in a convenient and understandable form to fit the area, regardless of its size. The presentation may be as tables but if data are numerous maps should be used.

Soil maps attempt to describe the distribution of soils over an area and to group those that have similar properties into mapping units. The map seeks to convey information about a specific point or points on a landscape to a map user. Their purpose is to say something precise about particular parts of the area that cannot be said about the whole.

General estimates of fertilizer requirements may not be directly useful to individual farmers or even to farm advisers. Some of the reasons for attempting an estimate of fertilizer requirements on a grand scale include: a) emphasize the need of fertilization, b) serve as guidelines for developing assistance programs that help in determining both the general nature of programs and where those programs should be implemented, c) help identify the more pressing problems and thus help to develop relevant research programs, and d) provide essential background material for sensible resource development, resource management, and resource conservation (Fox and Yost, 1980a)

Several different approaches can be used for estimating grand scale fertilizer requirements. Some approaches are appropiate for one nutrient and/or condition and some for another. Some of the approaches as described by Fox and Yost (1980a) are:

1. A socio-economic approach based on past trends, present programs and market conditions.
2. Balance sheet approach based on soil nutrients removed by crop and restoring the soil with nutrients removed by cropping.

3. Soil approach based on the requirements to bring soils to certain prescribed levels of nutrients.
4. Recommended fertilizer rates approach based on the extrapolations of fertilizer rates for crops in related areas to include major crops of the area.

Soil fertility and fertilizer-requirement maps can serve many purposes:

1. They can be used by research personnel for ordering research priorities.
2. They can be used as resource material for making all sorts of planning decisions.
3. They can guide more detailed recommendations for fertilizer applications based on soil test.

Work of this sort has been started already in Hawaii. Fox and Yost (1980) created two phosphorus requirement maps for the island of Hawaii. They used recently developed techniques of geostatistics as described by Matheron (1965) to deal with the spatial variability of soil properties and to interpolate values of the selected soil properties at unvisited sites.

The work presented here is a continuation of the efforts begun by Fox and Yost. The objectives are:

1. Determine and map certain chemical properties of soils of the western slopes of Mt. Haleakala, on the island of Maui.

2. Map requirements for lime and fertilizer to attain prescribed standard conditions that can be related to crop requirements.
3. Determine relationshsips between soil chemical properties and soil classification as well as climatic, biologic and geologic components.

II. LITERATURE REVIEW

Soil Surveys: Purposes, Components and Uses

Soil is continuous, but most information about soil--certainly information concerning its intrinsic properties--derives from observations at discrete places, often no more than a few centimeters across, more or less widely separated from one another. Soils cannot be described for every location. Yet those who commission soil surveys often want to be able to infer, or predict in a spatial sense, the nature of the soil at many unvisited or unrecorded places from relatively few observations made elsewhere (Webster, 1977).

The role of soil survey is to report the spatial distribution of soils and convey this information to persons using the soil. Because there are many different uses of soil, soil surveys attempt to provide facts about many different soil properties, not all of which are closely related to soil fertility management (Buol and Couto, 1978).

Buol and Couto (1978) defined the components of soil surveys as: classification, mapping and interpretation. They defined classification as being essentially the vocabulary of soil survey. By identifying and naming properties of the soil, information is conveyed from place to place and person to person.

There are two types of classification. Natural classification and technical classification. In a natural classification, one classifies in such a way that the name of each class will bring to mind many characteristics and will fix each group mentally in relation to all others. The objective here is to show relationships in the greatest number and most important properties (Cline, 1949). Natural classification is the basis for any technical classification. The objective of any technical grouping is to place the soils into groups that bring out their relationships to factors of use and management. This involves one or, at most, just a few selected characteristics or conditions (i.e., grouping soils according to their lime requirement) (Orvedal, 1941).

Mapping involves the delineation of areas on the landscape that are identifiable because they differ in some respect from adjacent areas, although it should be recognized that the boundaries between areas usually are gradational. Therefore, soils that are similar or have similar properties are placed into mapping units. Some soil map units include only one kind of soil as defined by the classification system but most units include many kinds of soil.

The third component of a soil survey is interpretation of mapping units in terms familiar to the user of soil information. Most soil surveys are made to further the understanding of soil scientists. In such cases identification is made only of individual soils in terms of soil classification units and how these units spatially fit into the mapping units. Other surveys may use separate interpretive or technical classifications that relate the potential use of the map unit for specific purposes such as irrigation, drainage, etc.

The uses of soil surveys are largely dependent on the objectives of the soil survey itself, thus one may say that there are as many uses of soil surveys as there are objectives of soil surveys. In any case, soil surveys can be used by land-use planners, soil scientists, civil engineers, land developers, agriculturists, farmers or any person that has anything to do with soils or land.

Soil Variation

Soils are continuous, three-dimensional bodies. They vary vertically from place to place in most, if not all, of its properties. Soils also vary with treatment and also with time (Cline, 1944). Variation can be attributed to a combination of experimental error, temporal variation, and spatial variation. Research has determined that spatial variation is usually the largest of the three (Cline, 1944; Ball, 1968).

Spatial variability can be divided into two broad categories: systematic and random (Wilding, 1978). Systematic variability may be seen as a function of the following factors:

1. Land forms - mountains, plateaus, basins, plains, terraces, fans, valleys, moraines, etc.
2. Geomorphic elements - summit, shoulder, backslope, and footslope.
3. Soil forming factors
    a) chronosequences - a function of geomorphic age and landscape stability.
    b) lithosequences - a function of parent material or bedrock types.
    c) toposequences - a function of topographic relief on similar parent materials.
    d) biosequences - a function of biology.
    e) climosequence - a function of climate; mainly the effect of rainfall and temperature on parent material.
4. Interactions of above factors.

These changes are manifested in kind, sequence, and arrangement of soil microfabrics, horizons, and individual and landscape entities. Historically, pedologists have concentrated their efforts on systematic changes in soil with less emphasis on identifying random changes.

Random variability is often complex, difficult to discern, and impossible to express analytically. Associated with random variability simultaneously and concurrently are those changes in soil properties that cannot be related to any known cause. These are termed random or chance variation. When the soil system is investigated in greater detail, some of the variation originally considered random may be recognized as systematic variation. Some of the causes for vertical and horizontal soil anisotropy that may yield spatial variability of a random nature include:

1. Differential lithology - function of physical, chemical, and mineralogical composition of parent material reflecting modes of origin, mechanism of transport, and sedimentary histories.
2. Differential intensity of weathering - function of modes and mechanisms of weathering, formation and transfer of weathering products, and landscape evolution.
3. Differential erosion and accretion - function of landscape stability and geomorphic processes.
4. Biological factors - functions of flora and fauna (including mans influence).
5. Differential hydrology - function of climate, relief, vegetation, and geomorphic position on landscape.

6. Sampling and analytical errors - function of population characteristics, sampling design, and error of field and laboratory determination.

Mapping Soil Properties

The purpose of a soil survey is to map the soils of an area and to place similar soils into mapping units. The utility of any soil map depends upon the precision of statements that can be made about delineated units versus the area as a whole. It may simply be a statement of fact: for example, the soil here is acid. Or, it may be a prediction; as for example, if this land is limed, yields could be increased 30% (Webster and Beckett, 1968).

The function of all soil maps is to show the distribution of kinds of soils so that knowledge gained in one locality about the usefulness or behavior of a kind of soil may be extended to other bodies of the same soil (Simonson, 1971). For the most part soil maps serve as a basis for organizing and extending knowledge about soils pertinent to their use to satisfy human needs.

Soil maps can be divided into two categories, detailed and general. Detailed soil maps generally show delineated bodies that can properly be named as phases of soil series, and are the product of detailed surveys. Detailed soil maps are generally used for soil classification purposes. Good examples of these kinds of maps are the soil survey maps of the different states of the United States.

On the other hand, general soil maps provide less than detailed information on the distribution of soils of a given tract of land and have been made by generalizing information from detailed surveys. The delineated bodies shown on general soils maps represent several phases of series, several series, or several classes in some category above the series level. They can either do one of two things: 1) show the broad distribution pattern of soils or 2) focus the attention on some component of the soil pattern. General soil maps are needed because the human mind can comprehend only a limited number of facts simultaneously. Their justification lies not in what can be shown on a map but in what can be grasped and understood. General soil maps may not be of much direct use to individual farmers but they may serve as a guide to more detailed studies within the farm. In general, soil fertility maps are generalized soil maps.

The fundamental components of a soil map are the mapping units and the scale of the map (Buol and Couto, 1978). Basically a map unit attempts to define and describe the range of conditions that occurs in a given area. Regardless of the scale almost every map unit has inclusions of soils not named in the map unit title. As the scale of the map decreases, it is necessary to include a wider range of soil properties into a given unit. This is accomplished by using both broad taxonomic units to name the soil and by including more than one category of soil within each map unit.

The data for a soil mapping unit comes from measurements made at discrete places in the landscape, but there is always the hope that all places mapped as any particular class will have soil properties similar to those recorded for that class, and different from those of at least some of the other classes. In here, prediction is inferred or involved and this prediction can be expressed in terms of classical statistics by assuming that the value of a property, Z_{ij}, at any place i in class j is the sum of three terms:

$$Z_{ij} = u + \alpha_i + E_{ij}$$

where u is the general mean of the property for the whole area, α_i is the difference between the general mean and the mean of class j, and E_{ij} is a random component distributed normally with a mean of zero and a variance (Burgess and Webster, 1980).

When measured data are sparse, as they often are, this approach to prediction and mapping is the only feasible one. Success obviously depends on there being an association between the property of interest and the classification scheme even though soil classes are not directly related. Such procedures take no account of the spatial arrangement of data points or relationship between data points and predicted points, nor of gradations in values across boundaries.

In such cases interpolation provides an alternative to classification for predicting values of a property at unvisited points. Soil properties can be mapped if the data are assumed to represent a statistical surface over the map plane, which can be represented by isarithms. Isarithmic mapping is often known as 'contouring', by analogy with the mapping of topographic height. However, topographic contours are usually drawn to join points of equal measured height, whereas soil isarithms join points of inferred equal value.

Kriging

Recently a method for surface interpolation known as 'kriging' was described by Krige (1951) and Matheron (1963). This method predicts values of properties without bias and with minimum variance.

Kriging has been applied recently to soil science . Users include: Campbell, (1978); Burgess and Webster, (1980a,b); Burgess, Webster and McBratney, (1981); Yost, Uehara and Fox, (1982a,b); McBratney and Webster, (1983); and Giltrap, (1983a,b).

The first step in kriging is to measure spatial variation in a soil property of interest. Spatial variability measurements provide the quantitative data necessary for interpolation, and also guides in choosing sampling techniques and strategy.

Campbell (1978) used geostatistical methods to compute and display semi-variograms for soil texture and soil pH of soils derived from loess and glacial-till. Vieira et al. (1981) used geostatistical methods to determine the spatial variability of the infiltration rate in a soil of California. In Hawaii, Yost et al. (1982a,b) have used geostatistical methods to determine spatial variability of soil chemical properties and to create isarithmic maps of soil properties and fertilizer requirements.

Spatial dependence of soil properties were first measured by Webster (1973), and Webster and Cuanalo (1975) by applying methods of time series. They computed correlograms from data along transects.

The first step in determining spatial dependence of properties is to compute the semi-variances for each of the properties being studied. These are computed from the formula

$$Y(\alpha,h) = \Sigma \{[z(x) - z(x+h)]^2\} / 2N$$

where N is the number of sample pairs at each distance interval (h), and Z(x) is the value of the soil property at field location (x), and α is the angle or direction. The semi-variance can also be represented as Y(h). The semi-variance, $Y(\alpha, h)$, is a measure of the similarity of the data, on the average, between points a given distance, h, apart. The more alike the points are, the smaller $Y(,h)$ is. Once semi-variances are computed, a plot of semi-variance vs. distance can be plotted. Such a plot is referred as a semi-variogram.

In the case of an ideal semi-variogram of a property, semi-variance increases as distance increases and eventually attains constant value (Figure 1).

The value of the semi-variance at which the graph levels off is called the sill of the semi-variogram and is denoted as C. The sill value is equal to, or generally approximates, the value of the variance of stationary data. The graph levels off at a point where the distance between sample locations is very large and therefore the sample values become independent of one another. The distance at which sample values become independent of one another is called the range of influence of a sample and is denoted as a. Within this range there is a systematic relationship or dependence between $Y(\alpha,h)$ and h, and an empirical equation can be fitted to this relationship (Clark, 1982). Another important feature of semi-variograms is the intercept, C_o, which is known in geostatistics as the nugget variance or nugget effect. C_o is the estimate of $Y(h)$ at h=0 and provides an indication of short distance variation (Yost et al., 1982a).

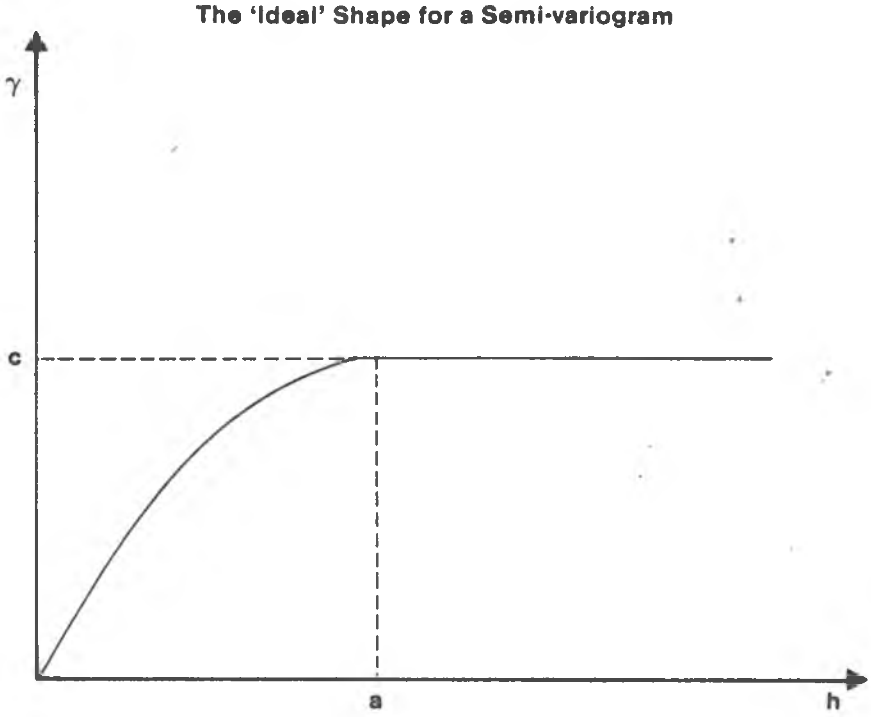

Figure 1. Theoretical semi-variogram for a spherical model, illustrating the range, a, the sill, c, and the nugget variance, C_o.

Burgess and Webster (1980a) suggested that in soil surveys the range will usually be a few hundred meters, and, exceptionally, two or three kilometers. However they point out that the range depends on the size of the area sampled. For example over a large landscape on the island of Hawaii Yost et al (1982a) observed that the range for pH was 14 to 32 km. When interpolating one should use only those points closer than the range to the predicted point.

The relationship between variability and spatial orientation of sample points found from the semi-variograms is used to make estimates of values at unsampled locations by the process of kriging. Kriging is a method of optimal, unbiased, minimal variance estimation of properties usually in two or three dimensions (Yost et al., 1982). Kriging is a form of weighted averaging that incorporates the spatial relationship of properties obtained from semi-variograms. It results in an unbiased estimate with a minimization of error variance, using a small number of neighboring sample points. An estimation variance is provided for each estimated point which gives an indication of the reliability of the location of the measured neighboring points of the kriged value. When points have been estimated, they can be plotted on maps and joined by isarithms thus creating a map. Users of kriging in the area of soil science include: Burgess and Webster, (1980a,b); Vieira et al., (1981); Burgess et al., (1981);

Yost et al., (1982b); McBratney and Webster, (1983)

Partitioning Variation of Soil Chemical Properties

How well do soil classification systems differentiate between different mapping units or classes of soil? Such a question is not asked often. And when the question is asked it is assumed that each successive subdivision in the soil classification system will improve the prediction of soil properties and behavior. However, statistical evidence of such is rarely presented (Yost and Fox, 1981).

Yost and Fox (1981) determined the ability of soil taxonomic categories, as described by Soil Taxonomy (Soil Survey Staff, 1975), to partition and predict variation in important soil chemical properties. To do this they used two different approaches. In the first approach they used regression methods to measure how much of the variation in soil properties was partitioned by single categories of the Soil Taxonomy. In the second approach they used a hierarchical analysis of variance patterned after the hierarchical classification sequence actually used in Soil Taxonomy. In both cases most of the variation within a soil chemical property was partitioned or explained at the great group level. Second in importance was the series level. This means that the criteria used by the Soil Survey (1975) to divide soils into different great groups is the most effective for grouping soils according to nutrient status. These workers pointed out that partitioning the variation within soil properties in a hierarchical model is better than partitioning the variation separately into each of the categories and then comparing them, because in the former case, independent improvement in partitioning the variation with increasing classification, detail is revealed. However, they also stated that the latter can serve as a reference for quick and useful predictions of soil properties given the soil taxonomic categories.

The Island of Maui

Maui, the second largest island of the state of Hawaii lies between 20° 40' and 21° North latitude and between 156° and 156° 40' West longitude. It is 77 kilometers long and 42 kilometers wide. The land area is 1885 square kilometers (Blumenstock and Price, 1967).

Two volcanoes, the East Maui volcano, or Haleakala, and West Maui volcano merged to form the island. The island is divided into three main areas: West Maui, East Maui, and Central Maui which is an isthmus. West Maui is a deeply dissected volcano that rises to 1765 m at Puu Kukui. East Maui is dominated by the 3055 m Haleakala volcano. Central

Maui, the isthmus that connects West and East Maui, is smooth and nearly level.

Mean annual rainfall in mountainous areas ranges between 250 and 9000 mm. Elevation ranges from sea level to 3055 m.

Central Maui is extensively used for sugarcane and pineapple production. Land on the eastern portion of Central Maui, or the western slopes of the Haleakala volcano, is used for pasture production and for forest.

Of the 191 soil series mapped in the state of Hawaii, 49 occur in Maui. These represent the following orders: Inceptisol, Ultisol, Mollisol, Oxisol, Histosol, Aridisol and Entisol. Central Maui is dominated by Inceptisols, Ultisols, Mollisols, and Oxisols.

Overview of the Soils of Hawaii

The soils of Hawaii have formed from basaltic igneous materials including lava, cinders and ash (Ayres, 1943; Hasan 1970). Generally, scientists of temperate regions believe that soils of the tropics are invariably highly weathered. However this is not the case. In tropical regions, including Hawaii, besides the highly weathered sesquioxides and 1:1 layer silicates soils, soils of the 2:1 clays also occur (Fox, 1982).

The tropics are characterized by continuous warm temperatures and not extremely hot temperature as is often believed by persons who have worked only in temperate regions. A important feature of temperature of the tropics is the absence of extremes. Even though temperture plays an important role in the formation of soils in the tropics, its role in Hawaii is not as important as that of rainfall. Rainfall in Hawaii is related to geographic features and varies greatly over short distances. For example, the range is 500 to 2500 mm along a transect of less than 20 km, northwest of Haleakala volcano mountain in Maui.

These climatic conditions of the Hawaiian islands are favorable for the development of highly weathered, desilicated soils. Desilication has been recognized as the dominant type of weathering and soil forming process in the Hawaiian islands (Ayres, 1943). Desilication can be described as the decomposition of clay minerals with leaching of silica, leading to the accumulation of free oxides of iron, aluminum and titanium. The other weathering factor, important in the development of tropical soils, is the formation of clay minerals of kaolinite type from the primary minerals.

Cline (1955) recognized and described four groups of desilicated soils and these are: a) those developed in regions having an annual rainfall ranging from 381 to 2032 mm; b) those developed in regions having an annual rainfall ranging from 1524 to 3810 mm; c) those developed in regions of very high rainfall, 3048 to 7620 mm; and d) those developed under a wide range of annual rainfall, 635 to 3810 mm. These four groups of soils occur on the island of Maui. Based on the properties of the soil as affected by these climatic conditions, these soils are generally classified as a) Ustox and Torrox; b) Humults; c) Hydrandepts; and d) Humox; respectively. Under alternating definite dry and wet seasons kaolinite and alumina increases in the early stages but as weathering progresses both decrease. Their silica content decreases with the age of weathering, whereas the content of iron and titanium oxides increases with weathering age. Generally associated with these conditions are the Ustox, Torrox, and Humox.

Under climatic conditions which have no definite dry season there is a rapid decomposition of minerals to free oxides and the alumina content increases as rainfall increases, whereas for silica and iron oxides the relationship is the reverse (Sherman, 1949). Generally associated with these conditions are Humults and Hydrandepts.

Other important soil groups that occur in Central Maui and which largely dominate the slopes of Haleakala includes Eutrandepts which are developed from volcanic ash under an annual rainfall between 508 to 1016 mm. They occur in high elevations and cool climates. They occur around Ulupalakua and Kula. Vitrandepts and Dystrandepts which also developed on deposits of volcanic ash, occur at much higher altitudes than the Typic Eutrandepts and are exposed to a higher rainfall (Soil Survey, 1972).

Soil Chemical Properties

Phosphorus

Agronomists agree that P, after nitrogen, is the plant nutrient most likely deficient in the tropics. Soils vary greatly in the amount of P fertilizer required to adequately provide P for plants. There is abundant evidence that the immediate source of P for plants growing in soils is the soil solution (Fox and Searle, 1978). Furthermore, a close relationship exists between P in solution and P in the sorbed state: the quantity of P sorbed varying directly with the concentration of P in solution. This relationship was used by Fox and Kamprath (1970) to plot P sorption curves that provide a basis for determining the amount of P necessary to maintain a given level of P in solution.

Extractable soil phosphorus. Various P extraction methods have been devised, however not all of them are appropiate for all soil conditions. Soil properties that influence P extractability vary from site to site and thus an extractant that works well on one site may not do so at another location.

Bray (1948) pointed out that a successful laboratory extractant should meet three criteria:

1. It must extract all or a proportionate part of the available forms of nutrients in soils with widely different properties.
2. The procedure must be rapid and accurate.
3. Amounts of nutrient extracted should correlate with the growth and response of each crop to the nutrient in question under various conditions.

Most soil tests do not meet the criteria given by Bray. The most widely used soil P tests are: Olsen (Olsen, Cole, Watanabe, and Dean, 1954), Bray and Kurtz No. 1 (Bray and Kurtz, 1945) and Mehlich No. 1 (Nelson, Mehlich, and Winters, 1953). The Olsen method, which uses 0.5 M $NaHCO_3$ adjusted to pH 8.5 as extractant, seems to have the widest application. This method not only extracts calcium and aluminum phosphate but also iron phosphate. On the other hand, the Mehlich method which uses a solution 0.05 $\underline{N}$ with respect to HCl and 0.025 $\underline{N}$ with respect to H_2SO_4 as extractant, and the Bray method which uses a solution 0.03 $\underline{N}$ with respect to NH_4F and 0.025 $\underline{N}$ with respect to HCl as extractant, are effective in extracting only calcium and aluminum phosphate. Due to such problem, the alkaline Olsen method is becoming more widely used and predicts yield response of several crops over a range of soils (Rudd and French, 1976).

The simplest concept of determining P in soils is probably P concentration in the soil solution or in water extracts. This measures an intensity factor. This can be done by equilibrating soil samples with water or using water to displace soil solution from a soil column.

Recent soil P research in Hawaii has concentrated on the use of P sorption isotherms as a basis to determine P requirements of soils (Fox and Kamprath, 1970; Rajan, 1973; Silva and Fox, 1974; Fox and Searle, 1978; Peaslee and Fox, 1978; Vander Zaag et al., 1979; Fox, 1981).

Phosphorus sorption isotherms. Early interest on the use of P sorption isotherms as a P-test was stimulated by Beckwith (1965) who proposed a standard equilibrium concentration to compare the sorption capacities of soils. He suggested a standard concentration of 0.2 ug P/ml in the soil solution because this is adequate for most plant species. Much confusion has developed because some scientists interpreted Beckwith's standard concentration as a P requirement for all crops. Fox (1979) and Vander Zaag

(1979) have shown that many crops require less P in solution and some require more. By no means is this concentration a universal P requirement for crops.

The important feature about P sorption isotherms is that they relate the intensity and capacity factors of P nutrition; the intercept at zero P sorption is an estimate of P in the soil solution (an intensity factor) and the slope of the curve is directly proportional to the buffering capacity of the soil (capacity factor). Fox and Kamprath (1970) gave the procedure for plotting P sorption curves. The values of P sorbed are plotted against log P in an equilibrium solution, usually when this is done a smooth P sorption curve is obtained.

A second important feature of P sorption curves is that P fertilzer requirements to attain standard concentrations in the soil solution can be estimated directly. Sorption curves have been used to predict the P requirement of several crops growing in diverse soils (Ozanne and Shaw, 1968; Fox and Kamprath, 1970; Jones and Benson, 1975; Juo and Fox, 1977; Vander Zaag et al., 1979; Fox 1981; etc).

Mechanisms of phosphate adsorption. It has been determined that P sorption is related to charge characteristics of soil particle surfaces (Mekaru and Uehara, 1972; Larsen, 1967). These surfaces fall into two categories: those dominated by variable charge materials (highly weathered soils) and those dominated by materials with constant charge (not so highly weathered soils). The variable charge materials include organic matter, silica and hydrated oxides of iron and aluminum. Rajan and Fox (1975) emphasized the importance of iron and aluminum compounds in P sorption by soils of the tropics. Parfitt et al. (1975) described the mechanism of P fixation by iron oxides. A possible mechanism for P sorption is that phosphate replaces hydroxyl ligands to become chemisorbed to the hydrated oxide surface (Mattingly, 1975).

Factors influencing P sorption. Many factors of soil mineralogy, chemistry and management are integrated in P sorption isotherms. Soil texture influences P adsorption capacity of soils because soil texture and specific surface are closely related.

Fox and Searle (1978) ranked phosphorus sorption by soils of the tropics according to mineralogy as follows: quartz = aluminum free organic matter < 2:1 clays < 1:1 clays < crystalline oxide of iron and aluminum < amorphous oxides of aluminum and iron. Juo and Fox (1977) quantified these relationships as follows:

Standard P Sorption ---ug P/g soil---	P Sorption Group	Usual Mineralogy encountered
< 10	very low	quartz, organic materials
10 - 100	low	2:1 clays, quartz 1:1 clays
100 - 500	medium	1:1 clay-oxides
500 - 1000	high	crystalline oxides
> 1000	very high	desilicated amorphous materials

Other factors which influence P sorption are: time, temperature, water content, mixing, supporting electrolyte, soil pH, ionic competition for adsorption sites, desilication of soils and surface area for adsorption. The influence of each of these factors on P sorption were discussed by Fox and Searle (1978).

External P requirements. The term "external P requirement" arose as a result of the fact that the growth of plants is related to the concentration of P in solution. It has been used to designate the concentration of P in solution required for 95% maximum yield. For example, Fox and Kamprath (1970) reported that yields of millet grown in pots on three soils required a concentration of approximately 0.2 ug P/ml in the soil solution to attain 95% maximum yield.

Further studies in Hawaii have determined that the external P requirement of crops varies with the species and the cultivar grown (Fox et al., 1974; Nishimoto et al., 1977; Vander Zaag, 1979). Rajan (1973), reported that the concentration of P in solution required by millet to attain maximum growth ranged from 0.022 to 0.6 ug/ml when grown in pots on different Hawaiian soils. He concluded that this requirement was inversely related to P sorption capacity of the soils. His conclusion is in accordance to that of Woodruff and Kamprath (1965) who reported that the growth of millet was related to the degree of saturation of P adsorption maximum. Soils with a large P adsorption maximum require a lower P saturation than soils with low adsorption maximum. These conclusions probably apply to pot studies where the barrier effect of pot walls adversely influences P uptake (Fox and Kamprath, 1970).

Fox et al. (1974) reported that corn grown on two soils required 0.05 ug P/ml in the soil solution. Nishimoto et al. 1977 reported the P concentration in the soil solution required by several vegetables to attain 95% maximum yield; most vegetables required between 0.2 and 0.3 ug P/ml. For example the external P requirement of tomato, chinese cabbage, soybean and cucumber was 0.2 ug P/ml, while that of head lettuce, leaf lettuce and egg plant was 0.3 ug P/ml. In another study, Nishimoto et al (1975) concluded that the external P requirement of chrysanthemums was 0.05 ug P/ml. Vander Zaag et al. (1979) reported that the external P requirement of potatoes grown under diverse soil and climatic conditions was 0.2 ug P/ml. Memon (1982) determined the external P reuirement of four cereal crops as follows: wheat 0.025 ug/ml, millet 0.018 ug/ml, sorghum 0.021 ug/ml, and maize 0.018 ug/ml.

The external P requirement of crops is influenced by many soil, plant and management factors. Recently Peaslee and Fox (1978) and Fox (1979, 1981b) discussed those factors in detail. Among the soil factors they included: buffering capacity of the soil for P and quantity of labile P, soil factors associated with root development, mycorrhizal associations, temperature, and species and concentration of salts in soil solution. Plant factors included: yield potential of the crop, differential uptake of cations by plants, effectiveness of roots and associated mycorrhiza in P uptake, and interactions of roots with solid-phase P. Management factors they mentioned the volume of soil fertilized and placement of fertilizer with respect to roots, and the time of fertilization in relation to the expected utilization.

Critical levels of soil extractable P. Critical levels of extractable soil P are those levels at which little or no response to fertilizer P is obtained (Kamprath and Watson, 1980). Olsen et al. (1954) reported that a level of 10 ppm $NaHCO_3$-extractable P was adequate for the growth of wheat, alfalfa, and cotton. Critical levels for Bray No. 1 method are generally around 25 ppm.

Thomas and Peaslee (1973) summarized the critical levels for both the Olsen and Bray No. I methods (Table 1).

Sulfur

Sulfur has been described as a neglected plant nutrient. Its essential nature was demonstrated more than a century and a half ago and yet this nutrient has received only sporadic studies by agronomists (Jordan, 1958).

In surface soils, sulfur is predominantly in the organic fraction, and native supplies of sulfur are closely related to organic matter levels. Native sulfur is supplemented by variable additions of sulfur from rainwater, irrigation water, direct absorption from the atmosphere, fertilizers, insecticides, and fungicides.

Table 1. Relative categorization of P concentrations into low medium, and high for the Olsen and Bray No. 1 methods.

Relative Soil Level	Extractant: 0.03 N NH_4F 0.025 N HCl	Extractant: 0.5 M $NaHCO_3$
	extractable P in soil, ppm	extractable P in soil, ppm
Low	0 - 15	0 - 5
Medium	16 - 30	6 - 10
High	> 30	> 10

The incidence of S deficiency in the world probably is more closely related to the S content of the atmosphere (precipitation) and irrigation waters than to edaphic factors (Fox, 1981). Thus S deficiency is a minor problem in areas where great quantities of fossil fuels are burned, but deficiencies are widespread in tropical, subtropical, and warm temperate areas where the S contents of the atmosphere, of rainwater, or of irrigation waters are low.

Highly weathered soils or variable charge soils have a capacity to sorb sulfate. This give rise to low sulfate concentrations in solution and this, in turn, to S deficient crops.

Extractable Sulfur. Various methods have been used to extract sulfur from soils. Williams and Steinbergs (1959) compared several extracting procedures. The procedures investigated included: cold water-extractable sulfate, phosphate-extractable sulfate, acetate-extractable sulfate, heat-soluble sulfur, hot water-extractable sulfate and $NaHCO_3$-extractable sulfate. Phosphate-extractable sulfate correlated best with plant response.

Fox et al. (1964) compared several extraction procedures for soils of Nebraska and Hawaii and determine correlations between extractable sulfur and yields of alfalfa. The methods used for extracting soil S were: heat soluble S

(Williams and Steinbergs, 1959), KH_2PO_4 extraction (Ensminger, 1954), $Ca(H_2PO_4)_2$ extraction (Fox, 1964), and H_2O extraction. They found that among the various extractants $Ca(H_2PO_4)_2$ extraction has the widest application over different soils and best predicted S uptake by alfalfa.

Sulfur sorption curves. The use of sulfur sorption curves as a research technique has gained limited acceptance among scientists involved in the research of sulfur in soils that sorb sulfate. Sulfate sorption curves are similar in form to phosphate sorption curves (Fox et al., 1971), however sorption of P is much greater than S sorption.

As with P sorption isotherms, sulfate sorption curves combine the intensity and capacity factors of S plant nutrition, and can be used to directly determine the sulfur required by soils to attain a particular concentration of S in solution. The work of several workers (Fox, 1976; Hasan, 1970; Fox et al., 1976; Ergle and Eaton, 1951; Elkins and Ensminger, 1971; Daigger and Fox, 1971; and Fox et al., 1977) indicates that most crops require approximately 5 ppm SO_4-S in the soil solution. This concentration is not a universal S requirement for crops. However, this sulfur concentration seems to be a good standard for comparing the sulfur sorption by different soils.

The capacity of soils to sorb sulfate is related to weathering products (Hasan, 1970). Under humid tropical conditions parent materials are altered very rapidly. As weathering progresses there is a heavy loss of silicon and bases, and there is an accumulation of Fe and Al oxides, thus the resulting soils have little permanent negative charge but a considerable pH-dependent charge. If soils are very acid, net positive charge develops. These conditions result in the retention of sulfate as well as phosphate.

Factors influencing S sorption. Sulfate sorption by soils is affected by several factors. Among these factors, mineralogy is most important. Kamprath et al. (1956) found that 1:1 type clay minerals sorb much more sulfate than 2:1 clay minerals. In Hawaii, Hasan et al. (1970) reported that soils composed of 1:1 clay-oxides sorbed less sulfate than the crystalline oxides, moderately weathered volcanic ash soils, and desilicated amorphous material (Andepts). However, they sorb more than the 1:1 clay and 2:1 clay soils reported by Kamprath.

Sulfate adsorption decreases with increasing soil pH regardless of the sulfate-sulfur concentration in the soil solution (Kamprath, 1956). Kamprath also reported that the amount of sulfur sorbed increases with increasing concentration of sulfate in solution and decreased with increasing phosphate concentration in solution.

Silicon

Studies on the role of silicon in plants has not been studied in great detail. Although silicon is a constituent of plant ash, attempts to establish an essential role in plant growth have been unsuccessful so far. If as Ayres (1943) suggested, that desilication is the dominant type of weathering and soil forming process in Hawaii, the concentration of Si in saturation extracts of soils should provide an index of the stage of weathering that soils have attained and Si concentration should correspond, in a general way, to several attributes of soil fertility, namely P sorption, P solubility, Al saturation, and SO_4-S sorption.

Relationship between soil properties and soil silicon solubility. The conditions found in the humid tropics result in intense weathering, with the formation of 1:1 clay minerals such as kaolinite, and as weathering proceeds further, free oxides of iron, aluminum and titanium accumulate (Sherman, 1949). Plucknett (1972) concluded that the silicon response in soils follows the rainfall pattern which to a large extent determines the degree of weathering. Fox (1981) concluded that silicon in saturation extracts should give a better evaluation of the state of weathering than silicon in a 1:10 soil:water extract because, although soils which have an abundance of sand-sized quartz lack the capacity to supply silicon at high concentration to large volumes of extractant, saturation extracts of such soils usually contain ample Si for soils. So one might expect greater responses by crops to silicon applications on highly weathered, silicon-depleted soils of the high rainfall regions than on soils dominated by quartz.

Crop response to silicon applications have been reported in Hawaii as well as in other tropical areas of the world. Examples of response have been reported in Hawaii (Clements, 1956a; Ayres, 1956; Fox et al., 1967b; Sherman et al., 1964 and Medina, 1981); Australia (Beckwith and Reeve, 1964); Mauritius (Halais and Parish, 1963; Halais, 1968); Taiwan (Shine, 1964); Puerto Rico (Alexander, 1968a); Samuels and Alexander, 1968) and Florida.

The concentration of silica in soil solutions varies among soils. Differences are mainly related to mineralogy. Fox et al. (1976b) reported the following ranking of soils with mineralogy in respect to silicon content and solubilty:

2:1 clays > 1:1 clays > Al and Fe oxides.

Silicon in solution is present in the form of monosilicic acid, $Si(OH)_4$, at pH below 9 (Alexander et al., 1954). The solubility of silicon is independent of pH in the range of 2 to 9, but increases sharply above pH 9 because of the formation of silicate ions. This increase in total soluble silicon at high pH can be explained on the basis of the following equilibrium:

$Si(OH)_4 + OH^- ==== (HO)_3SiO^- + H_2O$ (Alexander et al. 1954).

However McKeague and Cline (1963a,b) reported that by adding various concentration of soluble silicon to soils, the adsorption of monosilicic acid increased throughout the pH range 4 to 9. They concluded that a pH dependent reaction is involved in controlling the concentration of silicon in the soil.

Beckwith and Reeve (1963) observed that oxides of iron and aluminum sorbed monosilicic acid from solution, and that the reaction was pH-dependent. Even though the mechanism of reaction of monosilicic acid with excess sesquioxides does not appear to have been determined, it is reasonable to assume that the reaction which occurs at oxides surfaces is similar to that between iron and polysilicic acid. This has been written (Iler, 1955).

$-Si-OH + (Fe(OH))^{2+} ==== (-Si-O-Fe(OH))^+ + H^+$

<u>Beneficial effects of silicon applications for plant growth</u>. Sugarcane plantations of Hawaii apply calcium

silicates to soils that are silicon deficient. Medina (1981) summarized the work of Ayres (1966), Fox et al. (1967a), Silva (1971), Ikawa (1956), Mahilum et al. (1970), Clements (1956a), Clements et al. (1967), and Fox et al. (1978) on the beneficial effects of silicate applications as follows:

1. Increased soil pH.
2. Increased calcium levels.
3. Decreased phosphorus fixation.
4. Increased availability of soil phosphorus.
5. Increased plant resistance to insects and diseases.
6. Decreased potentially toxic elements such as iron, aluminum and manganese

Increased in sugar yields in Hawaii have been reported by Sherman et al., 1964; Ayres, 1966; Clements, 1956 a,b; Fox et al., 1967 b. Plucknett (1972) reported that great soil groups on which silicon responses have been obtained in Hawaii include: Humic latosol, Hydrol Humic latosol, Aluminuous Ferruginous latosol, and Humic Ferrugiouns latosol (today classified as Tropohumults, Hydrandepts, Gibbsihumox, and Acrohumox, respectively).

Extractable soil silicon. Various extractants of soil silicon have been tested. These include: water, phosphate-acetate (pH 3.5), ammonium acetate (pH 4.8), and dilute sulfuric acid. These methods give valuable information about the ability of soils to supply silicon to plants (Fox, 1967b). Water extractable silicon including silicon in saturation extracts, give a good indication of the intensity of silicon nutrition.

Medina (1981) compared three methods: water extraction, ammonium acetate extraction, and silicon in saturation extracts; and determined their correlation to uptake of silicon by sugarcane. He found that water extractable silicon gave the best correlation with plant uptake of silicon, and this was followed closely by silicon in saturation extracts. At the same time he reported that ammonium acetate gave poor correlation between soil silicon and plant uptake, his results are in accordance with those of Fox (1967b). Medina (1981) suggested that a possible reason for better correlation of water extractable silicon (1:10 ratio) as compared with silicon in saturation extracts is that a wide ratio of soil to extractant puts the soil under some stress and thus to some extent gives a measure of the soil silicon supply or quantity factor, whereas in the case of saturation extracts the soil is under no stress and thus this method provides only information about the intensity factor of silicon nutrition.

Critical levels of extractable soil silicon for Hawaiian soils (Fox et al., 1967b) are listed in Table 2.

Table 2. Suggested levels of soil silicon in relation to sugarcane.

	Extractant			
	Water	$Ca(H_2PO_4)_2$	$HOAc_2$	H_2SO_4
	ppm			
Low	< 0.9	< 50	< 20	< 40
Medium	0.9 - 2	50 - 150	20 - 40	40 - 100
High	> 2	> 150	> 40	> 100

Soil Acidity: pH, Exchangeable Aluminum, Buffering Capacity and Lime Requirement

The lime requirement of a soil usually is defined as the amount of liming material that must be added to a soil to raise pH to a prescribed value. Prescribed values are usually in the range pH 6 to 7, because this is an easily-attainable value and is within the optimum growth range of most plants. However, this definition as stated should not be used to define lime requirements of acid tropical soils. A better general definition should state that the desirable pH is that one at which the aluminum and/or maganese saturation is reduced to such a level as to suppress toxic effects on crop plants.

Soils are products of weathering by which environmental factors have acted upon parent materials through time (McLean, 1971). The influence of these factors is modified by topography and biological activity. Conditions for tropical soil development favor rapid chemical decomposition of the original minerals of the rock (Matsusaka and Sherman, 1964). Two reactions occur with the decomposition of the original rock minerals, namely; a) the original mineral breaks down to simple components, and b) the soluble constituents (the bases, including calcium) are leached by the percolating water, and the remaining constituents form relatively stable silicate clay minerals or, in the more humid regions, free oxides of aluminum, iron and titanium accumulate. The combined action of weathering (a) and leaching (b) has its greatest potential for expression in the development of tropical soils, and leads to soil acidity and associated conditions namely, toxic concentrations of Al and Mn, deficiencies of Ca and Mg, depleted K, and sorption of phosphate, sulfate, and molybdate, which in turn cause low crop yields in much of the humid tropics (Fox, 1981).

Soil pH. Tests of soil acidity were among the first routine soil tests. Perhaps soil pH provides more information about soil fertility than any other single measurement (Fitts and Nelson, 1956).

A given pH determination is influenced by several factors including the soil:water ratio. In general, pH determinations are made at as low a dilution as practical, since dilute salt contents tend to produce high values. Very narrow ratios pose problems because of incomplete soil mixing, poor electrical contact, and difficulty in rinsing the electrodes between samples. Soil:water ratios of 1:1 or 1:2 are generally used. Soil pH readings also depend on junction potentials. Standardized procedures should be followed, including keeping the soil suspended during measurement.

Several factors influence the concentration of soluble salts in soils. These factors cause soluble salt concentration to vary continuously throughout the year. Among these factors are the amount of rain percolating through the soil and the rate of nitrification in the soil, so that the apparent pH of a soil is often higher in wet weather than in dry weather, and under crop than under fallow (Kanehiro, Matsusaka, and Sherman, 1951).

For several reasons the soil pH usually considered best for crop production is between 6.5 and 7.0. Some of the reasons as discussed by McLean (1971) follow:

1. The availability of soil supplies of Ca, Mg, P, K, S, B, Cu, and Zn are greater at pH range 6.5 to 7.0. On the other hand, at this pH range Al, Mn, and Fe toxicities are unlikely to occur.
2. At higher base saturation, Ca and Mg are adsorbed at pH-dependent sites favoring hydrolysis reactions which increase the plant availability of these two nutrients
3. At a higher pH value, biological activity is more intense, more nitrogen is fixed by soil microorganisms; and, component elements are released by the more rapid decomposition of plant residues.

Work performed over the past several years has created some doubt about the need to lime soils to pH 6.5 or higher. Kamprath (1970) concluded that liming Oxisols and Ultisols to pH values greater than 6.0 is not only unnecessary but it may be harmful. In his opinion, the pH of the soil should be raised, by addition of lime, to a level which neutralizes exchangeable Al. Some of the reasons for not bringing soils

pH above 6.0, as given by Kamprath (1971) are as follows:

1. Reduced water percolation.
2. Reduced growth of legumes and non-legumes.
3. Reduced plant uptake of phosphorus, and
4. Reduced micronutrient uptake.

Even though Kamprath (1971) concluded that for tropical regions liming to neutrality may be detrimental, we must not forget to lime. Fox and Munns (1978) summarized the effects of liming. They included the following among the beneficial effects of liming:

1. Decreased H ion activity.
2. Decreased Al and Mn toxicities.
3. Increased Ca and Mg availability.
4. Increased solubilities and plant uptake of molybdate, sulfate, and phosphate.
5. Improved soil physical properties, and
6. Benefits associated with Ca as a complementary ion on the cation exchange complex.

They also pointed out, that in soils of variable charge, increasing pH increases effective cation exchange capacity, thereby retarding leaching of K and NH_4 ions.

In Hawaii soil pH is highly correlated with the degree of weathering and leaching to which the soil has been exposed. Ayres (1943) observed that soils from the humid districts he studied were all acid and that the pH range in the surface soils was from 4.5 to 6.0. He also observed that the subsoils were less acid than the corresponding surface soils with very few exceptions. Values in the subsoil ranged from pH 4.7 to 6.2.

Agronomic practices influence the pH of soils and thus they are important and must be considered when interpreting pH values. For example, cultivation increase soil acidity (Kanehiro et al., 1951). On the other hand liming increases soil pH.

Even though a measurement of soil pH is probably the chemical determination made most frequently; and although usually it is the first measurement made when a soil sample is collected; and even though many other soil properties are related to pH; correct interpretation of soil pH values may be difficult. Russel (1973) pointed out that the pH of a soil can have no precise significance in agricultural practice. This of course means that pH taken alone, has limited value. However, if the pH value is considered in combination with soil mineralogy, soil chemistry, and agricultural practices it becomes very meaningful data.

Exchangeable Aluminum. Although weathered soils frequently are rich in hydrated oxides of aluminum it does not follow that extractable aluminum is present in proportion to the abundance of free aluminum oxides in soils. In fact, gibbsite is much more stable in acid soil environments than are the layer silicate minerals (Fox, 1982).

Many acid soils of the tropics are characterized by variable-charge, low effective CEC, and high exchangeable aluminum saturation. In such soils the presence of exchangeable aluminum along with the loss of basic cations, Ca, Mg, K and Na due to continuous leaching is responsible for the development of acidity (Kamprath, 1970). If aluminum ions are displaced from surfaces by cations they hydrolize in the soil solution and the hydrolysis products are readsorbed by the clay minerals causing further hydrolysis. Hydrolysis of aluminum is responsible for the low pH of the solutions containing aluminum ions and for the buffer capacity of such solutions (Coleman and Thomas, 1967). The H ions resulting from the hydrolysis of aluminum and iron compounds react with and decompose soil minerals. This continuous hydrolysis of Al and Fe results in an increase in the hydrogen ion concentration and thus a reduction on pH. The reaction can be shown in a simplified form as follows (Coleman and Thomas, 1967).

$$Al^{3+} + H_2O \text{ -----> } Al(OH)^{2+} + H^+$$
$$Al(OH)^{2+} + H_2O \text{ -----> } Al(OH)_2^{\ +} + H^+$$
$$Al(OH)_2^{\ +} + H_2O \text{ -----> } Al(OH)_3 + H^+$$

Hydrolysis reactions can continue further with the formation of: $Al(OH)_6^{\ 3-} + H^+$ (McLean, 1976). Some of the aluminohexahydronium ions, $Al(OH)_6^{\ 3-}$, may remain in solution but most of them are adsorbed on cation exchange sites from which they are easily displaced with ordinary unbuffered salt solution such as 1<u>N</u> KCl, if the pH is below 5. If the pH is higher, $OH\text{-}Al^{2+}$ or $(OH)_2\text{-}Al^+$ is either formed before or after the ions are adsorbed to the cation exchanges sites. These ions polymerize as continuous layers on the interlayer surface of clay minerals, or they complex with reactive groups of organic compounds, neither of which are exchangeable with unbuffered salt solutions. Since these ions, both as monomers and as polymers, are only partially mineralized, they are acid and hence require a base such as lime for neutralization. Also when polymerized on the surface of clay minerals or complexed with organic matter, they are not readily accessible and may not be neutralized when lime is added. They obstruct exchange sites on the soil for other cations.

Adverse effects of Al on crop growth has been extensively investigated on Oxisols and Ultisols in Puerto Rico (Pearson, 1975). Adverse effects are usually noted when soil pH is 5.5 or less. Percentage aluminum saturation decreases very rapidly as the soil pH approaches 5.5 (Ayres et al., 1965; Fox et al., 1962; Pearson, 1975; McLean, 1976). Above pH 5.5 exchangeable Al is low and thus its detrimental effects on plant growth are minimal. Based on observations such as these Kamprath (1970) proposed that extractable Al serve as basis for liming soils.

The work of Ayres (1965) and his coworkers on Hawaiian soils show that small amounts of Al were extracted from the slightly weathered Dark Magnesium clay and Reddish brown soils (now classified as Vertisols and Ustollic Eutrandepts). Similarly only small quantities of Al were extracted from soils of highest pH belonging to the Low Humic latosols (now belonging to the Ustox and Torrox suborders). However, Al extracted from the soils of these suborders increased sharply with increased acidity. The mean value in the pH range 4 to 5 being 10 times greater than in the pH range 6 to 7. Greatest amounts of Al were extracted from the highly weathered Humic ferruginous, Humic and Hydrol Humic latosols (now classified as Humox, Humults, and Hydrandepts). Plucknett and Sherman (1963) found a direct relationship between rainfall and extractable aluminum.

Buffering Capacity. The pH buffering capacity of a soil is defined as the capacity of the soil to resist change in reaction with the addition of a base or acid (Matsusaka and Sherman, 1950). A soil with a high buffering capacity does not readily change its pH value. The buffering capacity of soils is affected by the amount and nature of the clay, as well as the organic matter content (Baver, 1931).

The buffering capacities of Hawaiian soils was extensively studied by Matsusaka and Sherman (1950). After studying the titration curves of over 100 Hawaiian soil samples some of their conclusions were:

1. Buffering capacities of Hawaiian soils are much lower than those of temperate regions.
2. Soils now belonging to the suborders Torrox, Ustox, and Humox are the least buffered, and soils now belonging to the great groups Hydrandepts and Dystrandepts exhibit the greatest buffering.
3. The organic matter of the soil affects the degree of buffering in a soil reaction above pH 5.5.
4. There is a direct relationship between the cation exchange capacity. The higher the exchange capacity the greater will be the buffering capacity of the soil.
5. Each soil group has a characteristic titration

curve. Thus the nature of the clay minerals determine the nature of the titration curve and the degree of buffering exhibited by the soil.

Lime Requirement. The lime requirement of soils is influenced by two main factors, namely soil pH and buffer capacity. For a given soil the lower the pH the higher the lime requirement and the higher the buffer capacity the larger the lime requirement.

The ultimate object of liming soils is improved crop production and thus the nature of the crop must be taken into consideration when lime recommendations are made. Different crops respond differently to lime applications even on the same soil and even more so, on different soils with different problems.

Methods for determining lime requirements have been studied extensively for many years. The direct approach is construction of lime curves. This is done by equilibrating small samples of soil with increasing amounts of lime. Soil pH vs. lime added is plotted. From such curves lime required to attain a desired pH can be obtained. Lime requirements in the temperate zone can be read directly from the curves. However, under tropical acid soils the observed lime requirement should be multiplied by a factor of 1.2 to obtain the amount of lime required for a field application

(Matsusaka and Sherman, 1964).

Kamprath's (1970) approach is based on exchangeable aluminum but it has a safety factor built in which suggests that more is involved than aluminum alone. The relationship for lime rate is as follows:

$$\text{meq exchangeable Al}/100\text{ g} \times 1.5 = \text{meq CaCO}_3/100\text{ g}$$

Using this factor approximately 86% of the exchangeable Al was neutralized. For very aluminum sensitive crops a factor of 2 should be used (Kamprath, 1970).

III. MATERIALS AND METHODS

The area selected for this study is commonly known as Central Maui. It extends from east of Puunene to the western slopes of the Haléakala volcano in a west to east direction, and from south of Ulupalakua to Pauwela in the south to north direction.

Elevation in the area sampled ranges from sea level to 1828 m, and the average rainfall ranges from 325 to 2500 mm, with a mean of 940 mm.

The area sampled is largely planted to sugarcane, pineapple, and pasture. A few of the sampled sites are used for forestry, and others for vegetable and flower production.

The study area included 18 soil series belonging to five different soil orders: Inceptisol, Ultisol, Oxisol, Mollisol, and Histosol. Inceptisols included the Andepts and the Tropepts. These soils are described in the soil survey of Hawaii (Foote et al.,1972). A brief description of the soil series follows.

Description of Soils

Inceptisols

Io Series (Typic Eutrandepts, medial, over cindery,isothermic). This series consists of well drained soils. These soils developed in volcanic ash and material weathered from cinders. They are moderately sloping to steep. Elevations range from 305 to 762 m. Mean annual rainfall is 635 to 889 mm and mean annual soil temperature is 20.5°C.

The surface layer is dark brown silty clay loam about 25 cm thick. The subsurface layer is dark brown silty clay loam about 18 cm thick. The subsoil, 25 to 76 cm thick, is dark brown and dark reddish brown clay loam that has subangular blocky stucture. The soil is neutral in the surface layer and mildly alkaline in the subsoil. Its permeability is moderately rapid and the runoff is slow to medium. These soils are used for pasture, truck crops, and wildlife habitat.

Kula series (Typic Eutrandepts, medial, isothermic). This series consists of well drained soils on uplands on the island of Maui. These soils developed in volcanic ash. They are gently sloping to steep. Elevations range from 607 to

1067 m. Mean annual rainfall is 635 to 1016 mm and mean annnual soil temperature is 19°C.

The surface layer is dark reddish brown loam about 20 cm thick. The subsoil, about 117 cm thick, is dark reddish brown loam, silt loam, silty clay loam that has subangular blocky stucture. The soil is slightly acid in the surface layer and slightly acid to neutral in the subsoil. Permeability is moderately rapid and runoff is medium. These soils are used for pasture, truck crops, and wildlife habitat.

Pane series (Typic Dystrandepts, medial, isothermic). This series consists of well drained soils on uplands in the island of Maui. These soils developed in volcanic ash. They are moderately sloping to moderately steep. Elevations range from 610 to 1069 m . Mean annnual rainfall is 762 to 1270 mm; it is well distributed throughout the year. Mean annual soil temperature is 19°C.

The surface layer is dark reddish brown silt loam about 20 cm thick. The subsoil, about 124 cm thick, is dark reddish brown, reddish brown, and dark brown silt loam and loam that has prismatic and subangular blocky structure. The soil is slightly acid in the surface layer and neutral in the subsoil. Its permeability is moderately rapid and runoff is slow to medium. These soils are used for pasture and wildlife habitat. Small acreages are used for pineapple.

Laumaia series (Typic Dystrandepts, medial, isomesic). This series consists of well drained soils on the island of Maui. These soils developed in volcanic ash and cinders. They are moderately sloping to very steep.. Elevations range from 1676 to 2438 m. Mean annual rainfall is 889 to 1778 mm. These soils are subject to cloud cover of fog most of the year. Mean annual soil temperature is 12°C.

The surface layer is very dark brown or black loam about 23 cm thick. The subsoil, about 84 cm thick, is very dark brown silty clay loam and silt loam that has subangular blocky structure or is massive. The soil is mildly alkaline in the surface layer and neutral to medium acid in the subsoil. Its permeability is moderately rapid and runoff is slow to medium. These soils are used for pasture and wildlife habitat.

Kaipoioi Series (Typic Dystrandepts, medial, isomesic). This series consists of well-drained soils on uplands on the island of Maui. These soils developed in volcanic ash and in material weathered from cinders. They are moderately sloping to steep. Elevations range from 1067 to 1829 m. Mean annual rainfall is 762 to 1143 mm, and mean annual soil temperature is 13°C.

The surface layer is black loam about 25 cm thick. The subsoil, about 129 cm thick, is black and very dark brown silt loam or silty clay loam that has subangular blocky structure. The substratum is ash and cinders. The soil is neutral in the surface layer and mildly alkaline to neutral in the subsoil. Its permeability is moderately rapid and runoff is slow to medium. These soils are used for pasture and wildlife habitat.

Uma Series (Typic Vitrandepts, cindery, isomesic). This series consists of excessively drained, sandy soils on intermediate mountain slopes on the island of Maui. These soils developed in volcanic ash and material weathered from cinders. They are on moderately sloping to very steep intermediate mountain slopes. Elevations range from 762 to 1829 m. Mean annual rainfall is 762 to 1016 mm. Afternoon fog and cloud cover are common. Mean annual soil temparature is 13°C.

The surface layer, about 15 cm thick, is black loamy coarse sand that has granular structure. The substratum is black, unweathered cinders. The soil is mildly alkaline in the surface layer. Its permeability is very rapid and runoff is slow. These soils are used for pasture, wildlife habitat and woodlands.

Haliimaile Series (Ustoxic Humitropepts, fine, kaolinitic, isothermic). This series consists of well drained soils. They are gently to strongly sloping. Elevations range from 152 to 610 m. Mean annual rainfall is 762 to 1290 mm of rain and mean annual soil temperature is 22°C.

The surface is dark reddish-brown silty clay about 38 cm thick. The subsoil, to a depth of more than 152 cm, is dark reddish-brown silty clay and very dark grayish-brown clay. It has subangular blocky and angular blocky structure. The soil is strongly acid in the surface layer and strongly acid to medium acid in the subsoil. Its permeability is moderately rapid and runoff is slow. These soils are used for sugarcane, pineapple and pasture.

Ultisols

Makawao series (Humoxic Tropohumults, clayey, oxidic, isothermic). This series consits of well-drained soils on uplands on the islands of Maui. These soils developed in volcanic ash and in material weathered from basic igneous rock. They are gently sloping to moderately sloping. Elevations range from 366 to 762 m. Mean annual rainfall is 1524 to 2286 mm, and mean annual soil temperature is 20°C.

The surface layer is dark reddish-brown silty clay about 23 cm thick. The subsoil, about 76 cm thick, is dark reddish-brown silty clay that has subangular blocky structure. The soil is strongly acid to medium acid in the surface layer and slightly acid in the subsoil. Its permeability is moderately rapid and runoff is slow. These soils are used for pasture, and small acreages are used for pineapple.

Haiku Series (Humoxic Tropohumults, clayey, ferritic, isothermic). This series consists of well-drained soils. Elevations range from nearly sea level to 336 m. Mean annual rainfall is 1270 mm to 2032 mm, and mean annual soil temperature is 21°C.

In a representative profile the surface layer is dark brown clay about 36 cm thick. The subsoil, about 79 cm thick, is yellowish-red, dark reddish-brown, and dark red clay or silty clay that has subangular and angular blocky structure. The soil is strongly acid throughout the profile. Its permeability is moderately rapid. These soils are used for pineapple and pasture.

Pauwela Series (Humoxic Tropohumults, clayey, ferritic, isothermic). This series consists of well-drained soils on uplands on the island of Maui. These soils developed in material weathered from igneous rock. They are gently sloping to moderately steep. Elevations range from 46 to 457 m. Mean annual rainfall is 178 to 3048 mm: it is well distributed throughout the year. Mean annual soil temperature is 21°C.

The surface layer is dark grayish-brown clay about 30 cm thick. The subsoil, about 53 cm thick, is dark reddish-brown clay that has angular blocky and subangular blocky structure. The soil is very stronly acid to extremely acid in the surface layer and subsoil. Its permeability is moderately rapid and runoff is slow. These soils are used for pasture and water supply. Small acreages are used for pineapple and woodland.

Mollisols

Pala Series (Typic Haplustolls, fine, kaolinitic, isohyperthermic). This series consists of well-drained soils on uplands on the island of Maui. These soils developed in material weathered from basic igneous rock. They are gently to moderately sloping. Elevations range from nearly sea level to 305 m. Mean annual rainfall is 635 to 1016 mm, and mean annual soil temperature is 23°C.

The surface layer is dark reddish-brown silty clay and clay about 48 cm thick. The subsoil, about 104 cm thick, is dark reddish-brown clay that has angular and subangular blocky structure. The soil is mildly alkaline in the surface layer and subsoil. Its permeability is moderate and runoff is slow. These soils are used for sugarcane.

Ewa Series (Aridic Haplustolls, fine, kaolinitic, isohyperthermic). This series consists of well drained soils on the islands of Oahu and Maui. These soils developed in alluvium derived from basic igneous rock. Elevations range from near sea level to 46 m. Mean annual rainfall is 254 to 762 mm, most of it occurring between November and April. Mean annual soil temperature is 23°C.

In a representative profile the surface layer is dark reddish-brown silty clay loam about 46 cm thick. The subsoil, about 107 cm thick, is dark reddish-brown and dark-red silty clay loam that has subangular blocky structure. The soil is neutral throughout the profile. Its permeability is moderate and runoff is slow. These soils are used for sugarcane and pasture.

Waiakoa Series (Aridic Haplistolls, fine, kaolinitic, isohyperthermic). This series consists of well-drained soils on uplands on the island of Maui. These soils developed in material weathered from basic igneous rock. The upper part of the profile is influenced by volcanic ash. These soils are gently sloping to moderately steep. Elevations range from 30.5 to 305 m. Mean annual rainfall is 305 to 508 mm; most of it occurs during the winter. The mean annual soil temperature is 23°C.

The surface layer is dark reddish-brown silty clay loam about 5 cm thick. The subsoil, about 58 cm thick, is dark reddish-brown and very dark grayish-brown silty clay loam that has prismatic structure or is massive. The soil is neutral in the surface layer and slightly acid to neutral in the subsoil. Its permeability is moderate and runoff is slow. These soils are used for sugarcane, pasture and wildlife habitat.

<u>Kamaole Series</u> (Aridic Haplustolls, clayey, over fragmental isothermic). This series consists of well drained soils on uplands on the island of Maui. These soils developed in volcanic ash. They are gently to moderately sloping. Elevations range from 457 to 701 m. Mean annual rainfall is 381 to 635 mm; most of it occurs in winter. Mean annual soil temperature is 20°C.

The surface layer is dark-brown and dark reddish-brown silt loam and silty clay loam about 20 cm thick. The subsoil, about 30 cm thick, is dark reddish-brown silty clay that has subangular blocky structure. The soil is medium acid and slightly acid in the surface layer and mildly alkaline in the subsoil. Its permeability is moderate, and runoff is slow to medium. These soils are used for pasture and wildlife habitat.

Pulehu Series (Cumulic Haplustolls, fine-loamy, mixed isohyperthermic). This series consists of well-drained soils on alluvial fans and stream terraces and in basins. They developed in alluvium washed from basic igneous rock. The soils are nearly level to moderately sloping. Elevations range from nearly sea level to 91 m. Mean annual rainfall is to 254 to 889 mm, and mean annual soil temperature is 23°C.

The surface layer is dark brown silt loam about 53 cm thick. This is underlain by dark-brown, dark grayish-brown, and brown, massive and single grain, stratified loam, loamy sand, fine sandy loam, and silt loam about 99 cm thick. Below this is coarse, gravelly or sandy alluvium. The soil is neutral in the surface layer and neutral to mildly alkaline below the surface layer. These soils are used for sugarcane, truck crops, pasture, and wildlife habitat.

Oxisols

Keahua Series. This series consists of well drained soils on uplands on the island of Maui. These soils developed in material weathered from basic igneous rock. They are gently sloping to moderately steep. Elevation range from 183 to 457 m. Mean annual rainfall is to 381 to 635 mm, and mean annual soil temperature is 23°C.

The surface layer is dark reddish-brown silty clay loam about 25.4 cm thick. The subsoil, about 127 cm thick, is dark reddish-brown silty clay loam and very dark gray clay loam that has subangular blocky structure. The soil is slightly acid in the surface layer and slightly acid to neutral in the subsoil. Its permeability is moderate, and runoff is slow. These soils are used for sugarcane, pasture and wildlife habitat. Small acreages are used for pineapple.

Molokai Series (Typic Torrox, clayey, kaolinitic, isohyperthermic). This series consists of well-drained soils on uplands on the island of Maui, Lanai, Molokai and Oahu. These soils formed in material weathered from basic igneous rock. They are nearly level to moderately steep. Elevations range mainly from nearly sea level to 305 m. Mean annual rainfall amounts to 508 to 635 mm, most of which occurs between November and April. The summers are hot and dry. Mean annual soil temperature is 23°C.

The surface layer is dark reddish-brown silty clay loam about 38 cm thick. The subsoil, about 145 cm thick, is dark reddish-brown silty clay loam that has prismatic structure. The soil is slightly acid to neutral, except those areas used for pineapple are commonly very strongly acid or extremely acid in the surface layer. These soils are used for sugarcane, pineapple, pasture, and wildlife habitat.

Histosols

Kaimu Series (Typic Tropofolists, euic, isohyperthermic). This series consists of well-drained, very shallow soils on uplands on the island of Maui. These soils developed in organic material. They are moderately sloping to moderately steep. Elevations range from 305 to 1067 m. Mean annual rainfall is to 762 to 1270 mm, and mean annual soil temperature is 20°C.

The surface layer is extremely stony black peat about 20 cm thick. The substratum is fragmental Aa lava that has a little soil material in voids and cracks. The soil is neutral in reaction. Its permeability is very rapid and runoff is very slow. These soils are used for pasture and wildlife habitat.

Very Stony land

This land type consists of areas where 50 to 90 percent of the surface is covered with stones and boulders. It is mapped on the islands of Maui, Molokai and Lanai. The slope ranges from 7 to 30 percent. Included in mapping were very steep gulches. On Maui, this land type consists of young Aa lava that has a thin covering of volcanic ash that locally extends into cracks and depressions. It occurs as large areas, mainly on the upper slopes of Mt. Haleakala at elevations between 1219 and 2743 m. Mean annual rainfall is to 762 to 1016 mm. The ash covered areas support a stand of shrubs and grasses.

Soil Sampling

Soil sampling was based on the following considerations:

1. Sample along transects (or on a grid) which traverse a range of one or more soil forming factors such as temperature, rainfall,and elevation.
2. Sample according to soil classification information.
3. Samples included soils that are predominant in an area.

Preliminary sampling was done in August of 1981. A total of 53 sites were sampled along two transects (refer to Figure 2 for location of sites and transects). Transect No. 1 (43 sites) lay in a south to north direction, starting from south of Ulupalakua in the south and going north along the Kula highway, past Pukalani, Makawao, Kokomo to Pauwela in the north. Transect No. 2 (10 sites) lays in a west-east

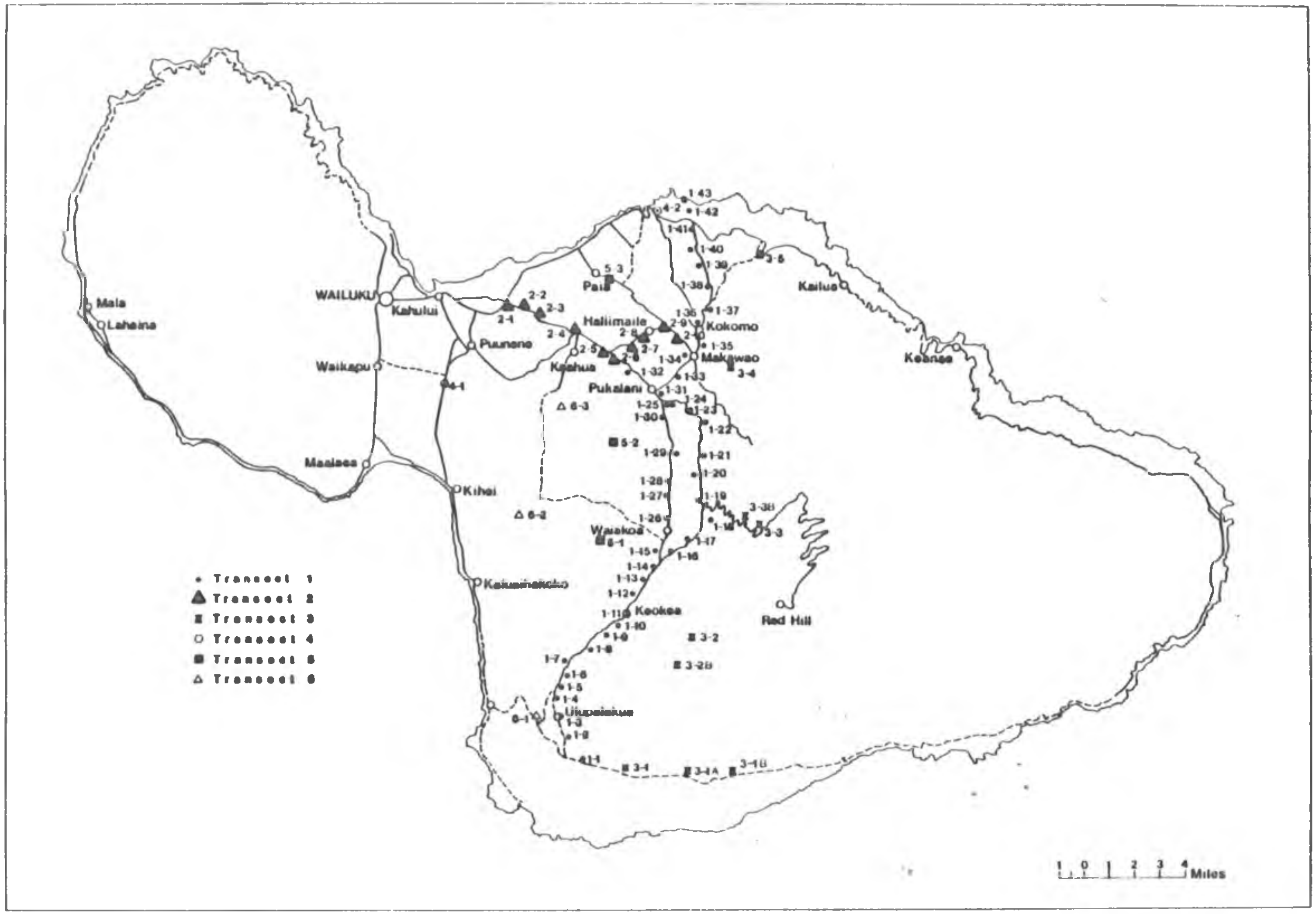

Figure 2. Location of sample sites, and transects on the island of Maui.

direction, starting near Puunene in the west, along the Haleakala highway, past Keahua, Haliimaile, and joins transect No. 1 at Makawao. Material from two depth increments, 0 to 15 cm and 30 to 45 cm, were collected at each site. The upper sample should reflect the prevailing nutrient status as affected by management, and the lower one is likely to be less affected by soil management. The lower sample may also indicate the kind of soil condition that will develop if erosion or earth moving exposes this material at the surface.

Soil samples were placed in plastic bags and labeled. Location, vegetation, and other important features of the sampled area were recorded on the soil survey maps as the samples were taken. Soil samples were air dried, and screened through a 2 mm sieve. Moisture of each soil sample was determined by weighing approximately 10 g of air dried soil and oven drying for 24 hours at 105°C.

Soil pH, phosphorus and silicon in saturation extracts, 1 N ammonium acetate Ca, Mg, Na and K, and KCl-extractable aluminum, were determined on all soil samples. Phosphate adsorption isotherms were constructed for all soil samples following the procedure of Fox and Kamprath (1970). These data along with the location of sites were stored in a computer, and isotropic semi-variograms for each of the properties were constructed. From these semi-variograms, the range of influence of each of the properties was determined, and an overall average range was calculated. The computed average range was used to determine an adequate approximate sampling distance for the second sampling.

A second sampling to fill in gaps, that were left unsampled during the first sampling was accomplished in August, 1982. A total of 17 sites were sampled. They constitute transects No. 3, 4, 5, and 6. All soil samples were then further analyzed for: Olsen P, Bray No. 1 P, and calcium phosphate extractable sulfur. Lime curves were constructed for all soils having a pH of 5.8 or less, and sulfate adsorption curves were constructed for all soil samples.

Analytical Methods for Soils

Soil pH

Soil pH was measured in a soil:water suspension in a 1:1 ratio. Ten grams of soil (oven dry basis) were placed on 50-ml centrifuge tubes and 10 ml of water were added. The mixture was stirred and equilibrated for 1 hour with occassional stirring. Soil pH was measured using a pH meter. The soil was stirred just prior to immersion of electrodes so that the measurment was made on a suspended sample.

Exchangeable Bases: Ca, Mg, Na and K

Calcium, magnesium, sodium, and potassium were extracted with 1 N Ammonium acetate adjusted to pH 7.0, by placing 5 g of soil in 250-ml Erlenmeyer flasks. One hundred ml of 1 N NH_4OAc (pH 7.0) were added into the flask, and samples were shaken for half an hour on a reciprocating shaker. Samples were then filtered through a Whatman No. 42 filter paper and the filtrate collected.

Calcium and magnesium in the filtrate, were determined by atomic absorption spectroscopy. Sodium and potassium in the filtrate were determined by flame emission spectroscopy and the concentrations read from appropiate standard curves. Concentrations of all the cations were expressed in meq base/100 g of soil.

Silicon in Saturation Extracts

Silicon in saturation extracts was determined by placing soil samples (> 50 g) into leaching tubes. Water was added slowly with a squeeze bottle until the soils were saturated after which the systems were covered with a plastic sheet and allowed to stand for two days. Then, 1 or 2 ml aliquots of water were added to the columns at intervals of 5 to 10 minutes until 8 to 10 ml of solution were displaced (Fox, 1981).

Silicon in solution was determined by the silico-molybdate method of Kilmer (1965). A suitable aliquot, usually 5 ml, was placed into a 50 ml volumetrick flask and glass distilled water was added until the flask was about two-thirds full. One milliliter of ammonium molybdate solution was added and mixed; this solutiom was prepared by dissolving 7.5 g of ammonium molybdate in 75 ml of water and then adding 10 ml of 18 N H_2SO_4 and diluting to a volume of 100 ml with water. Thirty minutes were allowed for color development. Three milliliters of 10% oxalic acid solution were added, care being taken to allow it to run down the glass neck of the flask to destroy any phospho-molybdate compound that had formed. After one to two minutes, l ml of reducing solution was added and mixed well. Thirty minutes were allowed for color development and the optical density was read at 650 nm. The Si concentration was obtained by referring to a standard curve and expressed in ug/ml of solution. The reducing solution was prepared by dissolving 0.7 g of sodium sulfite in 10 ml of water after which 0.15 g of 1-amino-2 napthal-4-sulfonic acid was added and stirred. This solution was then added to 9 g of sodium bisulfite dissolved in 90 ml of water. Glass distilled water was added to volume and mixed again.

Phosphorus in Saturation Extracts

Phosphorus in saturation extracts was recovered in the same manner as silicon in saturation extracts. Ten milliliters of solution were used for color development by the ascorbic acid method of Murphy and Riley (1962).

Olsen Phosphorus

Sodium bicarbonate extractable phosphorus was determined by the procedure of Olsen et al. (1954). Five grams of soil (oven dry basis) was extracted with 100 ml of 0.5 M $NaHCO_3$ (pH 8.5) in 250 ml Erlenmeyer flasks. Samples were shaken for half an hour in a wrist action shaker. The solution was filtered through a Whatman No. 42 filter paper, and the optical density of the aliquots was read at 700 nm. One to two milliliter aliquots were used for actual color development and optical density read again at 700 nm. For each milliliter of aliquot, one milliliter of 0.5 $\underline{N}$ H_2SO_4 were added so that the pH of the system would be correct for color development.

Bray and Kurtz No. I Phosphorus

Acid flouride extractable phosphorus was determined by the procedure of Bray and Kurtz (1945). Five grams of soil (oven dry basis) was extracted with 50 ml of solution which was 0.03 N in reference to NH_4F and 0.025 N in reference to HCl. Extraction was done on 250 ml Erlenmeyer flasks shaken for five minutes with a wrist action shaker. The solution was filtered through Whatman No. 42 filter paper and 10 ml aliquots were used for color development.

Phosphorus Adsorption Curves

The procedure for constructing P sorption curves was that of Fox and Kamprath (1970). Three gram soil samples (oven dry basis) were placed on 50 ml centrifuge tubes. Thirty milliliters of 0.01 M $CaCl_2$ containing increasing amounts of P as $Ca(H_2PO_4)_2$ were added and samples were equilibrated for six days. Two drops of toluene were added to each sample to retard microbial activity.

The samples were shaken twice daily for 30 minute periods. The equilibrated samples were centrifuged in a super-speed centrifuge at 15,000 rpm for 15 minutes. An aliquot, usually 10 ml, was used to determine P in solution. Phosphorus which dissappeared from solution was considered to have been sorbed. Plots of sorbed P against P in solution were constructed, and from them the amount of P sorbed at 0.02 and 0.2 ug P/ml were read and recorded. The buffering capacity of the soils, in relation to P, was determined by calculating the slope of the curve between 0.15 and 0.25 ug P/ml.

Exchangeable Aluminum

Aluminum was extracted from soil samples having a pH of 5.5 or less. The extractant was I N KCl. Five grams of soil (oven dry basis) was extracted with 125 ml of I N KCl in 250 ml Erlenmeyer flasks. Samples were shaken for half an hour in a wrist-action shaker and then filtered through a Whatman No. 42 filter paper. Aluminum in the filtrate was determined by titration using the procedure described by McLean (1965).

Extractable Sulfur

Extractable sulfur was determined by a turbidimetric method described by Fox (1983, in revision). Three grams of soil (oven dry basis) was extracted with 30 ml of 0.04 M $Ca(H_2PO_4)_2$ in 50-ml centrifuge tubes. Samples were shaken continuously for 16 hours in a reciprocating shaker.

The extractant was prepared by adding 89 g of phosphoric acid (88%) to about 5 liters of distilled water. A suspension containing 40 g of $CaCO_3$ in one liter of water was added to the above solution slowly and with constant stirring. The solution was then diluted to a little less than 10 liters and its pH adjusted to 4.0 with a saturated $Ca(OH)_2$ solution. Volume was made to 10 liters Blakemore et al.. (1981). The solution was then centrifuged in a super-speed centrifuge at 10,000 rpm for 10 minutes and 20 ml of the supernatant solution were decanted into another centrifuge tube.

Two tenths of a gram of activated charcoal were added and stirred occasionally. (The charcoal had been prepared by boiling 250 g of charcoal (e.g. Norit NK) with 250 ml of 1 + 1 HCl for 10 to 15 minutes. The charcoal was allowed to settle down and the supernatant liquid was decanted. The charcoal was then washed thoroughly in a Buchner funnel with distilled water and dried at 105° C). After 30 minutes, samples were filtered and the clear extract obtained was used for analysis. Five ml of the decolorized extract was transferred into a 30 ml beaker and evaporated to dryness in a drying oven at approximately 100°C. The residue is white. After the beaker containing the residue had cooled down, l ml of acid-sulfate spike solution was added. (The spike solution was prepared by adding 40 ml of 1 + 1 $HCl-H_2O$ and 20 mg of SO_4-S to a 1 liter volumetric flask and diluting to volume (one milliliter of this solution contains 20 ug of S)). The beaker was rotated continuously until the residue was dissolved, then l ml of $BaCl_2$-seed crystal gelatin reagent was added and the beaker swirled. (The $BaCl_2$-seed crystal gelatin reagent was prepared by dissolving 0.6 g of gelatin (Difco Bacto-Gelatin, Difco Laboratory Inc., Detroit Mich) in 200 ml of hot water (60-70°C). The preparation was then allowed to stand at approximately 4°C for 16 hours. One hundred ml of the gelatin solution were brought to room temperature and 1 g of $BaCl_2$-$2H_2O$ was added and mixed well until the $BaCl_2$-$2H_2O$ was dissolved. The reagent was stored in a refrigerator (maximum storage 1 week) and before using it, it was allowed to stand at room temperature for at least two hours). After 5 minutes, 10 ml of Barium chloride reagent, prepared by adding 10 g of $BaCl_2$-$2H_2O$ to 1 liter of distilled water, were added and contents in the beaker swirled again. After 30 minutes, the suspension was titurated with a rubber policeman, swirled and immediately transferred to a cuvette. Absorbance was read at 600 nm, and the SO_4-S concentration was determined from an appropiate standard curve.

Sulfate Adsorption Curves

For the purpose of constructing S sorption curves, 3 g soil samples (oven dry basis) were placed on 50-ml centrifuge tubes and equilibrated with 30 ml of 0.01 M $CaCl_2$ containing increasing amounts of SO_4-S. Equilibration was carried out on a reciprocating shaker by continuous shaking for 24 hours. Two drops of toluene were added to each sample to retard microbial growth. The equilibrated samples were centrifuged in a super-speed centrifuge at 10,000 rpm for 10 minutes. Appropiate aliquots of the supernatant solution were treated in the same manner as those for extractable sulfur to determine the SO_4-S remaining in solution. Sulfate sulfur which disappeared from solution was considered to have been sorbed. Plots of sorbed SO_4-S against SO_4-S in solution were constructed and from them, the amount of SO_4-S sorbed at 5 ug S/ml were read and recorded.

Lime Curves

Lime curves were constructed for all soils having a pH of 5.8 or less. From the curves the amount of $Ca(OH)_2$ required to attain pH 6.0, 6.5 and 7.0 were read and recorded.

Ten gram soil samples (oven dry basis) were placed on 50 ml centrifuge tubes. Increasing amounts of a saturated solution of $Ca(OH)_2$ (limewater 0.042 N) were added and the volume was adjusted to 25 ml with water. The samples were equilibrated for 8 days with occasional shaking. Soil pH was read on the sample every two to three days until equilibrium had been reached. Generally, the samples took 7 to 8 days to equilibrate. Plots of pH vs. meq $Ca(OH)_2$ added/100 g of soil were plotted.

Statistical and Geostatistical Analysis Procedures

Statistical calculations were made using the Statistical Analysis System (SAS) (Barr et al., 1979).

Semi-variances and semi-variograms were calculated and plotted using the method described by Matheron (1963). Interpolation of data points, was done by point kriging as described by Journel and Huijbregts (1978).

Mapping of both the original and kriged data was done by a contouring computer program as described by Bridges and Becker (1976).

Partitioning variation of soil chemical properties according to Soil Taxonomy (Soil Survey Staff, 1975), were done by using the General Linear Model (GLM) procedure.

IV. RESULTS AND DISCUSSION

Partitioning Variation in Soil Chemical Properties

Soil Taxonomy is a hierarchical classification system. It subdivides soils progressively into new groups or categories until individual soils are classified or identified. Thus, soil mineralogical and chemical properties and soil behavior, which is based on those properties, can be predicted more accurately by each successive subdivision of the soil classification system.

The model used in this study is the same model used by Soil Taxonomy in grouping soils, namely: order, suborder, great group, subgroup, family, and series. The mapping unit level was also included even though we recognize that it is not part of Soil Taxonomy. This same model was used by Yost and Fox (1981) for a similar study using soils of the suborder Andepts. In this study soils belonging to five different orders were considered.

A residual mean square was calculated for each successive category of the classification scheme (i.e. order, suborder, great group, etc.) and expressed as a percent of the total variance. These values were then plotted against the number of taxa in each taxonomic category (Figures 3 through 7). Residual mean square represents the random or unexplained variation that occurs among soils. Therefore, the residual mean square serve as good criteria to account for the variation of chemical properties among soils. The other component of variation among soils is systematic variation, which Soil Taxonomy should account for (Yost and Fox, 1981). The Soil Taxonomy category that gave the greatest decrease residual mean square was considered to be the best partition of variability among soils.

The variation among surface soils of exchangeable magnesium and potassium and for exchangeable magnesium in the subsoil (Figures 1, 2, and 5) was best partitioned at the family level. The mapping unit level produced the lowest percent residual mean square in the case of surface soils pH, exchangeable calcium, silicon in saturation extracts, and in the case of subsoil pH and exchangeable calcium (Figures 1, 2, and 5). However, the percent residual mean square associated with the mapping unit was not very different from that of the family level for these soil properties, and in fact the greatest decrease in percent residual mean square was associated with the family level. In other words, the variation in these chemical properties among soils is accounted best by the mapping unit; but moving within the hierarchical progression from the family level to the mapping unit level produces little refinement and thus, for all

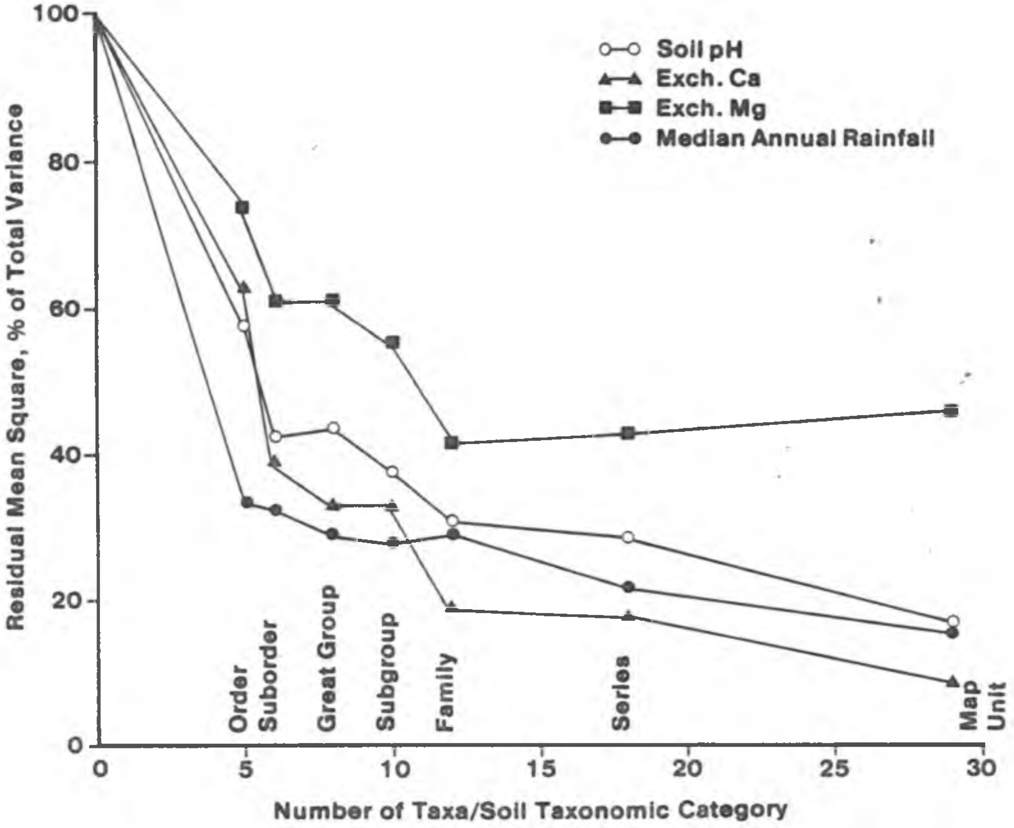

Figure 3. The variation of pH, exchangeable Ca and Mg, and annual median rainfall expressed as a percent of the total variance.

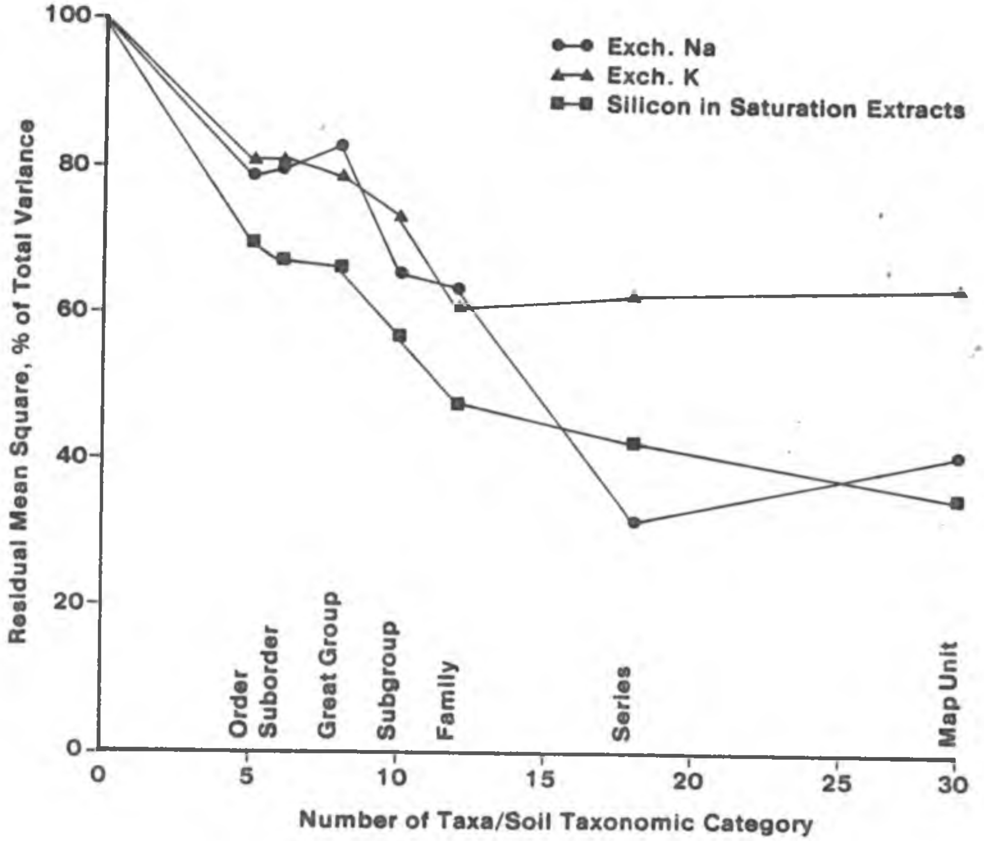

Figure 4. The variation of exchangeable Na and K, and Si in saturation extracts expressed as percent of total variance.

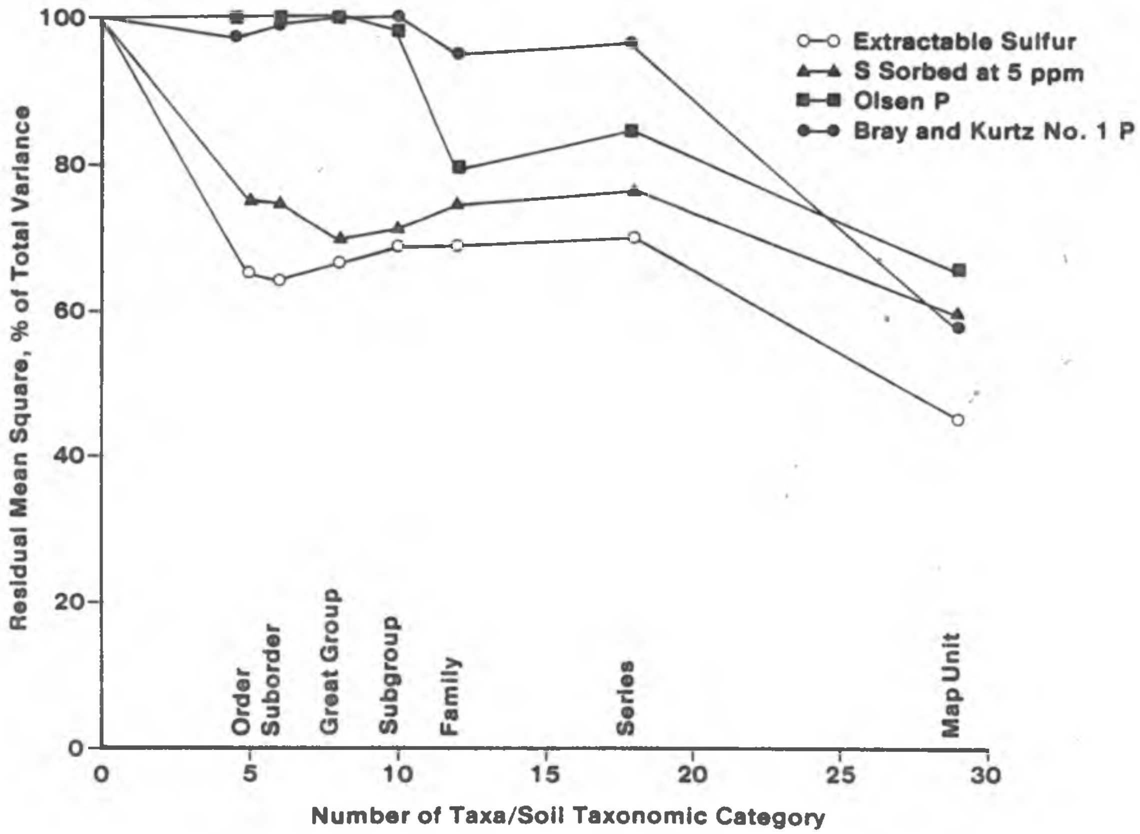

Figure 5. The variation of extractable S, S sorbed at 5 ppm, Olsen P, and Bray No. 1 P expressed as percent of total variance.

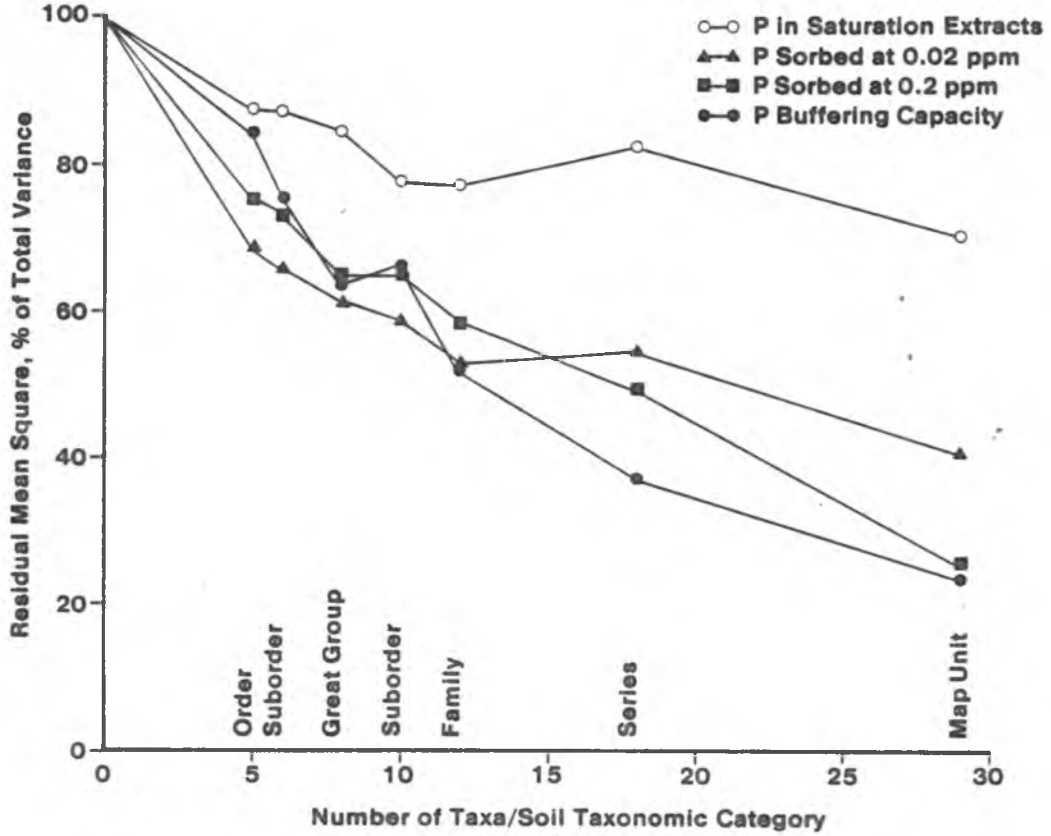

Figure 6. The variation of P in saturation extracts, P sorbed at 0.02 ppm, P sorbed at 0.2 ppm, and P buffering capacity expressed as percent of total variance.

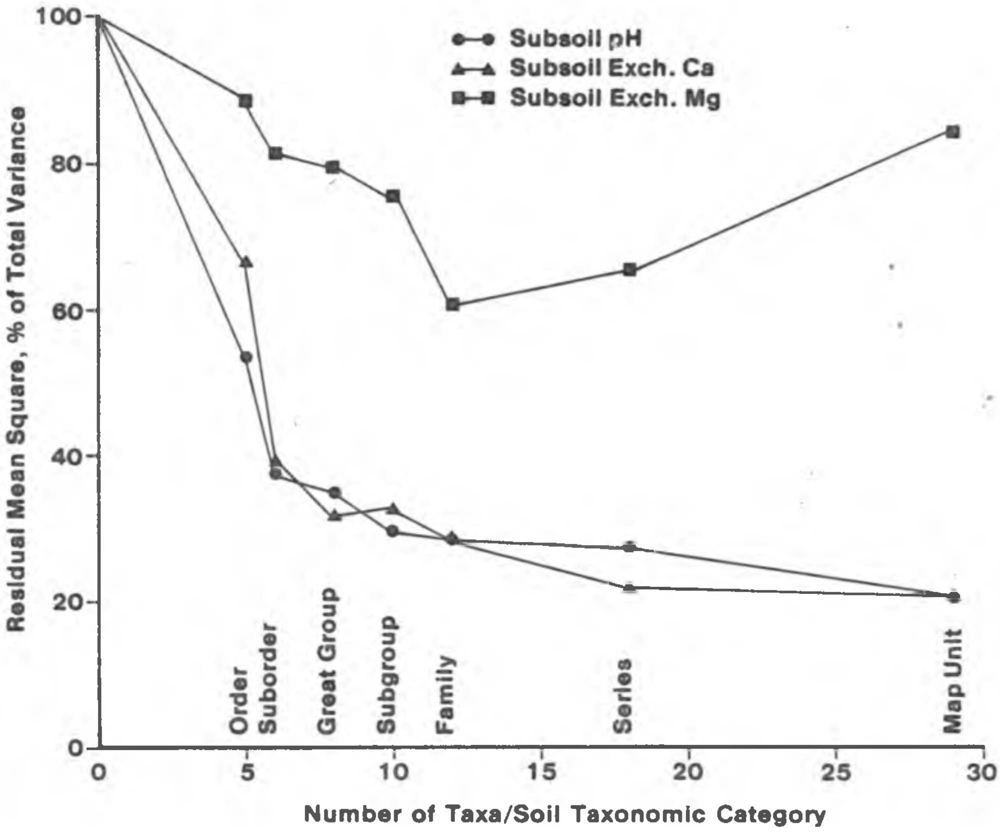

Figure 7. The variation of subsoil pH, and exchangeable Ca and Mg expressed as percent of total variance.

practical purposes, variation can be partitioned best at the family category. These results are not surprising because the criteria used by Soil Taxonomy to group soils into families are important for determining chemical properties; these are: broad soil textural classes average over control section or solum; mineralogical classes or dominant mineralogy of solum; and soil temperature classes based on mean annual soil temperature at 50 cm. depth (Soil Survey Staff, 1975; Buol et al., 1980).

The variation among soils in extractable sulfur, sulfur sorbed at 5 ppm, Olsen P, Bray No. 1 P, P sorbed at both 0.02 and 0.2 ppm, and P buffering capacity, was best accounted for by the mapping unit level. The criteria used to divide soils into mapping units is soil texture; thus, apparently soil texture plays a very important role in determining how much phosphate and sulfate can be sorbed by soils, and how much phosphate and sulfate can be extracted from the soil. Soil texture is first used in Soil Taxonomy at the family level. However, the variation of these chemical properties among soils was not effectively partitioned by the family level, probably because at this level only the broad soil textural classes are used. Only at the mapping unit level is the actual texture of the soil used as a criteria to group soils. As it will be seen later, the separation of means of sulfur and phosphorus was best at the mapping unit level. For example, in the case of extractable P, mean separation only occurs at this level. These results of course agree with the results of percent residual mean square. Soil texture influences P sorption and S sorption by soils because soil texture and specific surface are closely related. Thus, other factors being equal, soils with high specific surface sorb more S and P than other soils. How strongly soils tend to sorb or retain these anions may influence the amount of P and S that can be extracted. In this study, when the different mapping units were treated as distinct textural classes, those that were silt, silt loam, and silty clay also had the largest amounts of extractable P. Soils that were loams and clays corresponded to soils having the lowest amounts of extractable P.

Yost and Fox (1981) determined that the great group level gave the best partitioning of variation of chemical properties among selected soils of the suborder Andepts. The soils they worked with were similar, probably because they developed from similar parent materials which gave rise to similar mineralogical classes. In their study, the great group category accounted for approximately 75 percent of the variation of the chemical properties studied. This is expected because the great group was the first category into which soils were divided, and when working with soils belonging to only one taxa (i.e. Andepts) it is likely that the first subdivision will account for most of the variation. The study which is the subject of this thesis, soils of five different orders were selected; and as a result, the outcome from this study was different from that of Yost and Fox (1981).

Soil pH, Buffering Capacity, and Lime Requirement

The pH of surface soils ranged from 3.2 to 7.7 and the mean value was 5.5 (Table 3). In subsurface soils the average pH was 5.6 and values ranged from 3.1 to 7.6 (Table 4). Generally, the pH of subsurface soils was larger than that of the surface soils. Similar observations has been previously reported (Fox 1981; Fox, 1982).

Average pH values of soils belonging to different orders are presented in Tables 5 and 6. Ultisols, which developed under the wettest conditions and had the lowest concentration of exchangeable bases, had the lowest average pH value, 4.4. On the other hand, Mollisols which developed under relatively dry conditions and had large concentrations of exchangeable bases, had the largest average pH value, 6.3.

Under humid tropical conditions, it has been reported that best plant growth is obtained at the pH range 5.5 to 6.0 (Kamprath, 1970), because in this pH range Al and Mn toxicities are relatively unimportant and above pH 6.0

Table 3. Mean, standard deviation, minimum, and maximum of chemical properties of surface soils from the island of Maui.

Soil Chemical Property	Mean	Standard Deviation	Minimum	Maximum
pH	5.5	0.9	3.2	7.7
Ca (meq/100 g)	16.2	12.7	0.2	40.2
Mg (meq/100 g)	4.5	3.7	0.05	20.7
K (meq/100 g)	1.3	1	0.07	4.3
Na (meq/100 g)	0.5	0.8	0.05	5.8
Si in saturation extracts (ug/ml)	9.1	4.3	1.8	21.7
P in saturation extracts (ug/ml)	0.033	0.039	0.001	0.195
P required at 0.02 ppm (ug/g)	84	152	-300	385
P required at 0.2 ppm (ug/g)	520	345	58	1765
P buffering capacity (ug/g)	132	90	30	585
Olsen P (ug/g)	18	17	0.6	82
Bray No. 1 P (ug/g)	9.6	8.8	0.13	44
Al (meq/100 g)	0.36	0.79	0.0	3.32
SO_4-S (ug/g)	124	128	34	659
S required at 5 ppm (ug/g)	11	45	121	102

n=70

Table 4. Mean, standard deviation, minimum, and maximum of chemical properties of subsurface soil samples from the island of Maui.

Soil Chemical Property	Mean	Standard Deviation	Minimum	Maximum
pH	5.6	1.1	3.1	7.6
Ca (meq/100 g)	13.6	12	0.13	38.5
Mg (meq/100 g)	3.7	4.6	0.03	32
K (meq/100 g)	0.8	0.9	0.04	5.4
Na (meq/100 g)	0.5	0.6	0.05	3.8
Si in saturation extracts (ug/ml)	5.46	3.33	0.57	15.17
P in saturation extracts (ug/ml)	0.021	0.032	0.001	0.163
P sorbed at 0.02 ppm (ug/g)	215	211	-175	1080
P sorbed at 0.2 ppm (ug/g)	768	608	25	3760
P buffering capacity (ug/g)	169	144	17	840
Olsen P (ug/g)	12	14	0.5	73
Bray No. 1 P (ug/g)	4.3	5.8	0.09	24.9
Al (meq/100 g)	0.43	0.82	0.0	3.93
Sulfur (ug/g)	144	146	0.0	688
S sorbed at 5 ppm (ug/g)	35	66	-110	265

n=63

Table 5. Mean of chemical properties of surface soil samples partitioned by order.

Soil Chemical Property	Soil Order				
	Mollisols	Oxisols	Histosols	Inceptisols	Ultisols
			means		
pH	6.3a	5.9ab	5.8ab	5.6b	4.4c
Ca (meq/100 g)	11.6bc	9.5c	37.1a	21b	4.4c
Mg (meq/100 g)	7.1ab	4.4b	8a	4.9ab	0.9c
K (meq/100 g)	1.9a	1.3ab	1.7a	1.4a	0.4b
Na (meq/100 g)	1.6a	0.7a	0.4a	0.3a	0.2b
Si in saturation extracts (ug/ml)	12.5ab	10.3ab	13.1a	9.2b	4.6c
P in saturation extracts (ug/ml)	0.075a	0.034ab	0.045ab	0.031ab	0.016b
P sorbed at 0.02 ppm (ug/g)	-8b	68b	-187c	88b	233a
P sorbed at 0.2 ppm (ug/g)	188b	266b	235b	614a	712a
P buffering capacity (ug/g)	56b	57b	109ab	163a	141ab
Olsen P (ug/g)	26.4a	14.5a	19.6a	20.3a	11.8a
Bray No. 1 P (ug/g)	12.7a	8.7a	19.1a	9.6a	7a
SO_4-S (ug/g)	65b	70b	131b	89b	279a
Sulfur sorbed at 5 ppm (ug/g)	-10a	-21a	-147b	11a	25a
Al (meq/100 g)	0.012b	0.022b	0.0b	0.097b	1.455a
Median annual rainfall (mm)	570c	570c	758bc	849b	1696a

Means followed by the same letter are not significantly different at the 5% level by the Waller-Duncan K-ratio t-test.

Table 6. Mean of chemical properties of subsurface soil samples partitioned by order.

Soil Chemical Property	Soil Order			
	Mollisols	Oxisols	Inceptisols	Ultisols
	means			
pH	6.5a	6.0ab	5.8b	4.2c
Ca (meq/100 g)	10.1b	8.3b	14.4a	2.4b
Mg (meq/100 g)	6.1a	3.6ab	4.5ab	0.5b
K (meq/100 g)	1.4a	0.7ab	0.8ab	0.3b
Na (meq/100 g)	1.2a	0.7ab	0.5bc	0.2c
Si in saturation extracts (ug/ml)	6.2a	4.8a	5.8a	3.7a
P in saturation extracts (ug/ml)	0.024	0.020a	0.021a	0.0075a
P sorbed at 0.02 ppm (ug/g)	98a	125a	239a	277a
P sorbed at 0.2 ppm (ug/g)	373b	364b	944a	807ab
P buffering capacity (ug/g)	75b	81b	217a	159.9ab
Olsen P (ug/g)	11.7a	10.6a	12.9a	10.1a
Bray No. 1 P (ug/g)	5.2a	4.5a	3.3a	5.6a
SO_4-S (ug/g)	75b	66b	98b	324a
Sulfur sorbed at 5 ppm (ug/g)	-1.7b	8a	49a	38a
Al (meq/100 g)	0.005b	0.011b	0.167b	1.504a

Means followed by the same letter are not significantly different at the 5% level by the Waller-Duncan K-ratio t-test.

reduced plant growth may occur. Furthermore, to raise the pH of very acid soils above 6.0 is usually costly.

Calcium hydroxide titration curves were constructed for all soil samples having a pH of 5.8 or less. A total of 41 surface soils were represented in this group. Typical titration curves for each of the mineral soil orders are presented in Figure 8. Table 7 presents the average lime requirement to attain different pH's, average buffering capacity, and mean values of exchangeable Al for each of the soil orders.

Ultisols, represented in Figure 8 by a member of the Haiku series, required the largest amounts of lime to attain standard pH's. At the same time, they were the most buffered soils at pH ranges 5.5 to 6.0, and 6.0 to 6.5. At pH range 6.5 to 7.0 their buffering capacity was second largest. At this pH range Inceptisols were the most buffered soils. In the range 5.5 to 6.0 the buffering capacity is given only for Ultisols and Inceptisols because there were no samples belonging to Oxisols and Mollisols that fell in this range. Mollisols required the smallest amounts of lime to attain standard pH's, and were also the least buffered soils in the pH range 6.0 to 6.5. At pH 6.5 to 7.0 Oxisols were the least buffered soils. Results obtained in this study for Oxisols, Ultisols, and Inceptisols are not very different from those obtained by Fox when working with highly weathered

Puerto Rico soils (Fox, 1982). In that particular study, Fox found that Ultisols required the largest lime and were the most highly buffered, followed by Inceptisols, and then by Oxisols.

The results presented in Table 7, clearly show that these soils are weakly buffered in the pH range 5.0 to 6.0, but as pH increases to 7 the buffering capacity increases tremendously (Uehara and Gilman 1981). This seems to be a pattern followed by highly weathered soils which have a considerable pH dependent charge. Thus, largeamounts of lime are required to supply the OH^- ions necessary to neutralize protons which have been specifically adsorbed by the variable charge colloids. In this study consumption of lime at pH 6.5 to 7.0 was approximately twice the amount consumed at pH 5.5 to 6.0. Similar results have been reported by Fox for Puerto Rico, New Zealand, and Hawaii soils (Fox, 1981; Fox, 1982;). Therefore, only small quantities of lime may suffice to raise the pH of a soil to 5.5 or 6.0; however, to raise the pH to 6.5 or 7.0, which is required for optimum growth of some legumes, large amounts of lime are needed. This is expensive. As a result, for the most part in the tropics it will be economical to raise the soil pH to 5.5 thereby eliminating Al toxicities and providing exchangeable bases such as Ca, Mg, and K which are good for plant growth.

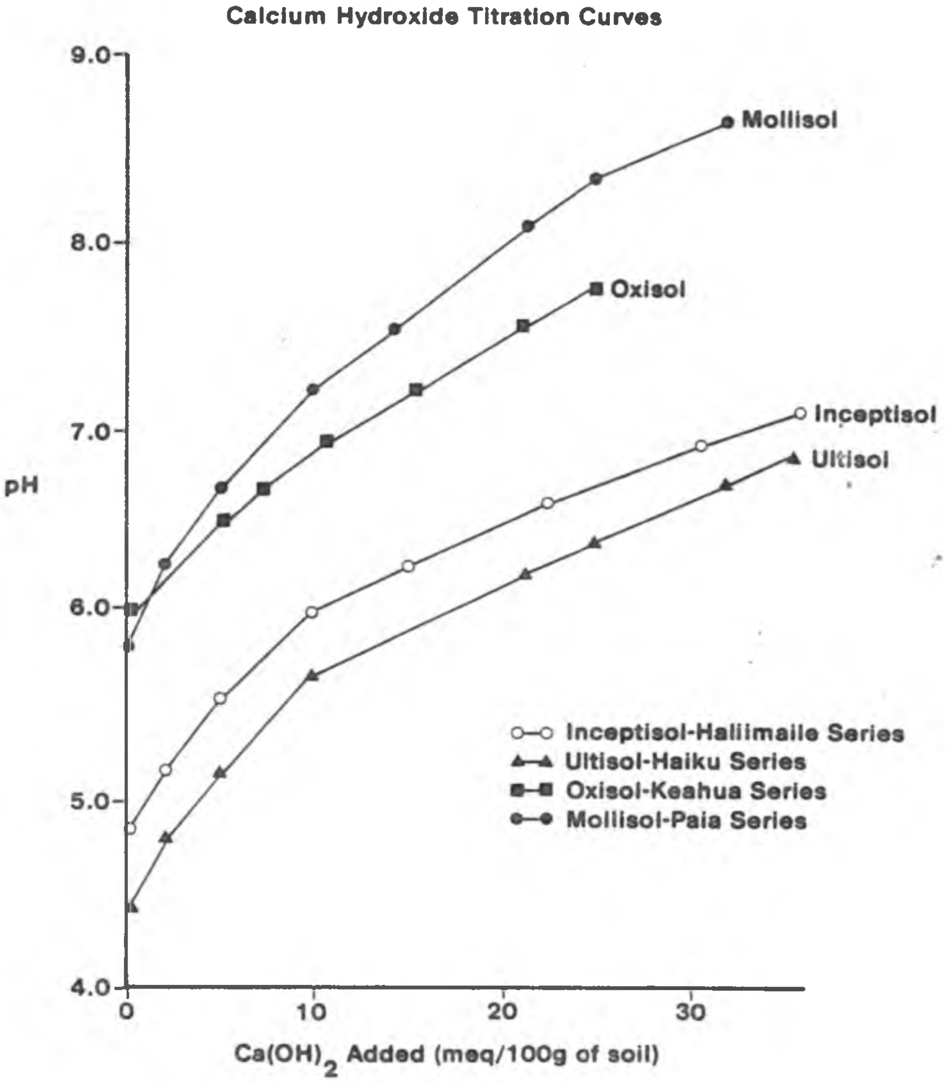

Figure 8. Calcium hydroxide titration curves for surface soils of selected soil orders of the island of Maui.

Table 7. Average lime requirements, buffering capacities, and exchangeable aluminum of surface soils belonging to the orders Ultisol, Inceptisol, Oxisol, and Mollisol.

	Ultisols	Inceptisols	Oxisols	Mollisols
$Ca(OH)_2$ required to attain indicated pH (m.eq/100 g)				
5.5	5.0	4.1		
6.0	8.6	5.6	0.0	0.5
6.5	15.1	9.3	3.2	2.3
7.0	25.0	22.6	8.0	7.9
Buffering capacity at indicated pH interval (meq/100 g)				
5.5 - 6.0	4.1	1.5		
6.0 - 6.5	7.5	3.8	2.3	1.9
6.5 - 7.0	9.9	13.3	3.7	5.6
Exch. Aluminum (meq/100 g)	1.46	0.10	0.02	0.01

Aluminum concentration of soils was measured on all soils having a pH of 5.5 or less. Means presented in Table 7 were calculated assuming that soils having a pH of 5.6 or above contained no Al. Ultisols had the largest concentraion of Al, 1.45 meq/100g of soil, followed by Inceptisols, Oxisols, and last Mollisols. Aluminum plays a very important role in soil acidity, and in most parts of the humid tropics lime is applied to reduce Al toxicities to plants. Above pH 5.5 Al saturation is reduced to a point where it is no longer harmful to plants, and therefore, liming to pH 5.5 is usually sufficient and economical for tropical soils (Kamprath, 1970). Lime requirements and buffering capacities of subsoil materials were generally smaller than those of surface materials. Also, the same tendencies observed in surface soils of the different soil Orders were observed for subsoils.

Silicon in Saturation Extracts

For surface soils silicon in saturation extracts ranged from 1.8 to 21.6 ug/ml and the (average was 9.1 ug/ml) (Table 3). For subsurface soil materials the average silicon concentration in saturation extracts was 5.5 ug/ml and the range was 0.57 to 15.2 ug/ml (Table 4).

Mean values of silicon concentration in saturation extracts of soils belonging to different soil orders are presented in Tables 5 and 6. Ultisols contained the lowest amounts of Si in saturation extracts and its mean (mean 4.6 ug/ml) was significantly different from the means of other soil orders. Histosols were highest in Si concentration (mean = 13.1 ug/ml) followed by Mollisols, Oxisols, and Inceptisols. The ranking was reversed when they were arranged according to median annual rainfall. Only the order Histosols was out of sequence, (Table 3). The average value of median annual rainfall for Ultisols was 1696 mm, which was significantly different from other soil orders. Ultisols had the lowest silicon contents because high rainfall hastens desilication and when accompanied by leaching, it results in the removal of silicon. Mollisols and Oxisols were associated with least rainfall and were highest and second highest in silicon contents when comparing the mineral soils. These results provide further evidence that silicon concentration in saturation extracts reflect the degree of weathering to which mineral soils have been exposed. In fact, the correlation coefficient for these two properties is -0.55 and highly significant (Table 8). A ranking of the soil orders according to the degree of weathering as reflected by their silicon solubility and rainfall can be given as follows: Ultisols > Inceptisols > Oxisols >

Mollisols.

The relationship between median annual rainfall and silicon in saturation extracts of surface soils is shown in Figure 9. Values for the seventy sites were plotted. The soils orders are designated by the first letter of their names. The highest contents of silicon were generally associated with lowest rainfall. High rainfall led to low silicon concentrations regardless of the soil order.

Except for few cases the contents of silicon in saturation extracts of surface soils were always higher than in corresponding subsoil samples. This is probably due to Si cycling by plants so that the surface soil is enriched at the expense of the subsurface horizons, and this in turn accounts in part for the difference in P sorption capacity between surface and subsurface soils as will be seen later (Fox, 1982). Mean values of Si content of subsurface soils of the different soil orders are presented in Table 6. The same relationship between median annual rainfall and silicon content observed in surface soils is observed for subsurface materials. Although the correlation coefficient for this relationship is low, -0.35, it is highly significant (Table 9). However, mean values for the different soil orders are not statistically different from one another.

The relationship between soil pH and silicon solubility was low but significant, r = 0.59, (Table 8). This

Table 8. Correlation matrix for chemical properties of surface soil samples.

Soil Chemical	pH	Si	Rainfall
	Correlation coefficient		
pH		0.59**	-0.57**
Ca	0.58**	0.41**	0.31*
Mg	0.68**	0.58**	-0.50**
K	0.49**	0.50**	-0.49**
Na	0.36**	0.44**	-0.27*
Si	0.59**		-0.55**
P in saturation extracts	0.43**	0.41**	-0.28*
P sorbed at 0.02 ppm	-0.48**	-0.64**	0.50**
P sorbed at 0.2 ppm	-0.30*	-0.62**	0.41**
P buffering capacity	-0.07	-0.39**	0.2
Olsen P	0.09	0.27*	0.27*
Bray No. 1 P	0.16	0.36**	-0.15
Al	-0.76**	-0.35**	0.51**
Sulfur	-0.69**	-0.32**	0.36**
S sorbed at 5 ppm	-0.3*	-0.6**	0.32**

* = significant at the 5% level
** = significant at the 1% level

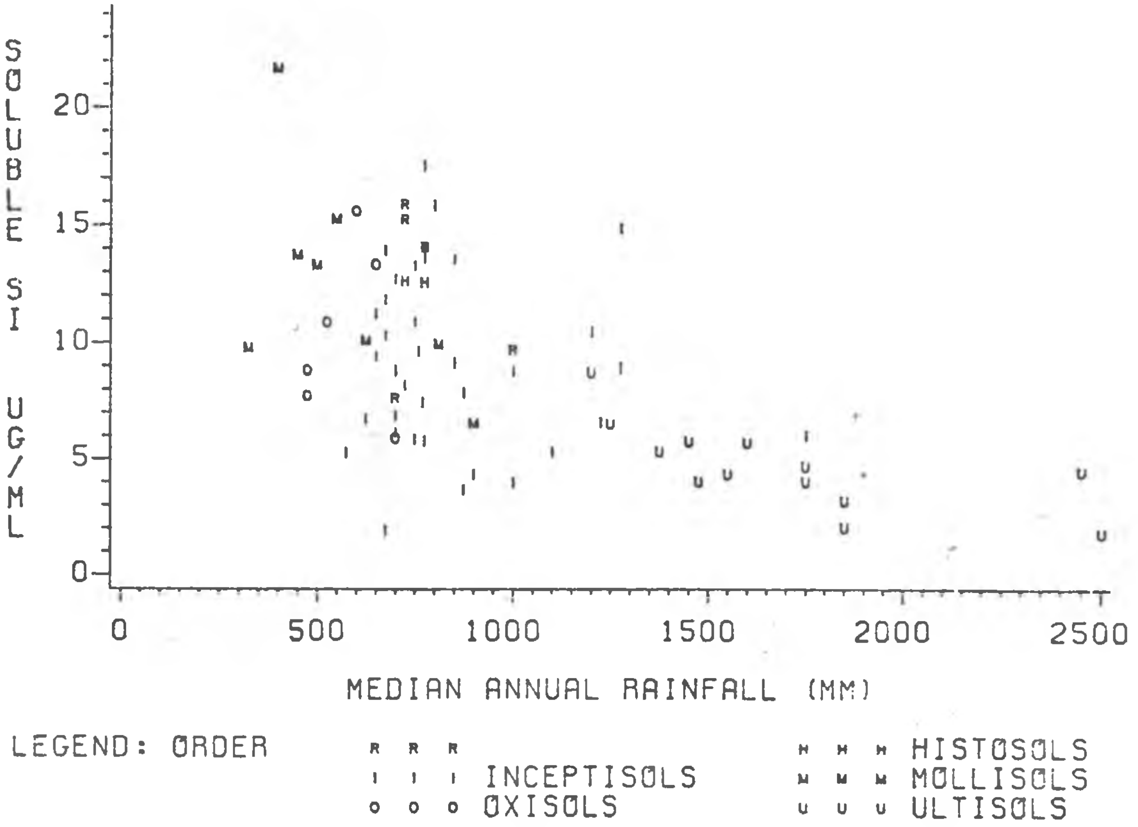

Figure 9. Silicon in saturation extracts of surface soils in relation to median annual rainfall.

Table 9. Correlation matrix for chemical properties of subsurface soil samples.

Soil Chemical	pH	Si	Rainfall
	Correlation coefficient		
pH		0.25*	-0.68**
Ca	0.66**	0.41**	-0.39**
Mg	0.60**	0.30*	-0.41**
K	0.36**	0.16	-0.31*
Na	0.56**	0.31*	-0.44**
Si	0.25*		-0.35**
P in saturation extracts	0.29*	0.29*	-0.12
P sorbed at 0.02 ppm	-0.22	-0.56**	0.23
P sorbed at 0.2 ppm	-0.09	-0.48**	0.18
P buffering capacity	-0.01	-0.40**	0.14
Olsen P	-0.07	0.48**	0.10
Bray No. 1 P	0.16	0.40**	0.07
Al	-0.79**	-0.16	0.54**
Sulfur	-0.68**	-0.08	0.48**
S sorbed at 5 ppm	-0.3*	-0.58**	0.21

* = significant at the 5% level
** = significant at the 1% level

relationship is probably a result or reflection of the degree of weathering to which the soils have been exposed. The coefficient of correlation between soil pH and rainfall is -0.57 (Table 8).

Phosphorus Determinations

The phosphorus status of soils was studied in several ways. First the amount of P in saturation extracts was measured. This measurement can indicate the intensity of P nutrition to plants. It estimates the concentration of P in the solution from which plants extract P. The second approach taken was to measure extractable P. Two methods were used: Olsen (Olsen et al., 1954) and Bray No. 1 (Bray and Kurtz, 1945). These two methods are now widely used for relating plant growth to the P status of soils. The third approach used, was the construction of P adsorption isotherms as described by Fox and Kamprath (1970). From these curves P sorbed at standard concentrations were read and recorded, along with the buffering capacity of the soils with respect to P.

Phosphorus in saturation extracts

The concentration of P in saturation extracts ranged from as low as 0.001 to 0.195 ug/ml in surface soils, and from 0.001 to 0.163 ug/ml in subsurface soil materials (Tables 3 and 4). In the surface soil, on the average, Ultisols had the lowest concentration of P in solution, 0.016 ug/ml (Table 5). This low concentration of P in solution is not sufficient to attain 95 percent of maximum yield for most agronomic crops. For example, Memon (1982) found that wheat requires 0.025 ug P/ml and maize requires 0.018 ug P/ml to attain 95 percent of maximum yield. Mollisols had, on the average, the highest concentration of P in solution, 0.075 ug/ml (Table 5). This concentration of P in solution may be adequate for some agronomic crops, however it is not adequate to sustain the growth of vegetables which generally require between 0.2 and 0.3 ug P/ml (Nishimoto et al., 1975). The means of P in solution for Ultisols and Mollisols were significantly different from each other, however they were not significantly different from the means of Oxisols, Inceptisols, and Histosols which fell in between those of Ultisols and Mollisols. The average values of P in solution for the different soil orders indicate that most of these soils are deficient in P for the optimum growth of most agronomic crops. This is especially true for the Ultisols which developed under the wettest conditions of any of the soil orders in this study. Oxisols, Mollisols, Inceptisols, and Histosols represented by these samples probably have adequate P for the growth of some cereals if compared to the P requirements reported by Memon (1982). However, additional P would be required for crops such as potato, and soybean which require higher concentrations of P in solution.

The concentration of P in solution is related to both pH and silicon solubility. In both cases it seems that the relationship is governed by the degree of weathering to which soils have been exposed. As has been pointed out before, desilication is the removal of Si and a dominant soil forming process in Hawaii. It is associated with low pH, high P sorption, and low P solubility because of the accumulation of Al, Fe, and Ti oxides which form very insoluble P complexes. Silicon in saturation extracts and pH are positively correlated with P in saturation extracts (Table 8). It is, therefore, no surprise that the lowest concentrations of P in solution were found on Ultisols which also have the lowest average soluble silicon content and lowest pH. At the other extreme are Mollisols; with the highest average pH, second highest silicon concentration and highest P concentration in the soil solution.

Concentrations of P in saturation extracts from subsurface soils were almost invariably lower than from corresponding surface materials. A comparison of means of P in solution from surface and subsurface soil materials of different soil orders (Tables 5 and 6), shows that mean values for subsurface materials are always lower than means for corresponding surface soils. The same trends of P concentration among the soil orders found in surface soils were found in subsoils; P concentration in soil solutions were greatest for Mollisols and lowest for Ultisols. However, mean values for all soil orders were not significantly different from one another. Also, the relationships between P in solution and Si solubility or pH were significant but only at the 5% level (Table 9).

Subsurface soils containes insufficient P to meet the requirements of most agronomic and vegetable crops. The P requirements, as well as their P sorption are high as will be seen later.

Phosphorus Adsorption

Typical phosphate adsorption curves of surface soils of the different soil orders represented in this study are presented in Figure 10. Clearly there are differences among the soil orders. Generally, Ultisols and Inceptisols have the steepest curves indicating greater P sorption capacities. Curves of Mollisols and Oxisols are relatively flat. Typical

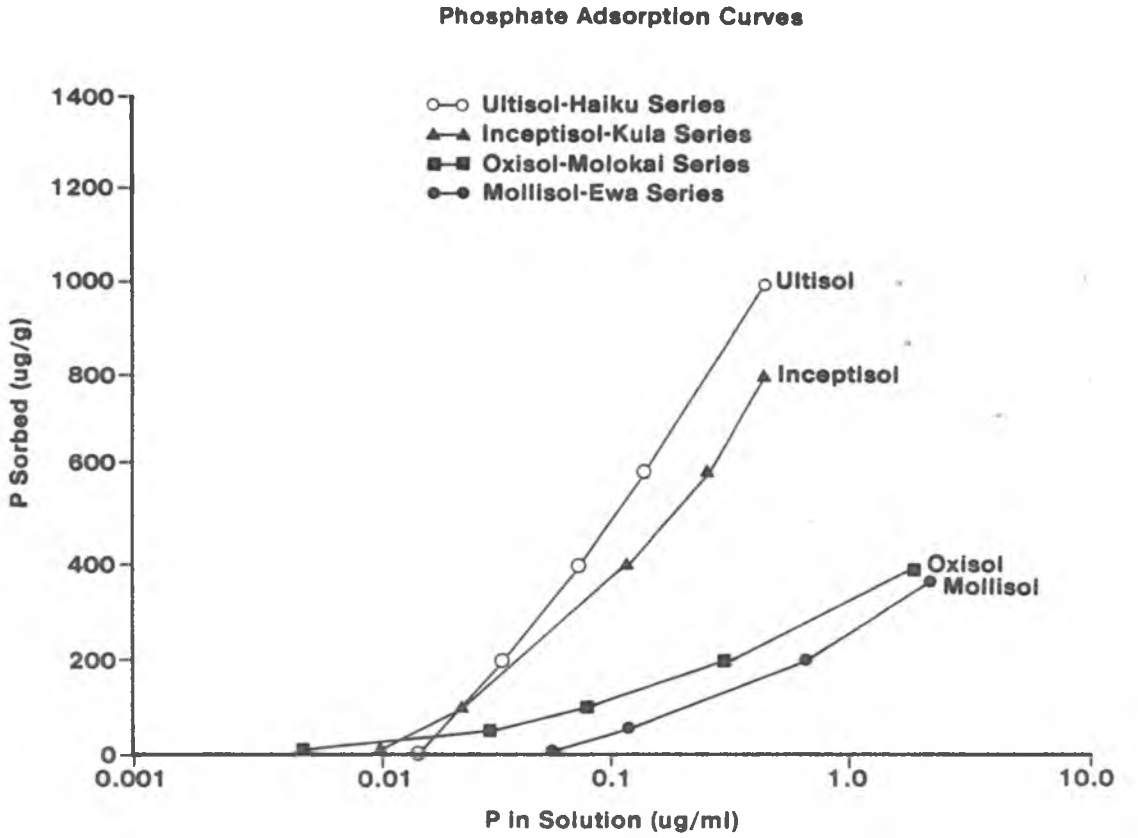

Figure 10. Typical phosphate adsorption curves for surface soils of selected soil orders of the island of Maui.

sorption curves of Mollisols were displaced far to the right indicating higher concentrations of P in these soils.

Phosphorus sorbed at 0.02 ug/ml ranged from -300 to 385 ug/g in surface soils, and from -175 to 1080 ug/g in subsoils (Tables 3 and 4). The amount of P sorbed at 0.2 ug/ml ranged from 58 to 1765 ug/g in surface soils and from 25 to 3760 ug/g in subsoils (Tables 3 and 4).

Means of P sorbed at 0.02 and 0.2 ug/ml by surface soils representing the different soil orders are presented in Table 5. Table 6 shows the same data for subsurface samples. Highest amounts of P sorbed at standard concentrations occurred in the Utisols, with mean values of 234 and 712 ug/g at 0.02 and 0.2 ug/ml respectively. P requirements of Inceptisols were the second highest followed by Oxisols, Mollisols, and Histosols. The means of P sorption of soils belonging to Mollisols and Oxisols were not significantly different, but were significantly different from those of Ultisols and Inceptisols. At 0.02 and 0.2 ug/ml the lowest P sorption was associated with soils of the orders Histosols and Mollisols respectively. In the scale suggested by Juo and Fox (1977), Inceptisols and Ultisols rank high in P sorption capacity, and Mollisols, Oxisols and Histosols rank medium.

The mean P sorption in the interval 0.15 to 0.25 ppm was higher for Inceptisols than the rest of the soil orders but was not significantly different from that of Ultisols and Histosols. The lowest mean slope of P adsorption curve was associated with Mollisols followed closely by Oxisols. The slope of the adsorption curve is a measure of the P buffering capacity of soils, and is frequently measured in the interval mentioned above because that range of P concentration in soil solution is suitable for many agronomic crops. The results indicate that Inceptisols are the most buffered soils, followed by Ultisols, Histosols, Oxisols, and Mollisols.

Highly significant correlations between P sorbed at standard concentrations and Si solubility, pH and rainfall were observed (Table 8). To help visualize these relationships Table 10 has been prepared from Table 5. At both standard concentrations the relationship between Si solubility and P sorption is highly significant; the lower the concentration of Si in saturation extracts the larger the P sorption. Thus, Ultisols, which have the lowest concentration of silicon in saturation extracts, have the highest P sorption capacity. On the other hand, Mollisols which have highest concentration of silicon in saturation extracts, have the lowest P sorption. This apparent relationship between P sorption and silicon solubility was reported by Fox (1982), substantiating previous work by the same author (Fox, 1974; Fox et al., 1971). This relationship probably results from the accumulation of Al, Fe, and Ti

Table 10. Means of phosphate sorption characteristics of surface soils grouped by soil order in relation to soil pH, Si in saturation extracts, and median annual rainfall.

Soil Chemical Property	Soil Order				
	Inceptisols	Ultisols	Oxisols	Mollisols	Histosols
	means				
P sorbed at 0.02 ppm (ug/g)	88b	233a	68b	-8b	-187c
P sorbed at 0.2 ppm (ug/g)	614a	712a	266b	188b	235b
P buffering capacity (ug/g)	163a	141ab	57b	56b	109ab
Si in saturation extracts (ug/ml)	9.2b	4.6c	10.3ab	12.5ab	13.1a
Median Annual rainfall (mm)	849b	1694a	570c	570c	758bc

Means followed by the same letter are not significantly different at the 5% level by the Waller-Duncan K-ratio t-test.

oxides which greatly sorb P. The more desilicated the soil, the higher the accumulation of these oxides and thus the higher the number of sorbing sites.

Because rainfall has a direct effect on desilication which in turn affects pH, we would expect pH to be correlated to P sorption. However, the effect of pH on P sorption capacity of soils is not direct; it occurs as a result of the loss of basic cations and accumulation of Al, Fe, and Ti oxides as desilication occurs. In fact, if pH had a direct effect on P sorption capacity of soils a significant relationship between the two should be observed at all depth increments, but the correlation coefficient between these two properties for subsoils is not significant (Table 9). On the other hand, low Si solubility is significantly related to high P sorption at both depth increments. At the same time, the relationship between median annual rainfall and P sorption of soil materials of the 30 - 45 cm depth increment is not significant. This suggests that rainfall is not the only factor that governs desilication and solubilty of Si in soils. Desilication may be affected by temperature and time also. Table 9 shows that of three factors, Si, rainfall, and pH, only Si has a significant effect on P sorption capacity of subsoils.

Phosphorus sorption capacity of subsurface soils (Table 6) is greater than that of corresponding surface soil materials. The difference between P sorption by surface and subsurface soils was higher for Oxisols and Inceptisols and lowest for Ultisols. Generally, Ultisols had the highest P sorption capacity at 0.02 ug/ml followed by Inceptisols, Oxisols, and Mollisols. However, mean values for the different soil orders were not significantly different from one another. Phosphorus sorption at 0.2 ug/ml was a little different: Inceptisols had the highest mean sorption capacity followed by Ultisols, however their means were not significantly different. Mean values for Oxisols and Mollisols were less than the mean for Inceptisols. Phosphorus sorption by Inceptisols at 0.2 ug/ml was approximately two and a half times larger than that of Oxisols and Mollisols, and approximately two times larger than that of Ultisols. This is because of higher P buffering capacity of Inceptisols as compared to the other soil orders. Lowest buffer capacity was associated with Mollisols, followed closely by Oxisols. Buffering capacity of subsurface materials was higher than that of surface materials. Fox (1982) pointed out four factors that are probably responsible for less P adsorption by surface soils than by subsurface soils:

1. Accumulation of P in the surface horizons at the expense of subsurface horizons as a result of P cycling by plants.

2. Blocking of phosphate adsorption sites by organic anions associated with plant residue decomposition.
3. Cycling of Si by plants so that the surface soil is enriched at the expense of the subsurface horizons. Silicates react with weathering products which would otherwise immobilize P by precipitation or adsorption.
4. Periodic dessication of the surface leading to relatively low reactivity of amorphous gel materials in the surface soil.

Extractable Phosphorus

Extractable P in surface soils ranged from as little as 0.63 to as much as 82 ug P/g when using $NaHCO_3$ as extractant, and from 0.13 to 45 ug P/g when using Bray and Kurtz No. 1 extractant (Table 3). Subsoil values were generally much lower than those for surface soil materials. The average value of extractable P in surface soils using $NaHCO_3$ as extractant was 18 ug/g, and 9.6 ug/g when using the Bray and Kurtz method.

The largest amounts of P were extracted from Mollisols. For this soil order $NaHCO_3$-extractable P ranged from 5.9 to 82 ug/g the mean value was 26 ug/g (Table 5). The highest value was associated with a pH of 6.4 and an median annual rainfall of 625 mm; the lowest value was associated with the highest rainfall for any of the Mollisols, 900 mm, and a pH of 5.9 which was much below the average for this soil order. A comparison of extractable P of Mollisols with the critical levels presented in table 1, leads to the conclusion that, on average, Mollisols are adequately supplied with extractable P for plant growth. However, critical levels of $NaHCO_3$ determined for temperate zone soils may not apply in the tropics. For example, Fox et al. (1982) determined that a level of P in solution suitable for maize will be obtained when $NaHCO_3$ extractable P is about 40 ug P/g in an Eutrustox. Furthermore, more P is extracted with $NaHCO_3$ extractant than with the acid fluride extractant. This of course is an example were information based on soil research done on temperate zones cannot be used for tropical soils. Comparing the critical level given by Fox with the level of $NaHCO_3$ extractable P of Mollisols leads to the conclusion that these soils are deficient in P.

If we divide Mollisols into its different soil series represented in this study we find that the Kamaole series has adequate levels of extractable P; 82 and 24 ug P/g for $NaHCO_3$ and Bray No. 1 methods respectively (Table 11). The Ewa and Waiakoa series would rank as medium having averages of 26 and 22 ug/g of $NaHCO_3$-extractable (Table 11). On the other hand the Paia and Pulehu series will rank as low in terms of both $NaHCO_3$ and Bray No. 1 methods (Table 11). The mean values of extractable P of Mollisols, 26 and 13 ug/g for Olsen and Bray No. 1 methods respectively (Table 5), would make this order to rank as medium in extractable P.

Oxisols are represented by two series in this study: Keahua and Molokai series. The average $NaHCO_3$ extractable P for this order is 14 ug/g and 8.7 ug/g for Bray No. 1 (Table 5). The Molokai series ranks low in extractable P, whereas the Keahua series ranks as medium in extractable P. For mean values refer to Table 11.

Histosols represented by only one soil series, Kaimu, rank as medium in extractable P, having a mean value of 20 ug P/g using the $NaHCO_3$ method and 19 ug P/g when extracted with acid fluoride extractant (Table 11).

Ultisols which developed under the wettest conditions of any of the soil orders represented in this study were generally low in extractable P by either method. In surface soils the mean value for $NaHCO_3$-extractant P was 12 ug/g and 7 ug P/g for Bray No. 1 P (Table 5). For subsurface soil materials the averages were 10 and 5 ug P/g for $NaHCO_3$ and acid fluoride extractable P respectively (Table 6). Mean values of $NaHCO_3$ and acid fluoride extractable P for soils of the Makawao series were 23 and 17 ug P/g respectively. Thus, they rank as medium in terms of extractable P. The Haiku and Pauwela series usually ranked low in extractable P,

Table 11. Means of extractable phosphorus of surface soils partitioned by soil series

Soil Series	Olsen P	Bray No. 1 P
	ug/g	
Pulehu	9.6	6.6
Waiakoa	22.4	12.0
Ewa	25.6	17.4
Kamaole	82.5	23.6
Paia	11.6	6.6
Keahua	17.4	8.8
Molokai	9.7	6.6
Kaimu	19.6	19.1
Makawao	23.4	17.1
Haiku	9.3	4.0
Pauwela	0.6	3.7
Io	33.1	13.4
Kula	16.7	8.2
Pane	14.7	5.7
Haliimaile	24.8	9.9
Laumaia	11.3	17.2
Kaipoioi	1.4	0.3
Uma	12.0	11.5

especially the Pauwela series whose averages for $NaHCO_3$ and acid fluoride extractable were 0.6 and 3.7 ug P/g for surface soil and subsurface soil respectively (Table 11).

The order Inceptisol was represented by seven soil series. The Io, Kula, Pane, and Haliimaile series ranked medium in terms of $NaHCO_3$-extractable P, whereas the Laumaia, Kaipoioi, and Uma series rank low (Table 11). Mean values of extractable P for surface soils belonging to the order Inceptisols are presented in Table 5. In the case of $NaHCO_3$ extractable P the mean value is 20 ug P/g, and when the extraction was made according to the Bray procedure the mean value was 10 ug/g. For the subsoil, mean values were 13 and 3.2 ug P/g for Olsen and Bray No. 1 P respectively.

Tables 5 and 6 compare the mean values of extractable P of the different soil orders of surface and subsurface soils. Mean values were not significantly different. These results imply that Soil Taxonomy was not able to distinguish the different soil orders based on extractable phosphorus. Fox (1982) reported a similar result; in that case no distinction was made by Soil Taxonomy when P sorption capacity of Oxisols and Ultisols of Puerto Rico was compared. Important soil properties such as mineralogy and texture, which greatly influence and control other soil properties such as phosphate and sulfate sorption, P solubility and P extractability, are not introduced in Soil Taxonomy until the family level. It is no surprise that differences between soil orders are not identified. Only at the mapping unit level were significant differences in extractable P among soils observed either by Olsen or Bray and Kurtz No. 1 methods. The mapping unit level is the lowest category in soil classification even though it is not part of Soil Taxonomy. The criteria used to divide soil series into different mapping units is soil texture, thus this soil property plays an important role in determining the amounts of P extracted from soils. If we tie these results to the results of partitioning variation of soil chemical properties discussed earlier we can see the relation between the results obtained. Only at the mapping unit level were means signficantly different, and the lowest residual mean square for extractable P was associated with the mapping unit level. The explanation for this observation seems to be that texture is governing the amounts of P that can be extracted from the soil. This result is further evidence of the usefulness of analyzing variance of soils in a hierarchical model.

The relationship between Si in saturation extracts and extractable P was positive and significant, and in keeping with that general relationship, the relationship between extractable P and annual median rainfall was negative and significant only for Olsen P. The observation that $NaHCO_3$-extractable P, and not acid fluoride extractable P was significantly related to rainfall (weathering) is evidence for the superiority of the $NaHCO_3$ method for these kind of soils. Reasons for this include the higher solution to soil ratio used with $NaHCO_3$ method as compared to the acid fluoride method. Furthermore, the strength of the acid fluoride extractant is reduced when extracting acid tropical soils because fluoride ions react with non phosphate bound Al complexes in the soil leaving little flouride to react with Al-phosphate complexes and as a consequence little P is released from these complexes. Also, as the F ions react with hydroxy-Al complexes, hydroxyl ions are released and they neutralize the acid; these set of factors occurring at the same time reduce the strength of the acid flouride extractant. The relationship of Si solubility and rainfall with extractable P are likely to result from variable weathering to which the soils have been subjected. Most P was extracted from silt loam soils, followed by silty clays, loams, and finally clays.

Sulfur Determinations

Two approaches were used to investigate the sulfur status of soils. First, SO_4-S was extracted with 0.4 M $Ca(H_2PO_4)_2$, an estimate of the quantity of available SO_4-S in the soil. The second approach used SO_4-S sorption curves, constructed following the pattern used for P sorption isotherms, to estimate SO_4-S sorbed at 5 ppm.

Extractable Sulfur

Extractable SO_4-S in surface soils ranged from 34 to 659 ug S/g (Table 3). In subsurface samples the range was 0 to 688 ug S/g of soil (Table 4). In most instances more SO_4-S was extracted from subsurface soil materials than from corresponding surface soil materials.

Ultisols contained the highest amounts of extractable S and its mean values, 279 and 324 ug SO_4-S/g for surface and subsurface soils respectively, were significantly different from the means of all other soil orders (Tables 5 and 6). Ultisols developed under the wettest conditions in this study, thus it is no surprise that they had the greatest concentrations of extractable SO_4-S because it has been reported that as much as 13.6 kg of S/ha/year can be added to the soil by rainfall (Fox et al., 1965). Furthermore, Ultisols sorb sulfate and $Ca(H_2PO_4)_2$ extracts sorbed SO_4-S (Fox et al., 1964). Even though for Ultisols $Ca(H_2PO_4)_2$-extractable SO_4-S was high we cannot conclude that levels were adequate for plant growth. Responses by crops to S fertilization on soils having high extractable S have been reported in several Hawaii conditions

(Stanford and Jordan, 1966; Fox et al., 1965; Fox, 1969), and in other regions of the humid tropics (McClung et al., 1959).

Histosols contained the second highest amounts of extractable SO_4-S, 131 ug S/g, and at the same time had the lowest mean of sorbed sulfate of any of the soil orders (Table 5). Therefore, much organic SO_4-S was extracted by $Ca(H_2PO_4)_2$. The mean value can be considered as high however, we must take into account that most of the extractable S comes from the organic matter and that this is not directly available to plants. It is known that $Ca(H_2PO_4)_2$ extracts organic S (Reisenauer et al., 1973).

Mollisols, Oxisols, and Inceptisols contained lower amounts of extractable sulfate than Histosols and Ultisols. Their mean values were not significantly different from one another and were not significantly different from the mean value of Histosols (Table 5). Mollisols contained the lowest concentration of extractable sulfate, and at the same time sorb the lowest amounts of SO_4-S.

As was the case with extractable P, soil classification was not able to distinguish between extractable SO_4 contents of Mollisols, Oxisols, Histosols, and Inceptisols. The distinction between soils belonging to these orders only appears at the series level when criteria such as soil color, texture, structure, consistency, reaction, chemistry, and mineralogy are introduced. Separation was best at the mapping unit level, a result which corresponds with conclusions based on the analysis of residual mean squares previously presented. The implications of these results seem to be that soil texture plays an important role in the extractability of SO_4-S from soils. However, effects of management on extractable S (and P) should not be discounted, nor should factors such as rainfall, elevation, and distance from the sea. These factors affect the amounts of SO_4-S in soils (Fox et al, 1965) and are not taken into consideration by soil classification. Furthermore the textural classes recognized in the field may not, in fact, be valid. Most of these soils, if completely dispersed, are clays.

Generally subsurface soil materials contained larger amounts of extractable SO_4-S than surface soil counterparts. The probable cause is that SO_4-S sorption capacity of subsoils is greater than surface soils, thus more SO_4-S has been retained and can be extracted with $Ca(H_2PO_4)_2$ from subsurface soils.

Within the order Inceptisols, soils of the suborder Tropepts contained the highest SO_4-S concentrations, their average value was 130 ug/g. Soils of the suborder Andepts were associated with a mean value of 75 ug/g. Within the suborder Andepts, mean values for Typic Dystrandepts was 78 ug/g, for Typic Eutrandepts was 74 ug/g, and for Typic

Vitrandepts was 71 ug/g, mean values were not significantly different from one another (Table 12). Tropepts were associated with an average median annual rainfall of 959 mm which is above the average rainfall for soils of this order, and lowest pH and silicon solubility, and the highest capacity to sorb sulfate than any of the surface soils belonging to the order Inceptisols. Thus, they contained larger amounts of extractable sulfate because of their low pH and larger amounts of sorbed sulfate.

Extractable SO_4-S was negatively related to soil pH and silicon solubility, and positively related to rainfall (Table 8 and 9). Figure 11 shows the strong negative relationship between soil pH and extractable sulfate for surface soils. The relationship is slightly better for subsoil samples. Large amounts of SO_4-S were extracted when soil pH was 4.0 or less, whereas little SO_4-S was extracted when pH was 6.0 or higher. The pH influences the amount of SO_4-S sorbed (Kamprath et al., 1956) which in turn influences the amounts of SO_4-S that can be extracted from the soil. As rainfall increases so does the amount of extractable sulfate. This can be accounted for as follows: a) greater additions of SO_4-S as rainfall increased, and b) higher sulfate sorption capacity of soils developed under high rainfall. The relationship between silicon in saturation extracts and SO_4-S is negative for both surface

Table 12. Means of extractable and sorbed sulfate in relation to pH, silicon in saturation extracts, and median annual rainfall of surface soils belonging to the different soil subgroups.

	Soil Chemical Property				
Soil subgroup	Extractable SO_4-S	SO_4-S at 5 ppm	pH	Silicon Solubility	Annual median rainfall
	---------ug S/g-------			ug Si/ml	
Humoxic Tropohumults	279a	25a	4.4e	4.6e	1696
Typic Tropofolists	131ab	-76b	5.8bc	13bc	758
Ustoxic Humitropepts	130ab	30.6a	4.8de	7.3de	954
Typic Dystrandepts	78b	50a	5.7bc	7.4de	989
Typic Eutrandepts	74b	2.3ab	5.9bc	10.3bcd	723
Typic Vitrandepts	71b	17ab	5.5cd	14.8b	1275
Typic Haplustolls	71b	11ab	5.4cd	8.2cde	855
Typic Torrox	70b	-21ab	5.9bc	10.3bcd	570
Aridic Haplustolls	65b	-19ab	6.4b	12.4bc	490
Cumulic Haplustolls	57b	-6ab	7.7a	21.7a	400

Means followed by the same letter are not significantly different at the 5% level by the Waller-Duncan K-ratio t-test.

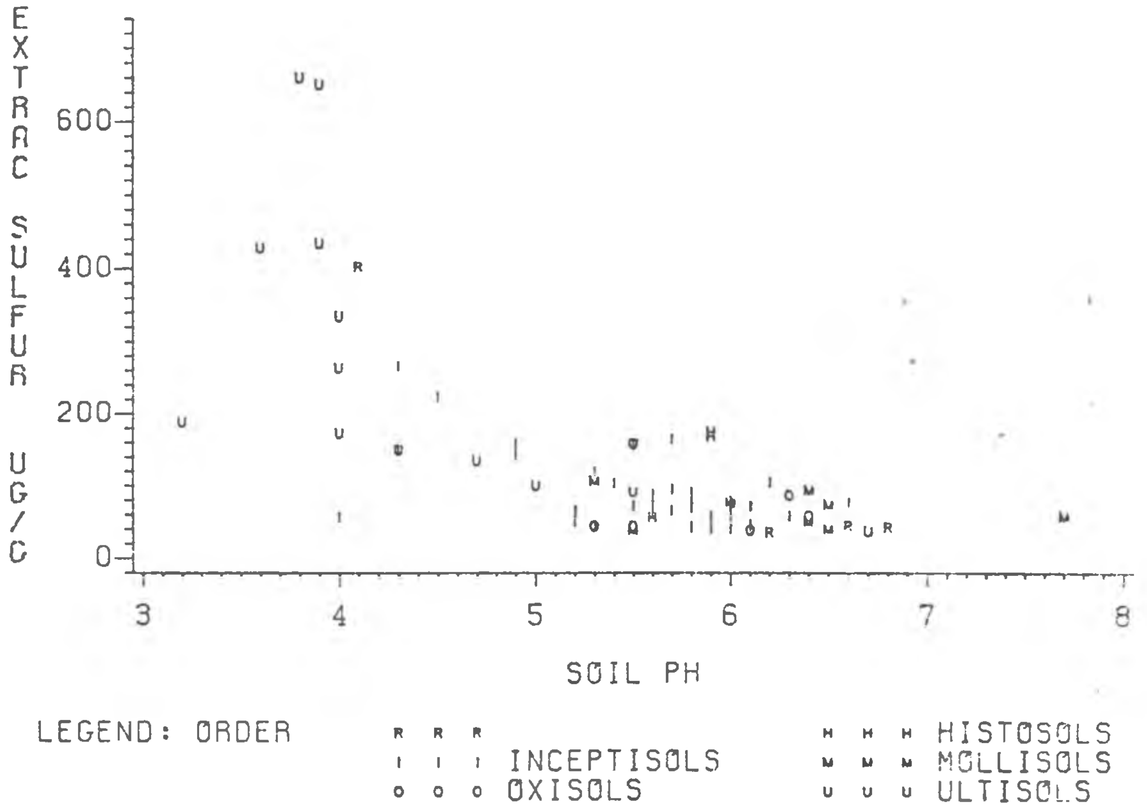

Figure 11. Extractable SO_4-S of surface soils in relation to soil pH.

and subsurface soil horizons, but is significant only for surface horizons. The relationships of silicon in saturation extracts and rainfall with extractable SO_4-S are a direct effect of the losses of cations and accumulation of Fe, Al, and Ti oxides which affect the pH as desilication occurs. Silicate ions may also compete with sulfate anions for adsorption sites and as a result less sulfate is sorbed and the amounts of extractable SO_4 decrease.

Even though mean values of extractable SO_4-S were generally high, and levels of sulfate would be adequate for plant growth in soils that sorb little or no sulfate, we cannot conclude that these values are sufficient for plant growth under tropical conditions because concentration as well as quantity is an important factor in availability. Responses to S fertilization have been obtained in the tropics when high levels of extractable SO_4-S were present in the soil (Fox, 1980).

Sulfate Adsorption

Typical sulfate sorption curves for the mineral soil orders represented in this study are presented in Figure 12. The most highly weathered soils, Ultisols and Inceptisols, sorbed the largest quantities of sulfate. At standard SO_4-S concentration (5 ppm) Oxisols and Mollisols sorbed no

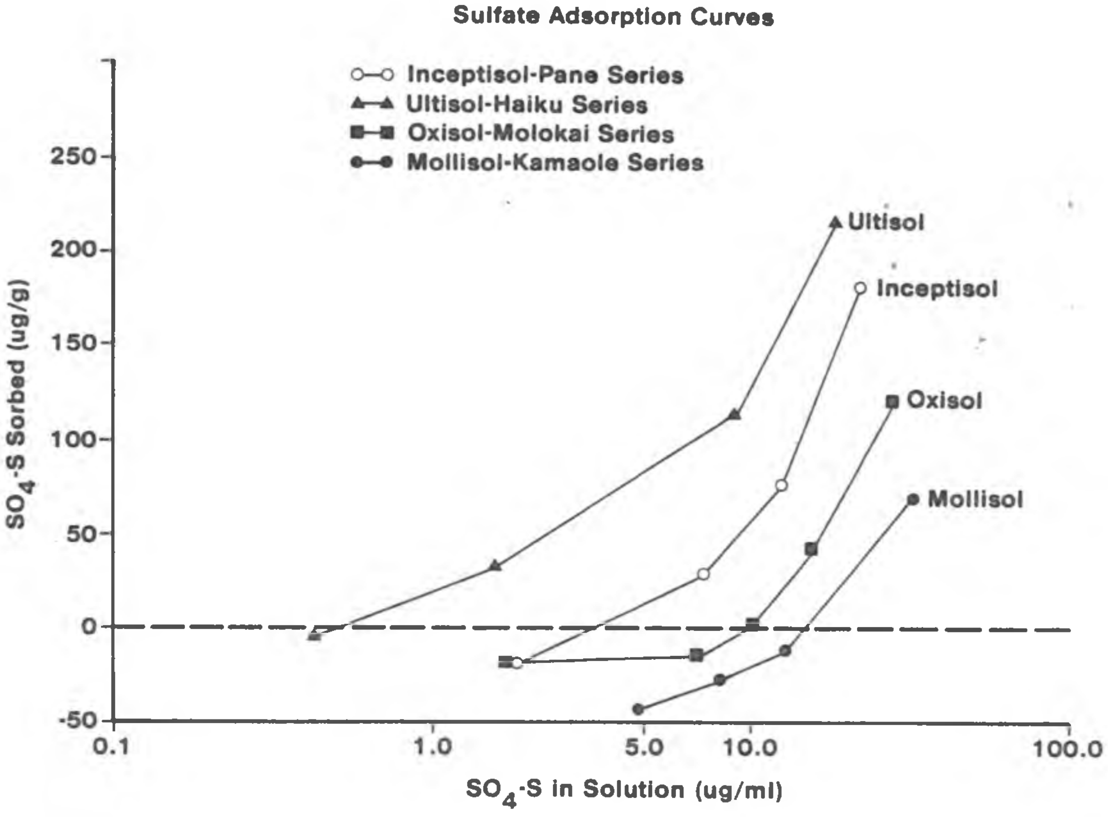

Figure 12. Typical SO_4-S adsorption curves for surface soils of selected soil orders of the island of Maui.

sulfate, in fact sorption was negative which predicts SO_4-S release if SO_4-S falls below 5 ppm in solution (Table 5).

In the case of Ultisols the amounts of sulfate sorbed at 5 ppm range from -61 to 99 ug/g and the mean value was 25 ug/g (Table 5). The relationship between silicon in saturation extracts and sulfate sorption is a reflection of the effect of weathering on the capacity of soils to sorb sulfate. Tables 8 and 9 show the correlation coefficients of this relationship for surface and subsurface soil materials respectively. The relation is negative and highly significant in both cases. Thus, low concentrations of silicon are associated with large amounts of SO_4-S sorption. Hasan et al. (1970) concluded that the capacity of soils to sorb sulfate is related to weathering products and under humid tropical conditions the losses of Si and bases, and the accumulation of Fe, Al, and Ti oxides result in soils with little permanent negative charge but with considerable pH-dependent, positive charge which resulted in sulfate and phosphate adsorption. Also there was little silicate to compete with sulfate for adsorption sites.

The range of sulfate sorption by soils of the order Inceptisols is -262 to 102 ug/g, and the mean sulfate sorption at standard concentration is 12 ug/g (Table 5) which is not significantly different from the mean value for Ultisols. Within the order Inceptisols, Typic Dystrandepts contained the largest amounts of sorbed sulfate followed closely by Ustoxic Humitropepts. Typic Vitrandepts contained approximately half as much sorbed sulfate as Ustoxic Humitropepts. Typic Eutrandepts contained the lowest amounts of sorbed sulfate of any of the Inceptisols (Table 12). The ranking given above is the reverse ranking for silicon solubility given for these same soils in Table 12. Thus, the more Si present the less sulfate sorbed because of the competition between silicate and sulfate for sorption sites. Mineral soils in this study ranked in the following manner for sulfate sorption:

Ultisols > Inceptisols > Oxisols > Mollisols.

However, the means were not significantly different from one another. The ranking given by Hasan et al. (1970) for the capacity of soils with various mineralogical systems to sorb sulfate resembles the order given above. Ultisols which contain large quantities of crystalline oxides and in addition tend to be strongly acidic sorb more sulfate than soils in which minerals with permanent negative charge predominate.

In the case of Mollisols, Typic Haplustolls contained largest amounts of sorbed sulfate and at the same time the largest amounts of extractable sulfate (Table 12). Cumulic Haplustolls contained the second largest amounts of sorbed sulfate, and the lowest SO_4-S sorption for this soil order were associated with Aridic Haplustolls. In this soil order silicon solubility followed the order Typic Haplustolls < Aridic Haplustolls < Cumulic Haplustolls and the same ranking was found when pH was the criterion for ranking. As a result, for these soils the relationship between high silicon solubility or pH and the low sorbed sulfate did not hold.

The relationship between soil pH and sulfate sorbed was negative and significant for both surface and subsurface soil materials (Tables 8 and 9). Kamprath et al. (1956) determined that sulfate adsorption decreases with increasing pH regardless of the sulfate sulfur concentration in the soil. In highly weathered soils the retention of sulfate as pH decreases is due to the considerable positive pH dependent charges which the soils have.

Sulfate sorption is concentration dependent (Kamprath et al., 1956; Chang and Thomas, 1963; Chao et al., 1962). This can be seen to a certain extent in this study; Ultisols which contained the largest amounts of sorbed sulfate, also contained the largest amounts of extractable sulfate. Second largest amounts of sorbed sulfate were observed in Inceptisols which at the same time contained the second largest amounts of extractable sulfate. However, in the case of Oxisols and Mollisols there is a discrepancy; Mollisols, which contained lower amounts of extractable sulfate than

Oxisols, contained larger amounts of sorbed sulfate than Oxisols, in both surface and subsurface soils. If we were to divide the soils of the order Mollisols into its different subgroups this discrepancy can also be seen (Table 12). This discrepancy is seen more strongly in soils of the order Inceptisol (Table 12). Ustoxic Humitropepts which contained larger amounts of extractable sulfate than Typic Dystrandepts contained lower amounts of sorbed sulfate than Typic Dystrandepts. Within the suborder Andepts this problem is also seen. For example Typic Eutrandepts contained larger amounts of extractable sulfate than Typic Vitrandepts but they had much lower amounts of sorbed sulfate than Typic Vitrandepts. The relationship between sorbed sulfate and extractable sulfate is not significant, which tells us that high SO_4-S sorption is not always associated with high SO_4-S concentrations (Table 13).

More consistent relationships exist between soil P properties, such as P sorbed at standard concentrations and P in saturation extract, with sorbed sulfate. In fact the correlation coefficients for these relationships are highly significant (Table 13). As a result, when concentrations of P in saturation extracts are higher for a group of soils as compared to others, the amounts of sorbed sulfate are lower because phosphate competes with sulfate for adsorbing sites and phosphate is sorbed more readily than sulfate (Kamprath

Table 13. Correlation matrix of sulfur characteristics of surface soils in relation to phosphorus characteristics

Soil Chemical Property	Extractable Sulfur	S sorbed at 5 ppm
	Correlation coefficients	
Extractable sulfur		0.06
P in saturation extracts	-0.21*	-0.41**
P sorbed at 0.02 ppm	0.40**	0.57**
P sorbed at 0.2 ppm	0.25*	0.57**
P buffering capacity	-0.06	0.43**

* = significant at the 5% level
** = significant at the 1% level

et al., 1956; Chang and Thomas, 1963). If the soil is able to sorb large amounts of phosphate it is also able to sorb large amounts of sulfate. Thus, Ultisols which sorb the highest amounts of P also sorb the highest amounts of sulfate.

Generally subsoils sorb more sulfate than corresponding surface soils. Considering all soils, subsurface soils sorb approximately 3 times the amount of sulfur sorbed by surface soils. In the case of Inceptisols they sorb 4 times more. Some of the reasons for this include:

1. Larger concentrations of sulfate in the subsoil than in surface soils.
2. Lower concentrations of P in solution in subsurface soils which otherwise would compete with sulfate for sorption sites.

As was the case with extractable sulfate and phosphate, soil classification was not able to determine any significant differences in sorbed SO_4-S between the different mineral soil orders. Significant differences in sorbed sulfate started to be seen when the soils were divided into subgroups, and refinement was seen as the classification system went as far as the mapping unit. At this point the best mean separation for this soil property was seen. These results coincide with those of partitioning variation of chemical properties presented before, and in which the lowest residual mean square for this property was associated with the mapping unit. This perhaps, tells us that textural classes have an effect on the amounts of sorbed sulfate. However as pointed out before we can not discount the effects that cultural practices may have had upon sulfate sorption and other soil properties, which will not be elucidated by Soil Taxonomy, and could possibly only be shown if the different mapping units were divided into smaller groups according to management variables.

Exchangeable Calcium, Magnesium, Potassium, and Sodium

Ranges of the amounts of exchangeable bases of surface and subsurface soils are presented in Tables 3 and 4. They show the large variability in cation concentration among soils. Calcium was the exchangeable cation present in largest amounts and made up approximately 70% of the exchange complex of soils except Mollisols whose exchange complex was made largely as a combination of both Ca and Mg.

Aridic and Cumulic Haplustolls contained the largest amounts of exchangeable bases for surface soils of the order Mollisols (Table 14). In the case of Aridic Haplustolls the exchange complex was dominated by Ca followed by Mg. In contrast, Cumulic Haplustolls contained larger amounts of exchangeable Mg. Typic Haplustolls contained approximately

Table 14. Means of exchangeable calcium, magnesium, potassium and sodium in relation to pH, and silicon solubility of surface soils belonging to the different soil subgroups.

Soil subgroup	Soil Chemical Property					
	Exchangeable					Silicon in saturation extracts
	Ca	Mg	K	Na	pH	
	--------meq/100 g---------					---ug/ml------
	means					
Humoxic Tropohumults	4.4d	0.9d	0.4b	0.2c	4.4e	4.6e
Typic Tropofolists	37.1a	7.9ab	1.7ab	0.4c	5.8bc	13.1bc
Ustoxic Humitropepts	6.6cd	1.7d	1.1ab	0.2c	4.8de	7.3de
Typic Dystrandepts	17.7dc	5.2bcd	1.1ab	0.3c	5.7bc	7.4de
Typic Eutrandepts	28.2ab	6.3bc	1.6ab	0.4c	5.9bc	10.3bcd
Typic Vitrandepts	35.7a	3.5bcd	0.4b	0.5bc	5.5cd	14.8b
Typic Haplustolls	5.7d	3.1cd	0.8b	0.4c	5.4cd	8.2cde
Typic Torrox	9.5cd	4.3bcd	1.3ab	0.7bc	5.9bc	10.3bcd
Aridic Haplustolls	14.6cd	7.6b	2.3a	1.6b	6.4bc	12.4bc
Cumulic Haplustolls	8.3cd	12.3a	2.3a	3.7a	7.7a	21.7a

Means followed by the same letter are not significantly different at the 5% level by the Waller-Duncan K-ratio t-test.

one-half the total amount of exchangeable cations contained in Aridic and Cumulic Haplustolls; this is not surprising because Aridic Haplustolls, as their name implies, developed under dry conditions and have been exposed to little weathering and leaching. At the same time accumulation of nutrients has occurred on Cumulic Haplustolls as indicated by their name. On the other hand Typic Haplustolls developed under wetter conditions resulting in greater weathering and leaching as compared to Aridic and Cumulic Haplustolls. Mollisols are not deficient in any of the exchangeable cations. For example, the range of exchangeable Ca for suface soils was 3.5 to 39 meq/100 g of soil; values which are much larger than the critical level of 0.5 meq Ca/100 g for sugarcane given by Humbert (1963).

Critical levels for exchangeable Mg were presented by Doll and Lucas (1973) as follows:

0 - 0.2 meq/100 g - deficiency symptoms will be observed on most field, vegetable, fruit, and glasshouse crops.

0.21 - 0.41 meq/100 g - deficiency symptoms will be observed in sugar beets, potatoes, fruits, and glasshouse crops.

0.43 - 0.83 meq/100 g - most field and vegetable crops will respond little to Mg fertilizer. Level is however, deficient for fruit, glasshouse, and grassland crops.

0.84 - 1.5 meq/100 g - tomatoes, cucumbers, peppers, and other vegetable crops will respond to Mg above this level and requirements will be dictated by the specific needs of each crop.

1.6 - 2.1 meq/100 g - vegetable crops grown in the glasshouse will respond to additions of Mg.

For exchangeable K Doll and Lucas (1973) presented critical values for different soil types as follows:

Sands and loamy sands = 0.22 meq K/100 g
Sand loams and loam = 0.26 meq K/100 g
Silt loams and clays = 0.32 meq K/100 g

Histosols, represented by Typic Tropofolists, had adequate amounts of exchangeable bases for plant growth. They occur near Kula along with soils of the Kula series which belong to the Typic Eutrandepts. Restriction of Histosols to sustain good plant growth lies in their shallow soil profile; no subsoil samples were taken because rocks were encountered within 12 to 15 cm from the surface. Typic Tropofolists contained the largest amounts of exchangeable bases for any of the soil subgroups (Table 14).

Soils of the suborder Andepts, contained large amounts of exchangeable bases. Those classified as Typic Eutrandepts occur at the south of the sampled area where rainfall is relatively low, and were not deficient in any of the exchangeable bases. They represent the largest group of soils in this study and are now largely used for pasture. A few sites are used for vegetable and flower production which have high requirements of exchangeable bases. They are, without any doubt, very fertile. In a few sites the profile was shallow and as a result it was impossible to collect subsoil samples.

Typic Dystrandepts and Vitrandepts contained similar amounts of exchangeable bases to those of Typic Eutrandepts. Thus, they have adequate levels of exchangeable bases to sustain good plant growth. As with Typic Eutrandepts, they are generally used for pasture, however they also occur under forest. They differ from Typic Eutrandepts in that they develop at higher elevations and wetter conditions.

Ustoxic Humitropepts contained the lowest amounts of exchangeable bases for any of the Inceptisols. Calcium deficiencies will not be likely to occur in these soils if compared to the critical level given by Humbert (1963). However, some sites are deficient in both K and Mg thus require additions of these elements. These soils generally developed under wetter conditions than other Inceptisols.

Typic Torrox contained adequate amounts of exchangeable bases for plant growth as can be seen from their means (Table

14). They are generally planted with sugarcane and developed under approximately 600 mm of annual rainfall. All sites classified as Typic Torrox have adequate amounts of exchangeable cations.

Humoxic Tropohumults which largely represent soils in the north portion of the area sampled, contained the lowest amounts of exchangeable bases (Table 14). Even though the means of exchangeable cations are well above the critical levels there are sites which are deficient in these nutrients. As an example, sample 39 transect 1 has contents of 0.21, 0.05 and 0.07 meq/100 g of exchangeable Ca, Mg, and K respectively. This site without any doubt is deficient in all these nutrients. This particular soil developed under approximately 1800 mm of rainfall and has pH values of 3.2 and 3.1 for surface and subsurface soils respectively. These pH values are the lowest for all soils sampled. The exchangeable bases were also very low in the subsoil of this site. The large extent of weathering and leaching to which this site has been exposed is the probable reason of the low concentration of cations. At the same time there has been a large accumulation of exchangeable Al in this site (approximately 2.6 and 2 meq/100 g for surface and subsurface soils respectively).

Exchangeable bases gradually increased as the pH increased from 3.2 to 6.0 (Tables 8 and 9). However, above pH 6.0 the concentration of cations increased little as is shown for exchangeable Ca and Mg in Figures 13 and 14 because as the pH increases the negative charge of variable charge soils increases creating a large affinity for cations.

The relationship between Si in saturation extracts and exchangeable bases was also positive and significant even though the r values were low (Tables 8 and 9). Thus larger amounts of exchangeable bases were found on soils containing the largest amounts of Si in saturation extracts. The relations of exchangeable cations with both pH and silicon in saturation extracts are a direct result of the effect of rainfall (weathering) upon the soils. As rainfall increases pH and silicon in saturation extracts decrease because of increased desilication, leaching, and accumulation of Al, Fe, and Ti oxides.

Geostatisical Analysis of Soil Chemical Properties

Isotropic semi-variograms ($90^{\circ} \pm 90^{\circ}$) were computed for each soil chemical property studied. For most chemical properties of soils of the area studied, semi-variograms clearly illustrate that semi-variance increases without limit as the distance increases. In other words, semi-variance does not level off as expected for

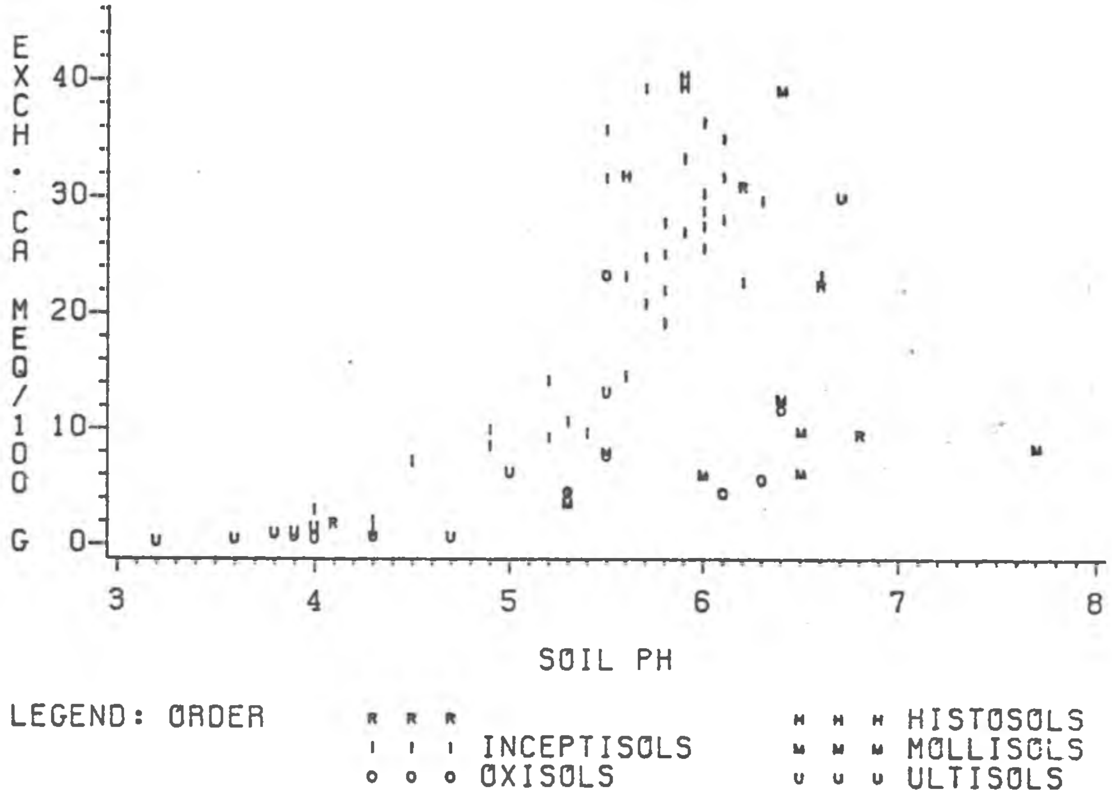

Figure 13. Exchangeable calcium of surface soils in relation to soil pH.

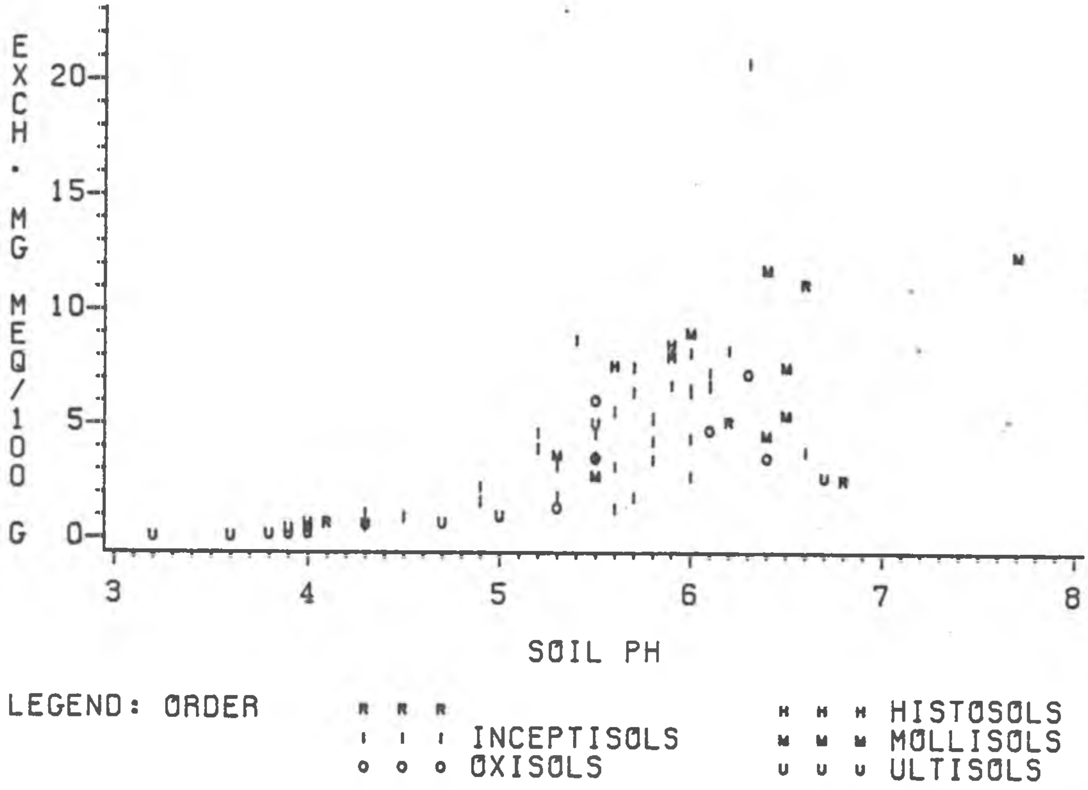

Figure 14. Exchangeable magnesium of surface soils in relation to soil pH.

stationary phenomena. These results indicate the presence of strong directional trends in most of the properties studied over the area sampled.

The isotropic semi-variogram of the pH of surface soils is shown in Figure 15. Clearly, the semi-variance increases with increasing distance. Therefore, soil pH follow certain patterns. These patterns are evident in the map of soil pH (Figure 16); for example, soil pH increases in a north to south direction, and decreases in a west to east direction. The area of Maui shown on Figure 16 is the area enclosed in Figure 17 which also shows sample sites. All subsequent maps of properties of soils of the island of Maui presented in this thesis will only show the enclosed section shown in Figure 17. Semi-variograms for exchangeable calcium, magnesium, sodium, and potassium, silicon in saturation extracts, P sorbed at 0.02 ug P/ml, extractable S, and exchangeable Al similarly revealed the presence of strong directional trends in these soil chemical porperties. Directional trends revealed by semi-variograms are also shown in isarithm maps of these properties. As an example, the isarithm map of silicon in saturation extracts (Figure 18) shows that the concentration of silicon in saturation extracts increases in a north to south direction from less than 5 ppm to greater than 15 ppm, and at the same time, it decreases in a west to east direction.

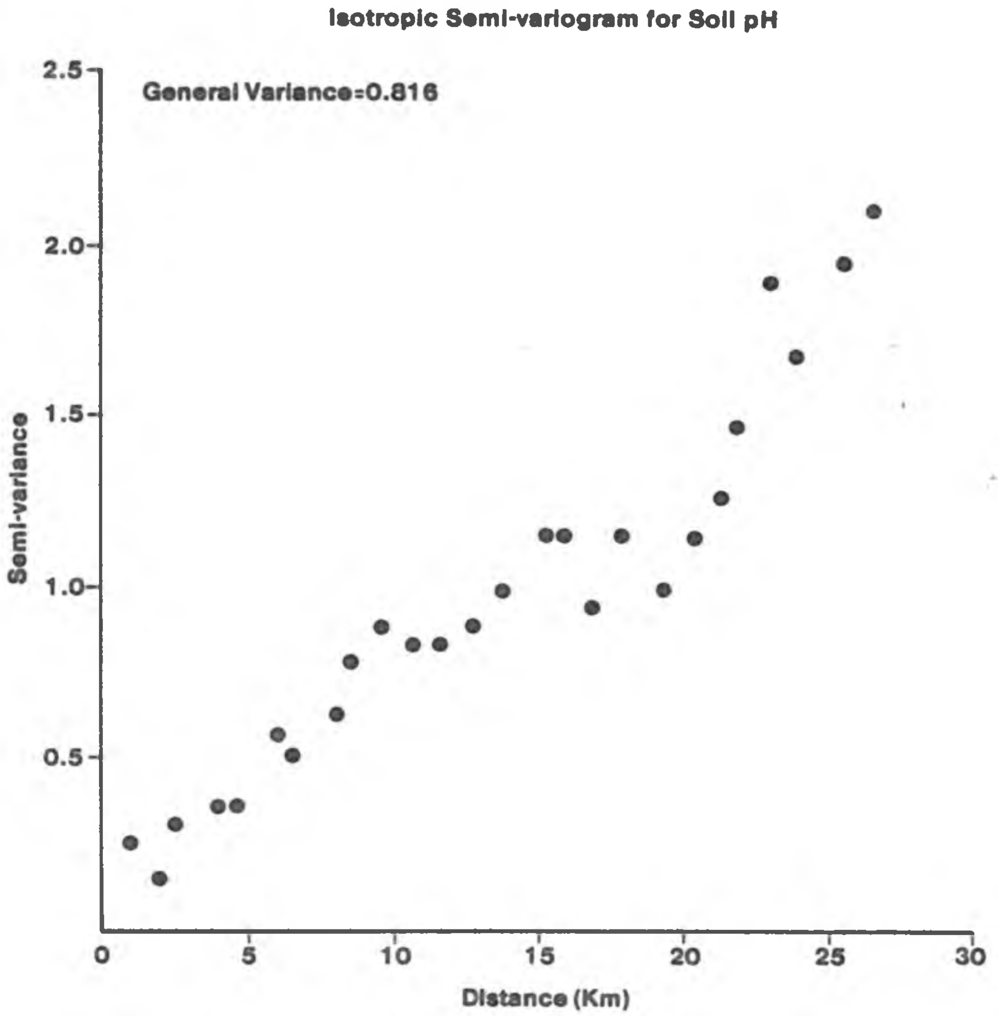

Figure 15. Isotropic semi-variogram for pH of surface soils of the Island of Maui.

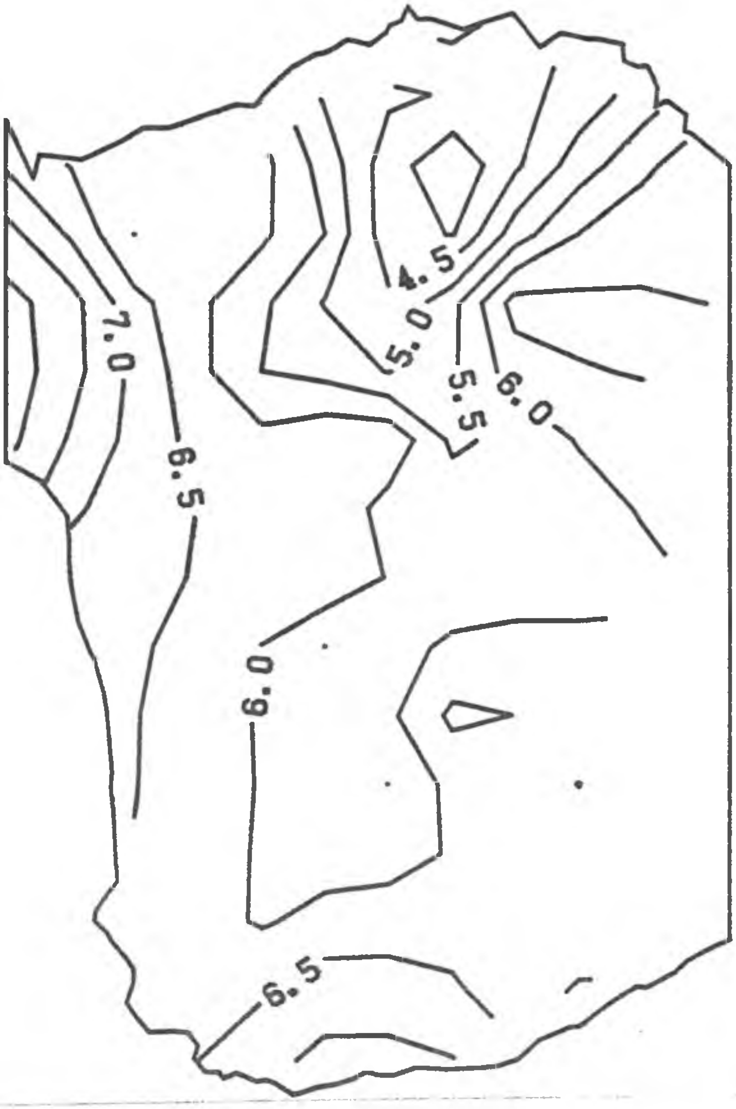

Figure 16. Isarithm map of pH of surface soils of the Island of Maui.

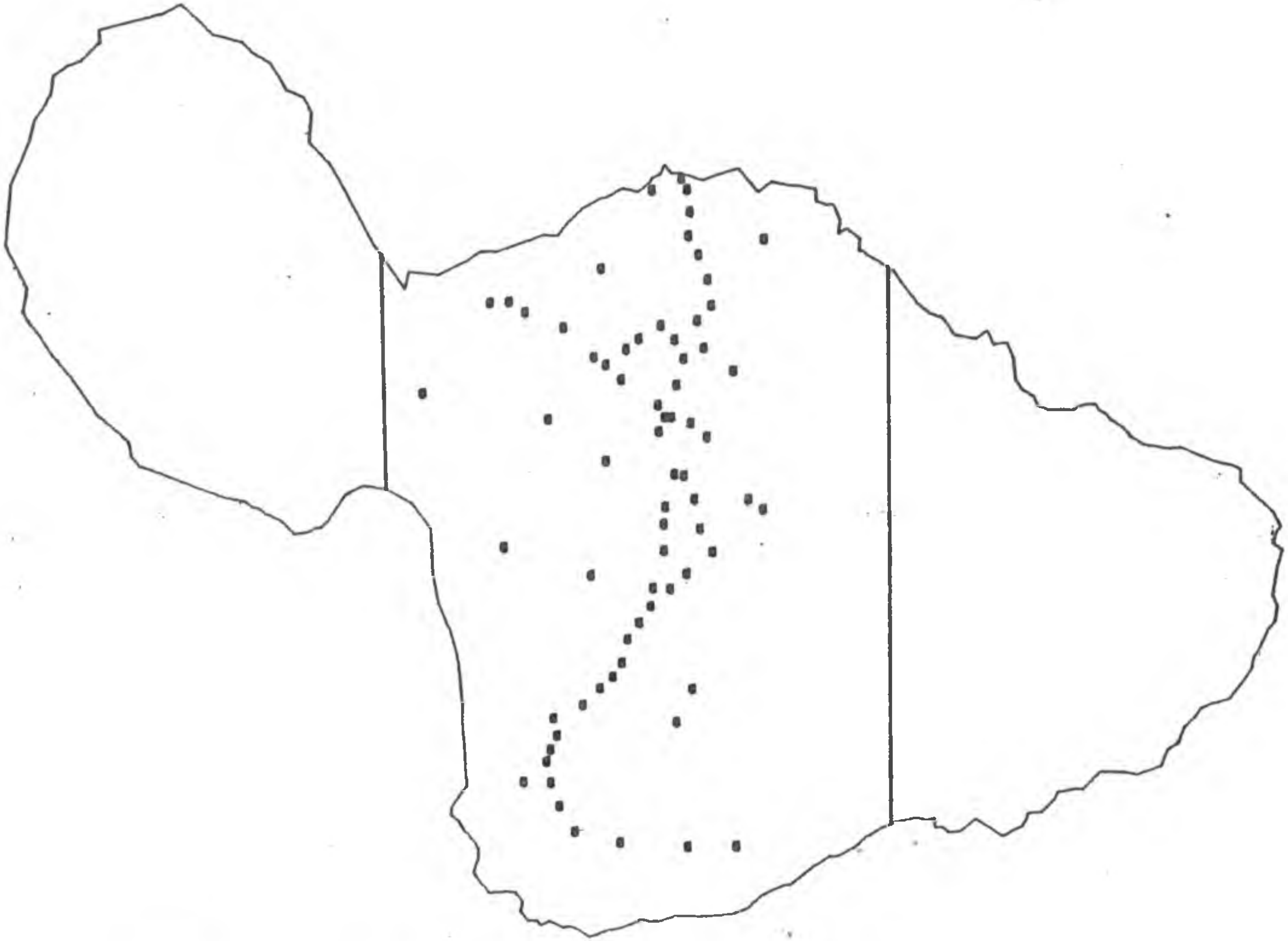

Figure 17. Study area on the Island of Maui.

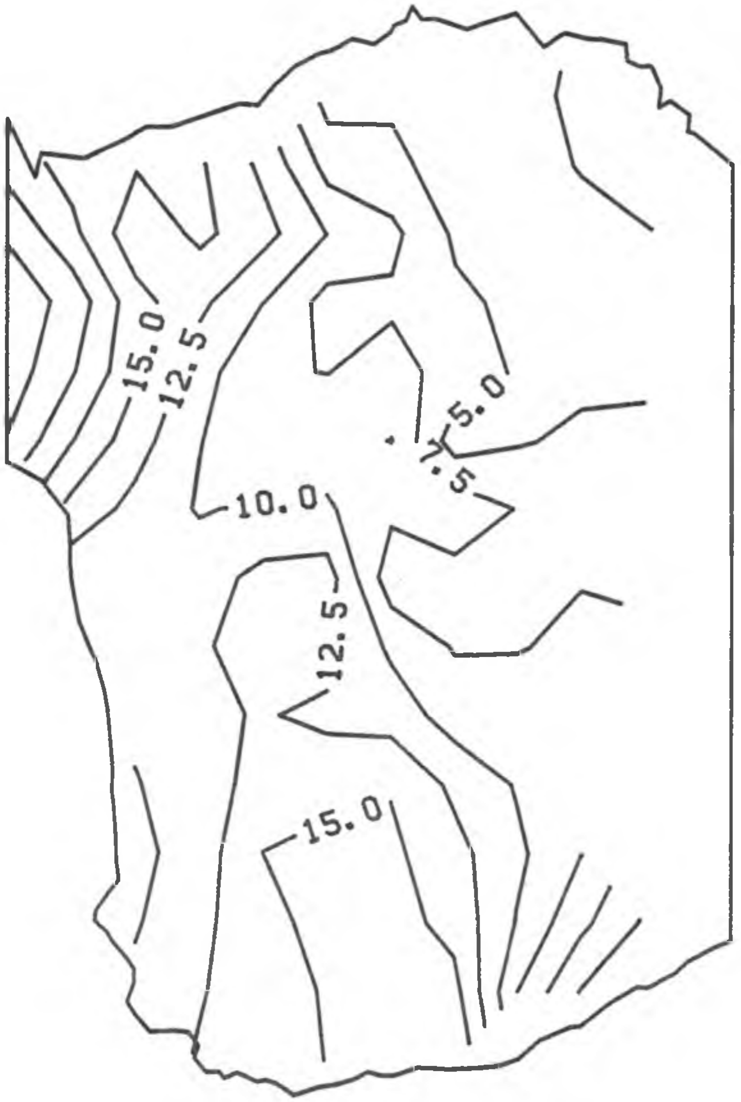

Figure 18. Isarithm map of silicon in saturation extracts of surface soils of the island of Maui.

Semi-variograms for P in saturation extracts and extractable P were more stationary than those of the above properties, that is, their semi-variance increased with distance and then leveled off. Semi-variograms for acid fluoride extractable P had better structure than those for $NaHCO_3$ extractable P where the sill was larger than the general variance, possibly indicating a weak trend. The semi-variogram for P in saturation extracts was somewhat more structured than those for $NaHCO_3$- and acid fluoride-extractable P, however some points are out of the pattern.

For most soil chemical properties semi-variograms have little or no nugget effect. The nugget effect as defined in geostatistics is the Y intercept of the graph or, the value of the semi-variance at which the curve intercepts the Y axis. This value is a reflection of short distance variation or specifically variation at distances smaller than the sampling distance. Thus, the sampling distance used in this study was adequate and it can be increased for future sampling of the area.

Directional trends revealed by semi-variograms of soil properties studied, are likely to be the effect of one or more factors acting upon these soil properties at the same time. Such factors may include: parent material, rainfall, elevation, temperature, age, distance from the ocean, flora, fauna, and management practices. The isotropic semi-variogram for median annual rainfall (Figure 19) indicates the presence of directional trends on rainfall; the semi-variance increases as the distance increases, then it levels off for a short distance, and again starts increasing as the distance increases. Trends revealed by the semi-variogram of median annual rainfall can also be seen in the map of rainfall (Figure 20). Rainfall in the area sampled increases in a west to east direction. In a north to south direction, rainfall decreases then increases then decreases again. Such non-uniform trends in rainfallprobably account for directional trends in soil chemical properties revealed by their semi-variograms and observed in the isarithm maps. Rainfall plays an important role in the formation of soils in Hawaii and apparently is responsible for directional trends observed in some of the soil chemical properties studied. Some of the properties affected by rainfall include pH, silicon in saturation extracts, exchangeable calcium and potassium. These four soil properties vary inversely with rainfall; highest values are found in dry areas and lowest values area found in wet areas (Figures 16, 18, 21 and 22). Other properties affected by rainfall include P sorption capacity, S sorption capacity, and extractable S. These three soil properties are highest in areas of high rainfall and lowest in areas of low rainfall

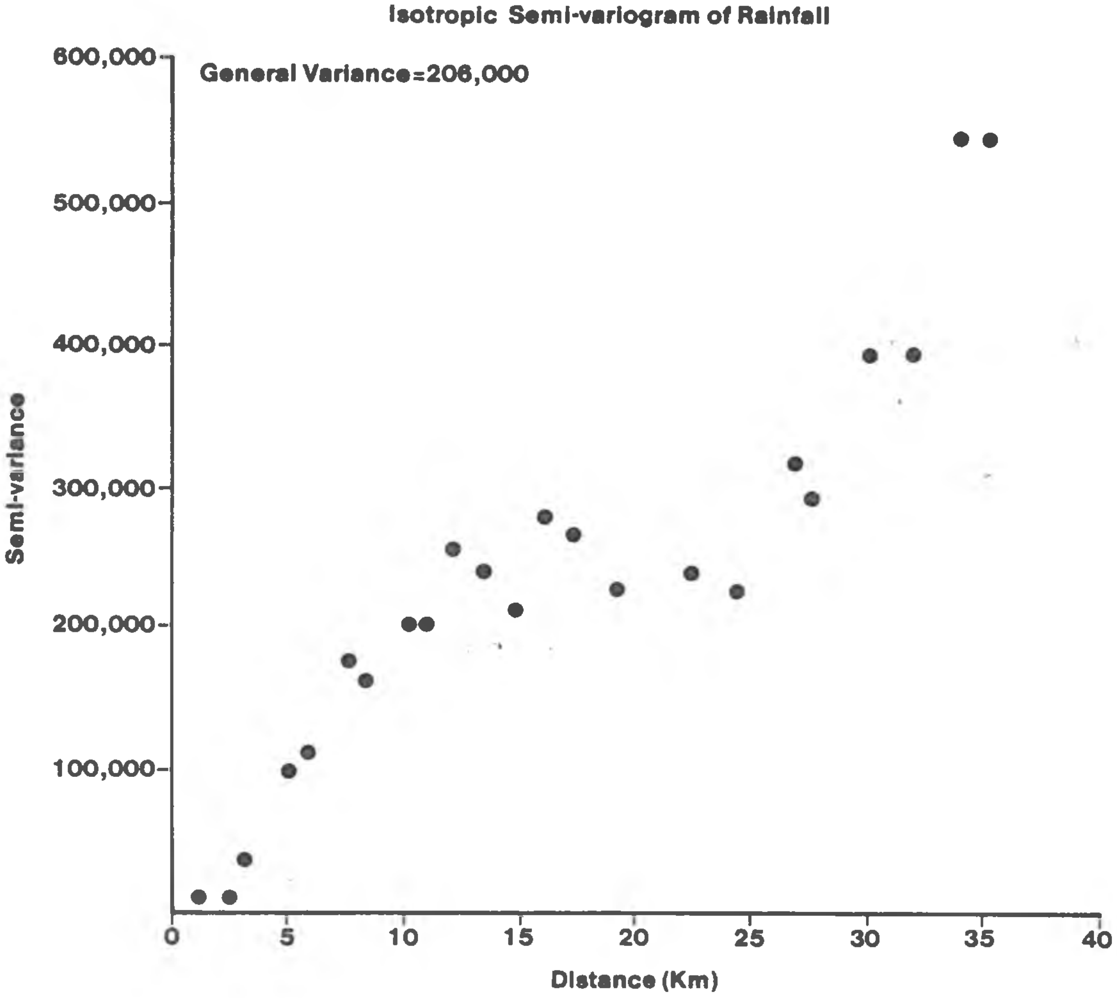

Figure 19. Isotropic semi-variogram for median annual rainfall of the island of Maui.

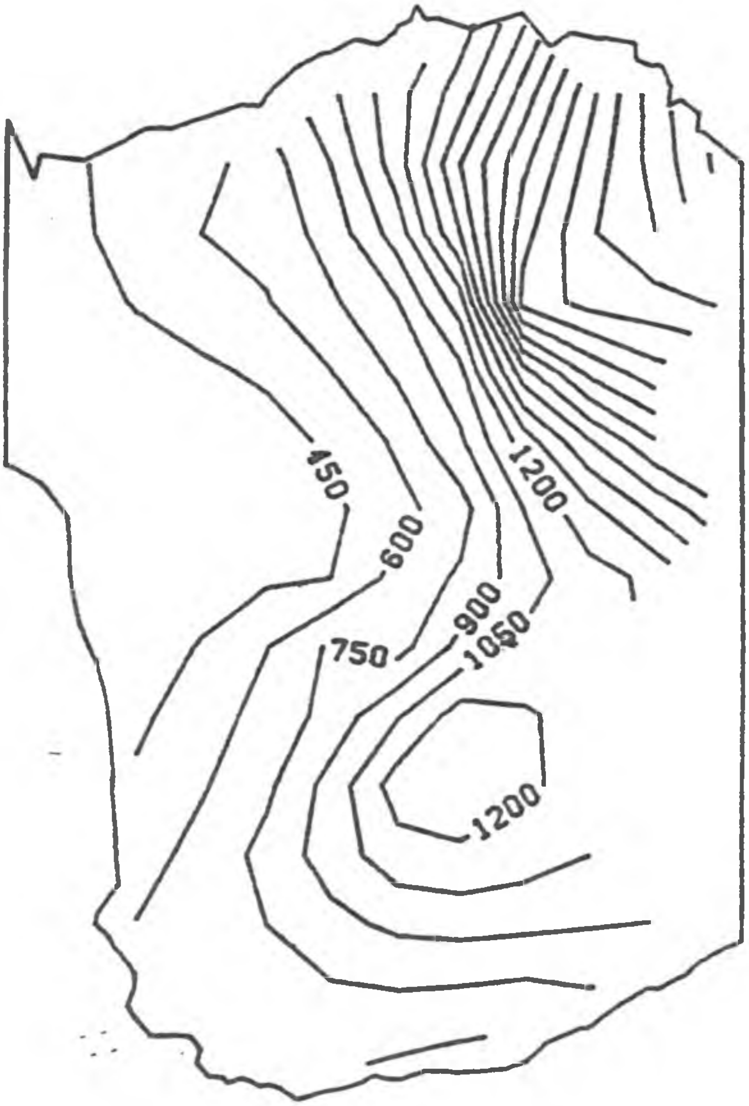

Figure 20. Median annual rainfall distribution of the island of Maui.

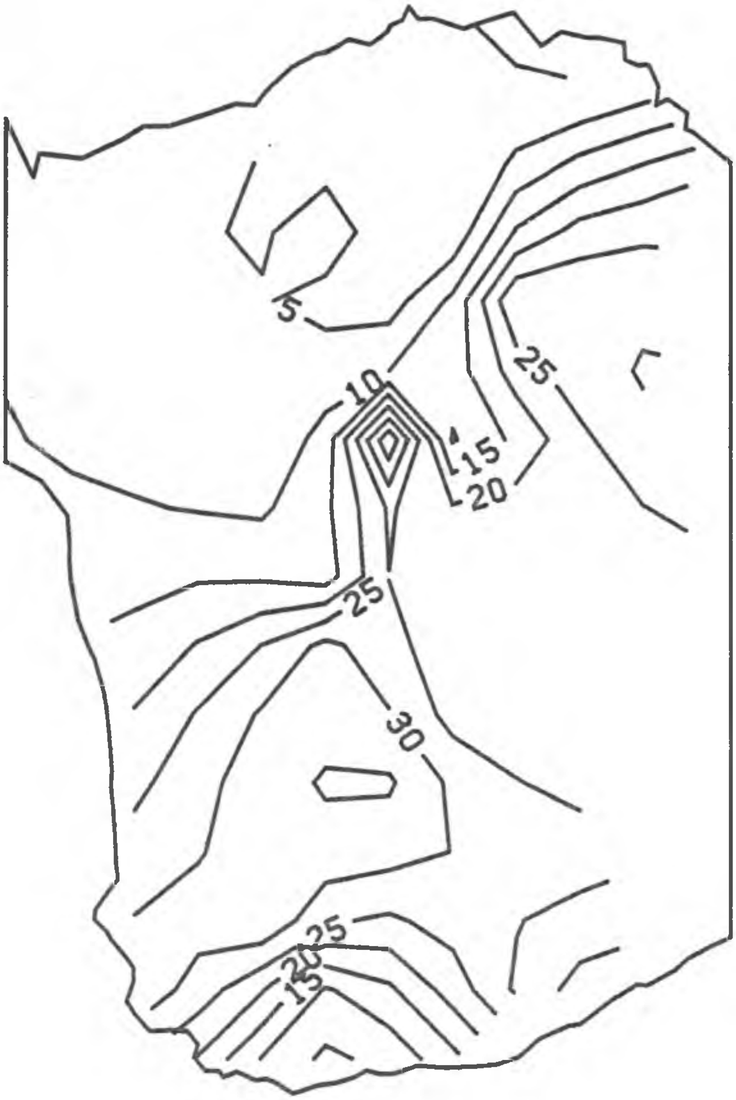

Figure 21. Isarithm map of exchangeable calcium of surface soils of the Island of Maui.

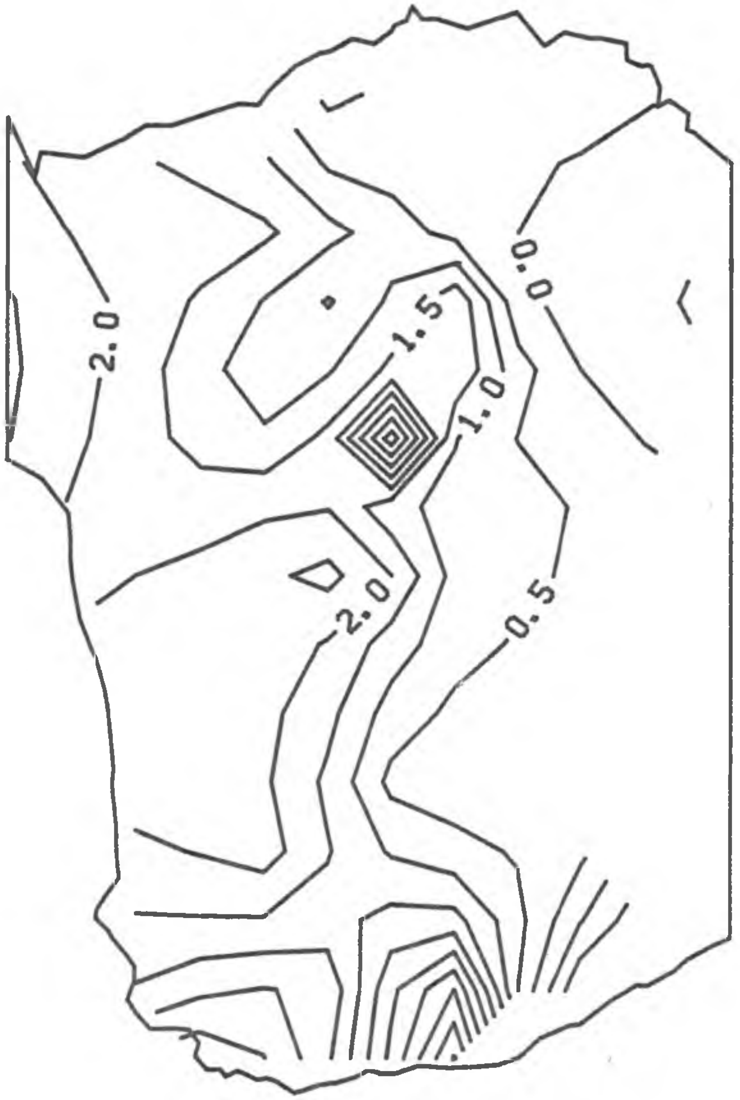

Figure 22. Isarithm map of exchangeable potassium of surface soils of the island of Maui.

(Figures 23, 24, 25, and 26).

Directional trends revealed by semi-variograms of exchangeable magnesium and sodium, and shown in isarithm maps for these soil properties (Figures 27 and 28) seem to be the effect of both rainfall and distance from the ocean. In general, lowest amounts of these two cations were found in areas of high rainfall, whereas the highest amounts were found on dry areas as in the west of the area sampled. However, the contours of these two properties follow trends that are related to the distance from the ocean. The closer the soil is to the ocean the higher the amounts of exchangeable magnesium and sodium, and as one moves away from the ocean the concentration of these cations in the soil decreases. This pattern can be clearly seen in the maps for both of these soil properties, especially in the west of the sampled area (Figures 27 and 28). The concentration of these cations in sea water is high: Na = 10,500 ppm and Mg = 1350 ppm, and more importantly they are very stable in sea water as revealed by their very long residence time. Residence time is defined as the time required to replace completely the amount of a given substance in the ocean, and apparently is related to the chemical behavior of each element. Elements affected little by sedimentary or biological processes generally have residence times of many millions of years, and elements used by organisms or readily incorporated

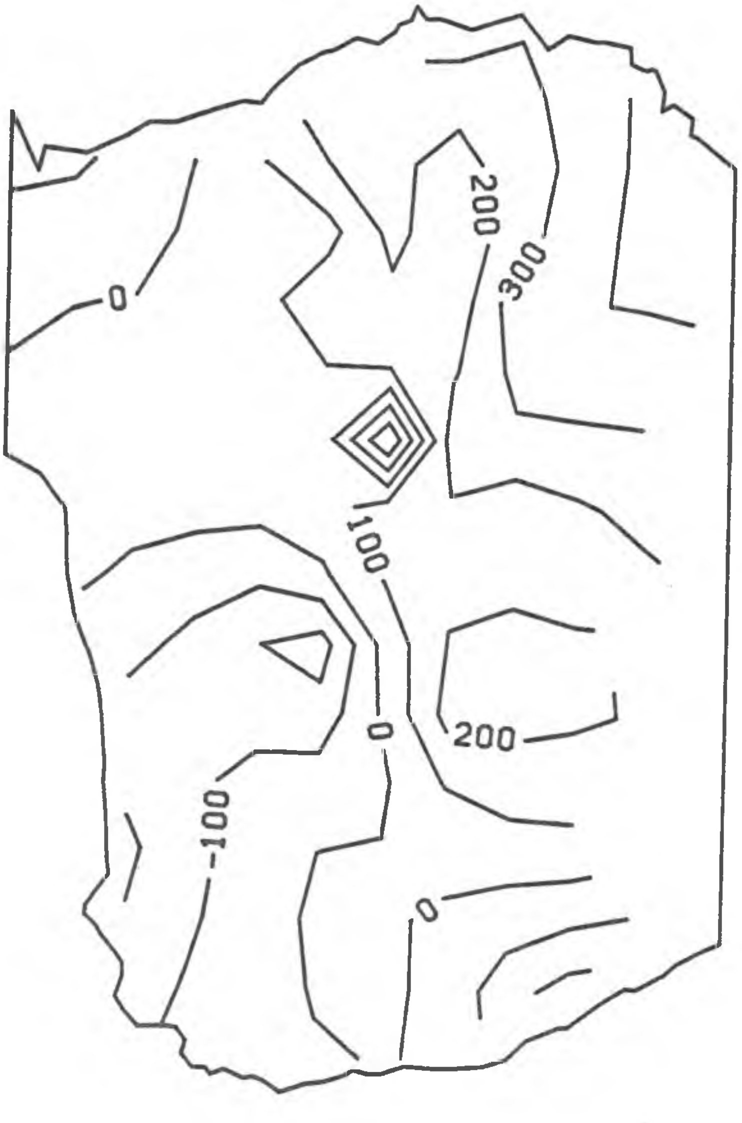

Figure 23. Isarithm map of P sorbed at 0.02 ppm by surface soils of the island of Maui.

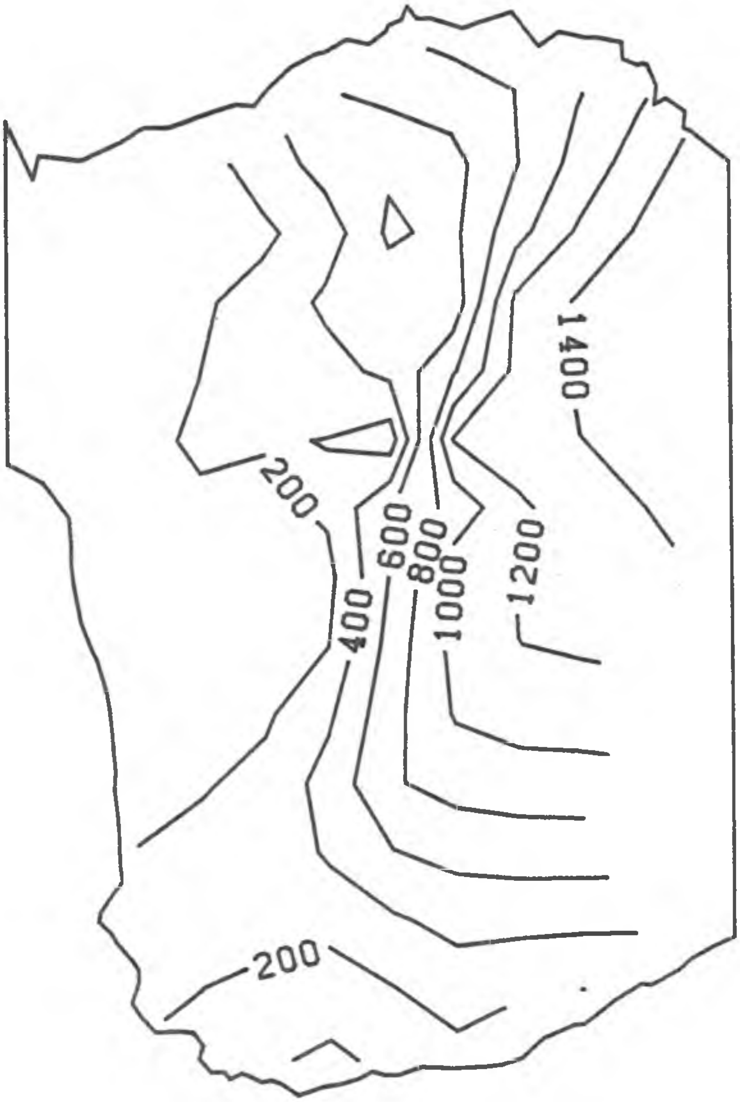

Figure 24. Isarithm map of P sorbed at 0.2 ppm by surface soils of the Island of Maui.

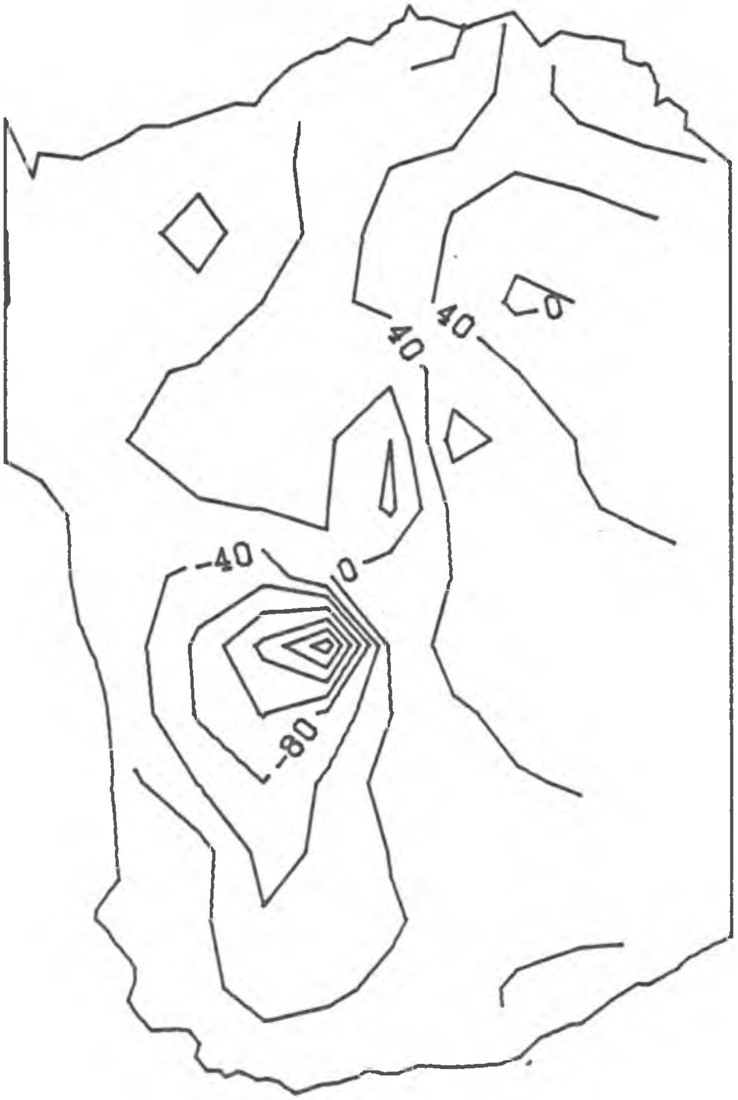

Figure 25. Isarithm map of SO_4-S sorbed at 5 ppm by surface soils of the Island of Maui.

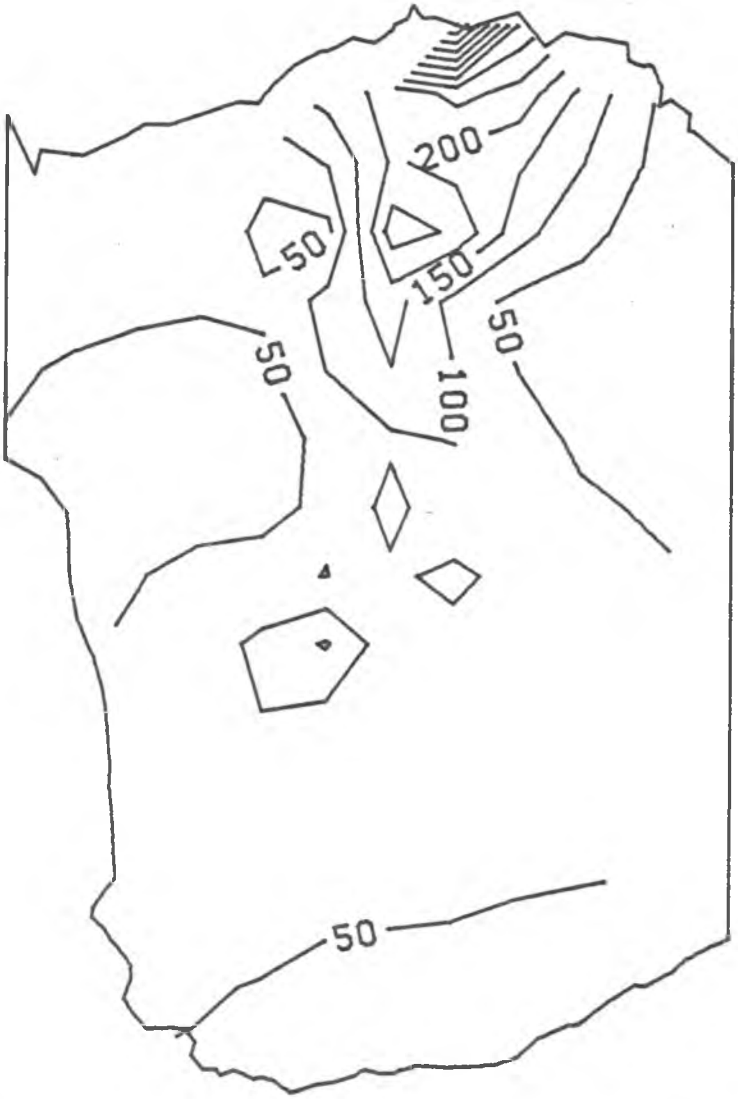

Figure 26. Isarithm map of extractable sulfur of surface soils of the island of Maui.

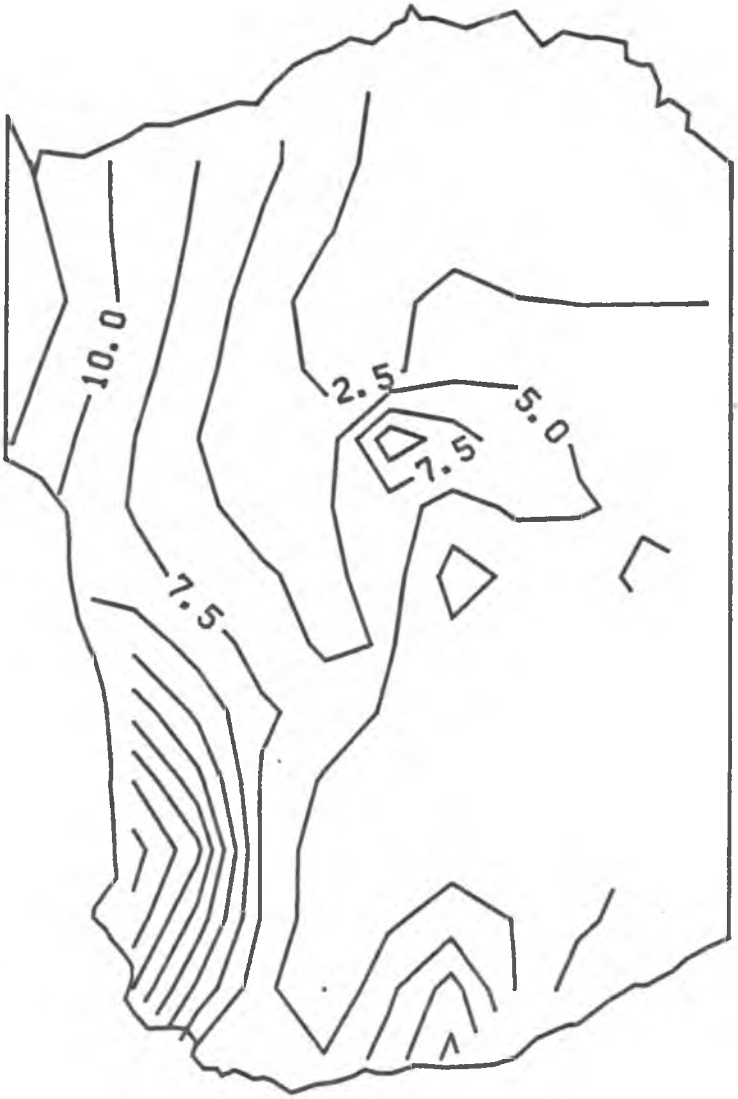

Figure 27. Isarithm map of exchangeable magnesium of surface soils of the island of Maui.

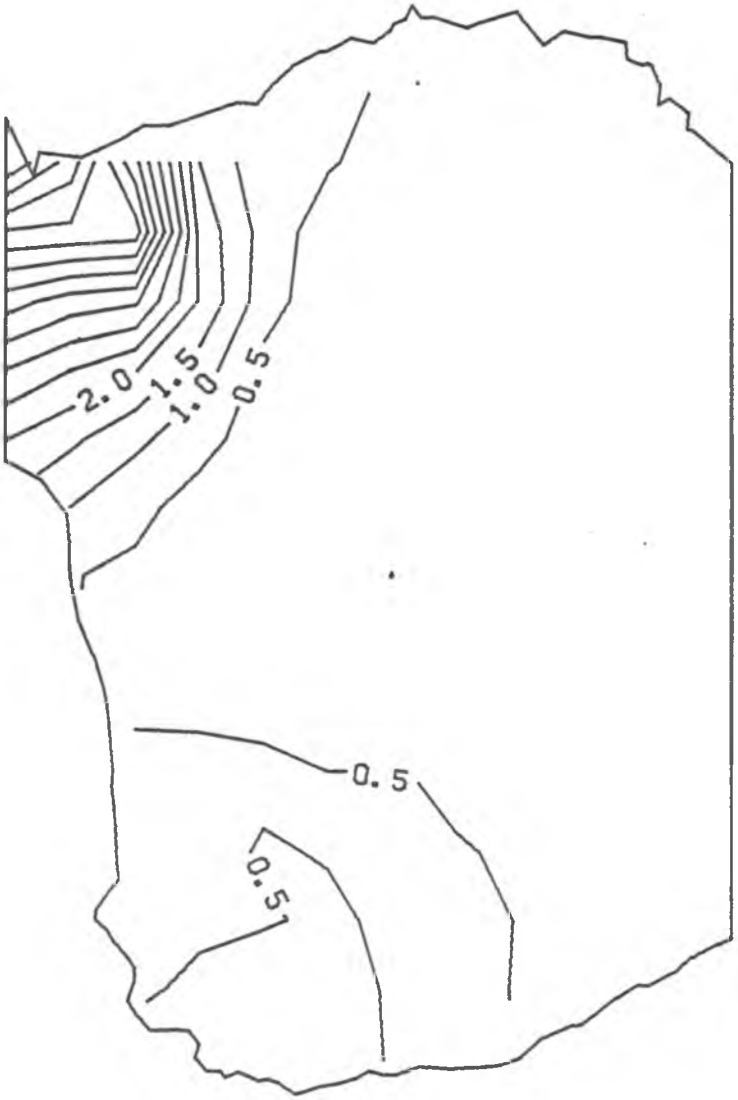

Figure 28. Isarithm map of exchangeable sodium of surface soils of the island of Maui.

in sediments tend to have much shorter residence times ranging from a few hundred to a thousand years (Gross, 1972). The concentration of Ca in sea water is much lower than that of Na and Mg, 400 ppm, and has a very short residence time.

A summary of the spatial dependence of chemical properties of soils based on isotropic semi-variograms is presented in Table 15. Ranges of the semi-variogram for soil chemical properties varied. The range of a semi-variogram is defined as the distance at which the curve of the semi-variogram levels off, and is an indication of the distance at which a pair of locations is dependent on one another (Clark, 1982). Beyond this distance, values of the properties studied are independent from one site to the other. For P in saturation extracts the range was 19 km, 15 km for P sorbed at 0.2 ppm, 20 km for acid fluoride extractable P, and 4.3 km for $NaHCO_3$ extractable P. These ranges are much larger than the mininum sampling distance used in this study. Thus, sampling distance seemed to be adequate. We attempted to sample at a distance interval less than one half the range of the semi-variogram for the selected soil property. The ranges presented above are relatively large. They indicate that the variation of these properties occurs at rather large distances. This could be the case because much of the area studied is farmed to plantation crops or in ranches. These farms are large, and

Table 15. Spatial dependence of chemical properties of surface soils of the island of Maui.

Soil Property	Range (a) km	Sill (c)	Nugget Effect (Y intercept)	General variance
pH	-	-	0	0.82
Ca	-	-	0	161.1
Mg	-	-	1.6	13.4
K	13	0.89	0.39	0.92
Na	-	-	0	0.66
Si	-	-	0	18.3
P in saturation extracts	19	0.89	0.00065	0.0015
P sorbed at 0.02 ppm	-	-	8399	23331
P sorbed at 0.2 ppm	15	143060	35765	119216
Olsen P	4	338.8	263.5	313.7
Bray No. 1 P	20	87.8	41.6	77.1
Extrac. Al	12	0.61	0.41	0.68
Extrac. S	7	10855	5921	16448
S sorbed at 5 ppm	11	5150	1962	4088
Annual Median rainfall	-	-	0	206124

\- = non-stationary property

crop and fertilizer management practices are similar over large areas. However, other factors such as rainfall, temperature, elevation, and vegetation influence the variation of chemical properties over the landscape. These factors contribute differently, and with different degrees of influence, to the variation of chemical properties of soils, and thus it is difficult to separate the factor most affecting the spatial dependence of chemical properties of this study.

Using the information obtained from the semi-variograms, values were kriged at 62 unsampled locations (Figure 29) for pH, exchangeable K, Si in saturation extracts, P sorbed at 0.02 ppm, P sorbed at 0.2 ppm, extractable S, and S sorbed at 5 ppm. Kriged values were then mapped and are shown in Figures 30 to 36.

Estimates of pH of surface soils (Figure 30) shows clearly that soil pH was highest in the dry regions of the south (Ulupalakua), and in the west between Puunene and Kihei. On the other hand low pH values occur in the north of the sample area where soils developed under wet conditions and are classified as Ultisols. Trends shown by the map of kriged values for pH are the same as shown by the isarithmic map of the original values of soil pH previously shown (Figure 16). However, the contours on the map with kriged values are smoother and cover the area more evenly.

Estimates of the amounts of P sorbed at 0.2 ppm by surface soils are shown in Figure 34. Again, it can be seen that trends observed on the isarithmic map of the original values of P sorbed at 0.2 ppm (Figure 24) are also revealed by the map of the kriged values. But comparing the two maps it is obvious that the contours are smoother on the map with kriged values. In fact if we compare the maps of the raw or original data with those with kriged values for the different soil properties, we find that contours in maps with kriged values are smoother than those with corresponding original values, and at the same time they show same trends. Kriged maps should demonstrate smoother contours than corresponding maps with original values because kriging does optimal interpolation, so values are smoothed according to neighborhood values and their weight in the predicted value is based on the spatial dependence as estimated by the semi-variograms. Furthermore locations at which values were kriged are uniformly distributed, giving rise to a well balanced number of locations for subsequent contouring by the mapping program. Actual samples were non-uniformly distributed over the area and because the mapping program does not consider spatial dependence, contours were cut off sharply leaving gaps in the map. These observations suggest that ideally, better maps can be obtained by sampling at uniform distances and in straight lines parallel to one another over the landscape of the area to be studied rather than in random fashion. This kind of sampling can be done by drawing a grid over the area to be sampled. Such an approach is seldom practical because of inaccessability to the proposed sample sites and difficulty in locating sample sites. Furthermore, rigid sampling grid may have sites that are obviously not good for sampling such as urban areas, garbage dumps, graveyards, etc. A good sampling plan could benefit from detailed soil survey maps, if available, along with the spatial relationships of soil properties as revealed by semi-variograms. With the use of detailed soil survey maps, areas that are obviously not good for sampling can be located thus saving time and effort. Furthermore, such maps display predominant soils of the area, type of terrain, and to some extent the accesability to different locations. With the use of the spatial dependence of soil properties an adequate sampling distance interval can be selected so that a large percent of the variation in chemical properties can be included in the sample plan. Thus, sampling does not have to be done in a uniform grid or at random, but rather in some way in which major soils of the area are sampled and a distance that will take into account most of the variation of soil chemical properties.

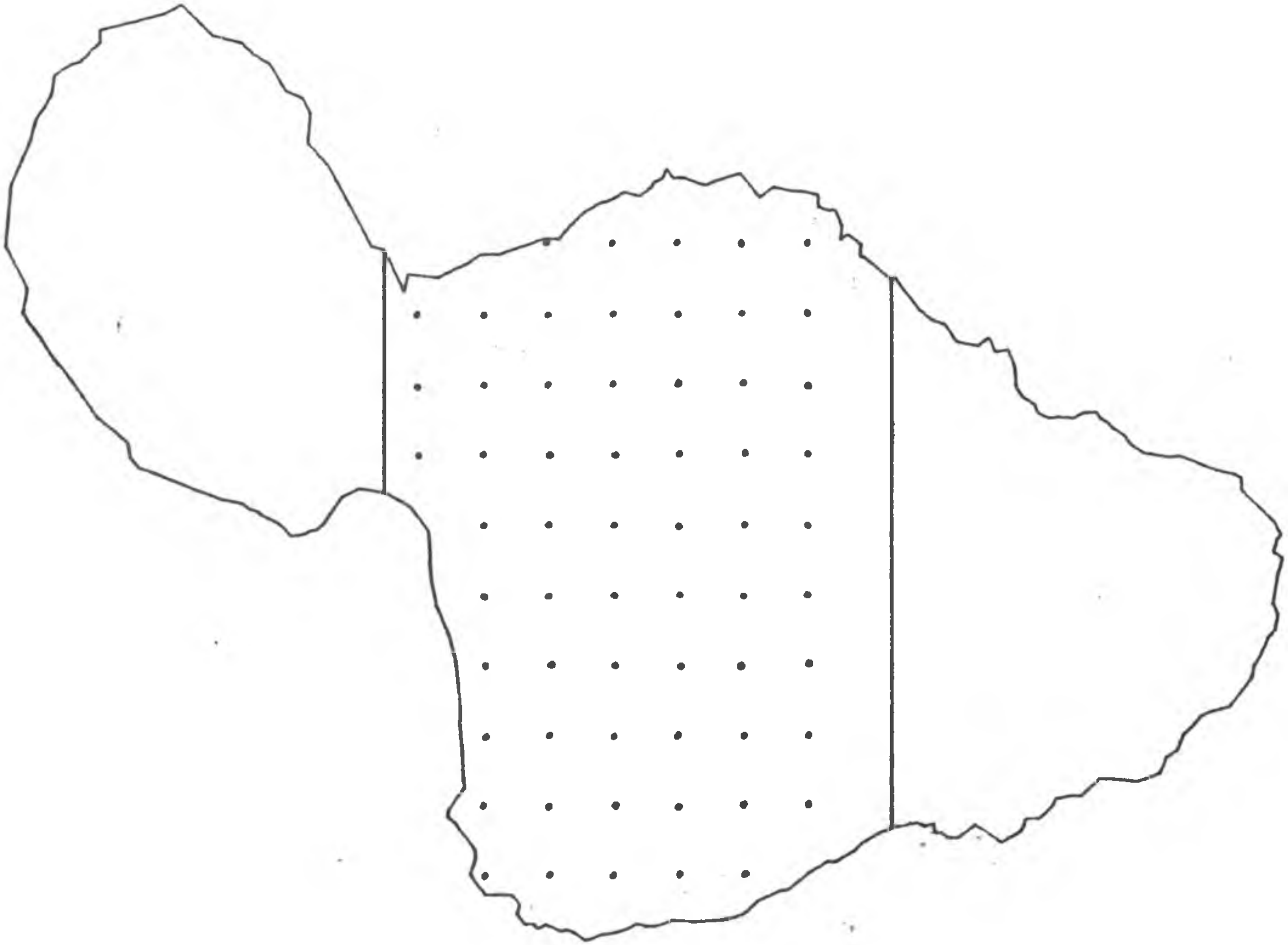

Figure 29. Location of kriged points on the Island of Maui.

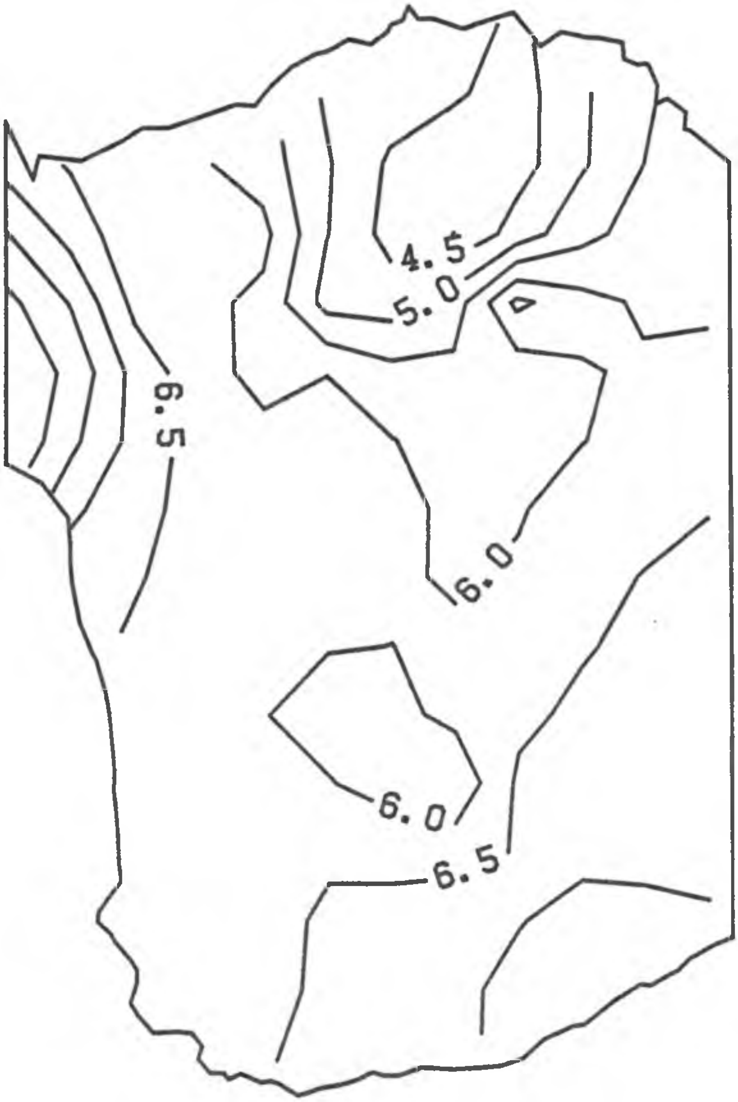

Figure 30. pH of surface soils of the island of Maui using kriged estimates.

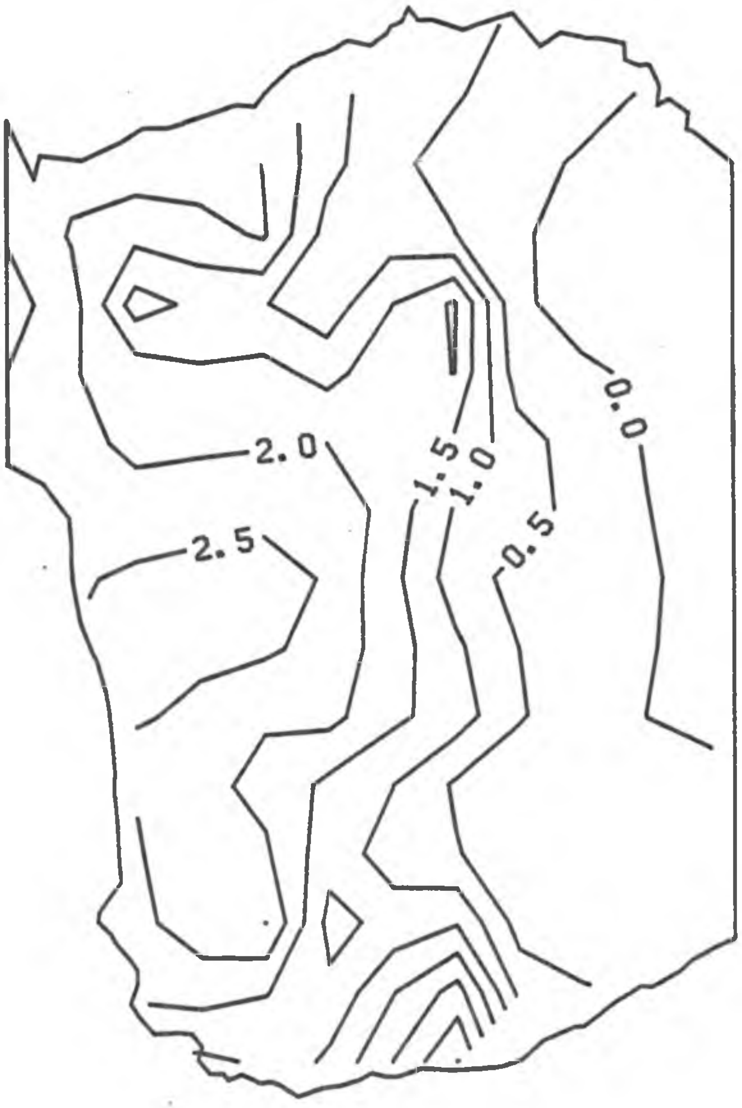

Figure 31. Exchangeable potassium of surface soils of the island of Maui using kriged estimates.

Figure 32. Silicon in saturation extracts of surface soils of the Island of Maui using kriged estimates.

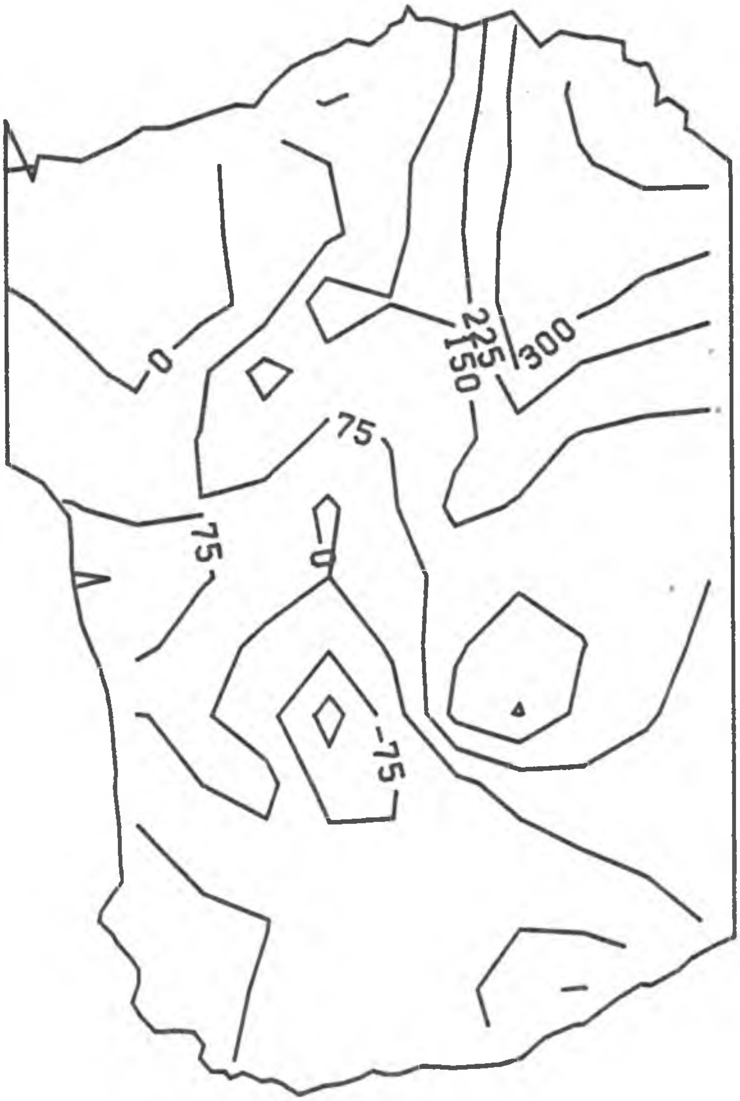

Figure 33. Phosphorus sorbed at 0.02 ppm by surface soils of the island of Maui using kriged estimates.

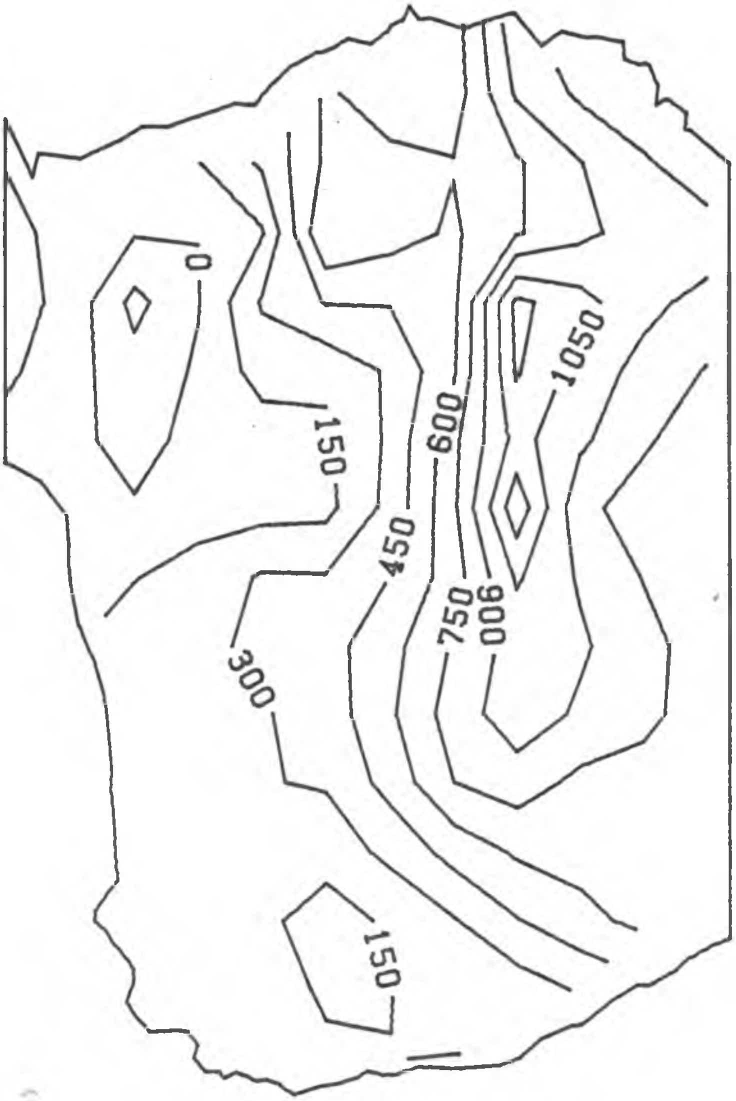

Figure 34. Phosphorus sorbed at 0.2 ppm by surface soils of the island of Maui using kriged estimates.

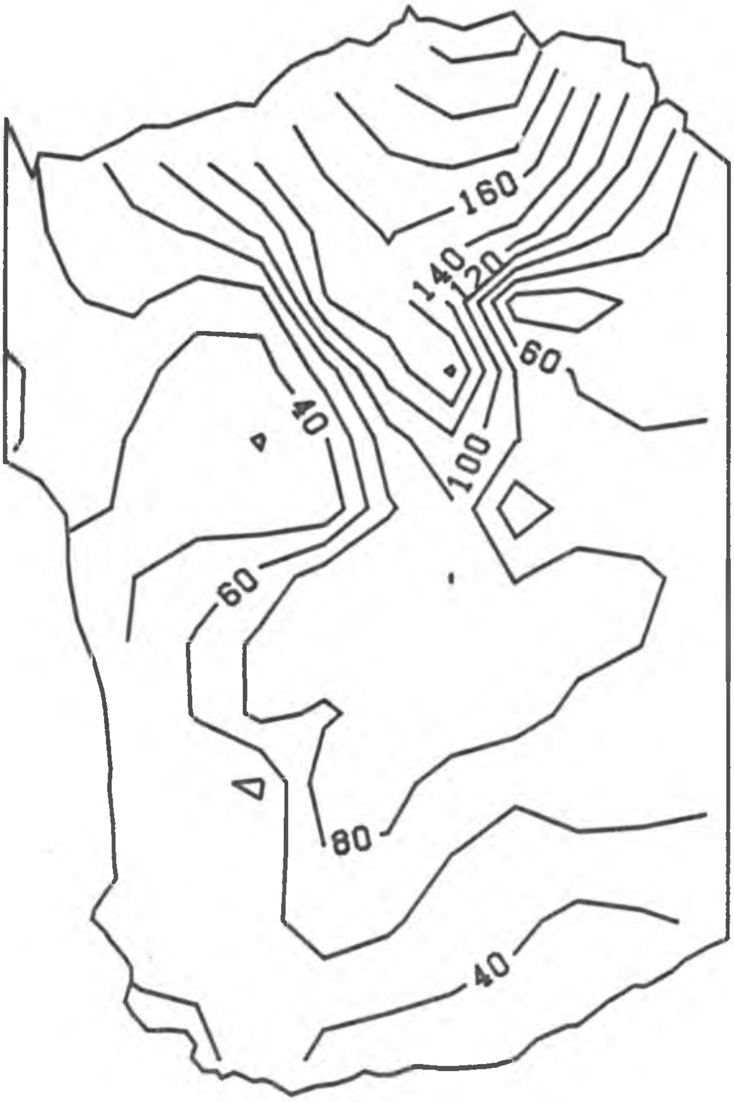

Figure 35. Extractable sulfur of surface soils of the island of Maui using kriged estimates.

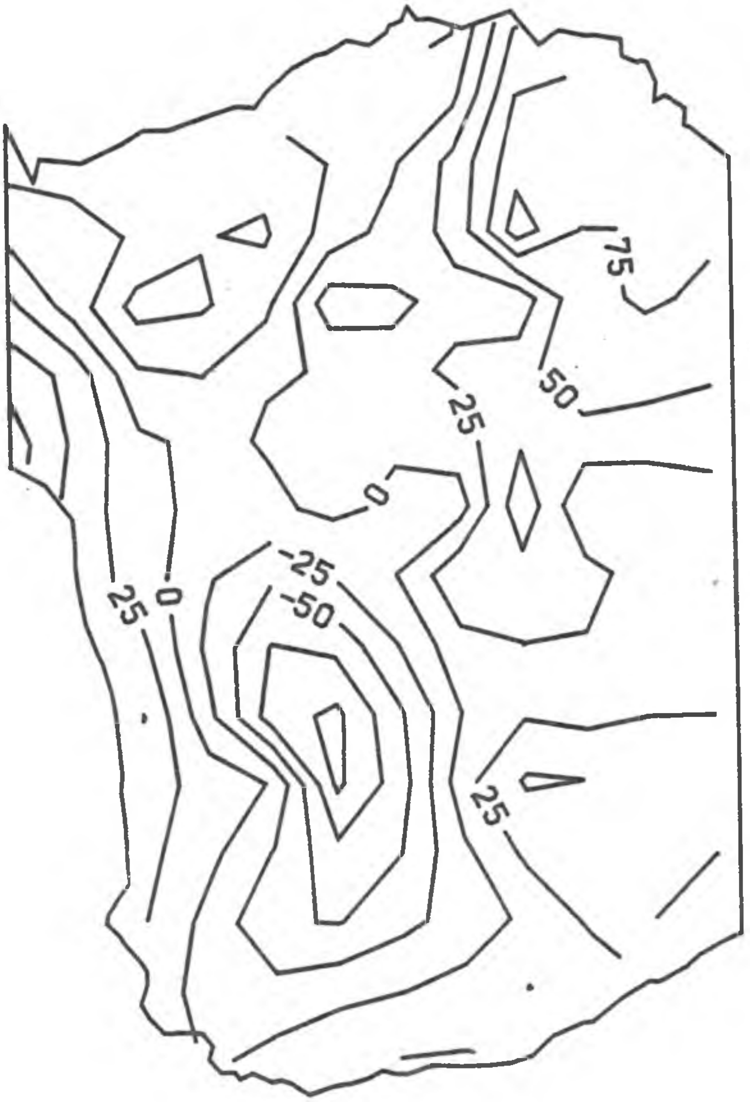

Figure 36. Sulfate sulfur sorbed at 5 ppm by surface soils of the island of Maui using kriged estimates.

V. SUMMARY AND CONCLUSIONS

Soil samples were collected at seventy sites on the island of Maui within an area extending eastward from Puunene to the western slopes of Mt. Haleakala. These samples were analyzed for selected chemical properties and, based on the results, soil fertility maps were prepared. Relationships between soil chemical properties and soil classification were studied. Furthermore, the spatial dependence of soil chemical properties was determined by using semi-variograms. With the information obtained from these semi-variograms, values of chemical properties were estimated at unsampled locations by the method of kriging. Kriged values were mapped in the same manner as the raw data values.

Elevation in the study area ranges from sea level to 1828 m, and median annual rainfall ranges from 325 to 2500 mm. In the study area, rainfall increases in a west to east direction. In a north to south direction, rainfall decreases then increases then decreases again. Lowest rainfall occurs in the Ulupalakua, Makena, Kamaole, Kihei, Paia, Puunene, and Keahua areas. In these areas, median annual rainfall amounts to 600 mm or less. Soils of these areas belong to the Haplustolls, Tropofolists, and Torrox great groups. Some Eutrandepts are also encountered in the south of Ulupalakua. In the Pukalani, Pulehu, Waiakoa, Keokea and north of

Ulupalakua areas median annual rainfall ranges from 600 to 1000 mm. For the most part, soils of these areas are classified as Eutrandepts. Moving east from the upper Kula road towards the slopes of Mt. Haleakala, median annual rainfall ranges from 1000 mm to approximately 1300 mm, and soils of the area are for the most part Dystrandepts but also some Eutrandepts. The northeast corner of the sampled area is the wettest portion and median annual rainfall ranges from 900 mm to 3000 mm. Soils of these area belong to the Tropohumults and Humitropepts great groups.

The pH of soils in the south, west, and central parts of the study area, where Haplustolls, Torrox, Tropofolists, Eutrandepts, and Vitrandepts occur, is adequate for most agronomic crops, the average pH is approximately 6.0. Soils in the Makawao, Haliimaile, Haiku, Pukalani, and Pauwela areas have low pH, generally 5.5 or less. These soils can require large amounts of lime to bring their pH to a level suitable for the production of many acid sensitive agricultural crops.

The concentration of exchangeable bases followed rainfall patterns. Thus soils developed in high rainfall areas such Tropohumults and Humitropepts as well as Dystrandepts which occur at high elevations, contained lower amounts of exchangeable bases than the Haplustolls, Torrox, Tropofolists, Eutrandepts, and Vitrandepts which occur in regions of lower rainfall. However, for the most part, the soils contained adequate amounts of exchangeable bases for plant growth. Exchangeable bases were low in soils from many sites where the soils were mostly Tropohumults (Makawao, Haiku, and Pauwela areas). Such soils require additions of these elements to sustain good plant growth. Some sites where the soils are Humitropepts (Haliimaile area), are deficient in both potassium and magnesium. These soils develop in areas of relatively high rainfall and therefore cations have been leached.

Exchangeable sodium and magnesium in soils was also affected by distance from the ocean; soils closest to the ocean, and particularly in dry areas, contain the greatest amounts of these elements. Thus, soils in the Makena, Kamaole, and Kihei areas contain the greatest amounts of exchangeable sodium and magnesium, the concentration of these elements in the soil decrease with increasing distance from the coast.

The concentration of silicon in saturation extracts was highly correlated with rainfall. Soils in the Ulupalakua, lower Kula, Makena, Kihei, Puunene, Keokea, Waiakoa, Pulehu, and Paia areas which developed under low rainfall, contained approximately 12 ppm of Si in saturation extracts. On the other hand, soils in the Pukalani, Makawao, Kokomo, Haiku, and Pauwela areas, which developed under relatively high rainfall, contained approximately 5 ppm of Si in saturation extracts. These soils belong to the Tropohumults and Humitropepts great groups. Dystrandepts which developed under high rainfall and at high altitudes contained amounts of Si in saturation extracts similar to those of Tropohumults and Humitropepts.

The amounts of P sorbed by soils at 0.2 ppm increased in a west to east direction in the study area. In the same manner, rainfall increased. Thus, a significant relationship between P sorption and weathering products was found. Haplustolls which occur in the Makena, Kamaole, and Kihei areas, as well as Tropofolists which occur in the south of Ulupalakua, sorbed the least amounts of P, 200 ug/g or less. These soils require only a small amounts of P. They also sorb the least amounts of sulfur. Eutrandepts and Dystrandepts, which occur in the north of Ulupalakua, Keokea, Waiakoa, Pulehu, and upper Kula areas sorb P in amounts ranging from 600 to 1000 ug/g. They require additions of P fertilizer. The Torrox and Typic Haplustolls which occur east of Puunene, Keahua, and Paia sorb amounts of P ranging from 300 to 700 ug/g. They require additions of P fertilizer in quantities smaller than those required by Eutrandepts and Vitrandepts. The Dystrandepts, which occur at high elevations on the slopes of Mt. Haleakala, and the Humitropepts and Tropohumults, which occur in the northeast corner of the study area, sorb amounts of P ranging from 600 to 1500 ug/g. Thus, they require large amounts of P. They also sorb the largest amounts of sulfur.

Largest amounts of extractable sulfur were contained on soils belonging to the Tropohumults, Humitropepts, and Dystrandepts great groups which developed in areas of high rainfall. On the other hand, soils occurring in low rainfall areas, such as in the Ulupalakua, Makena, Keokea, Kamaole, Kihei, Puunene, Keahua, and Paia areas, contained the lowest amounts of extractable sulfur.

Variation in chemical properties can be assigned to the various taxa. Variations in exchangeable Ca, Mg, Na, and K, and Si in saturation extracts among soils were mostly accounted for at the family level. The mapping unit level accounted for additional variation among soils in extractable sulfur and phosphorus, and sulfur and phosphorus sorption.

Semi-variograms indicated the presence of such strong directional trends in most soil chemical properties that the data were considered non stationary. Directional trends were also revealed by fertility maps. Such trends result from one or more factors acting upon soils at once. Such factors include: rainfall, parent material, elevation, temperature, flora, fauna, distance from the ocean, and numerous management practices. Among these factors, rainfall is most important because of its major role in formation of soils in

Hawaii. Rainfall was related to soil pH, exchangeable Ca and K, Si in saturation extracts, P sorption, S sorption, and extractable sulfur and aluminum. Rainfall was responsible for much of the directional trends in these properties revealed by semi-variograms. Distance from the ocean was a major factor affecting the distribution of exchangeable magnesium and sodium; soils closest to the ocean, in drier areas, contained the largest amounts of these elements. Concentrations of these elements in soils decreased with increasing distance from the ocean.

Geostatistics is a useful tool for studying soil properties because it reveals spatial dependence as well as the presence of directional trends, if any. Spatial dependence of soil properties, as indicated by semi-variograms, can be used to determine an appropiate sampling distance (interval) to account for a large percent of the variation in soil chemical properties associated with soil fertility and fertilizer requirements. The sampling interval used in this study was 3.5 km which was much lower than the average range of soil chemical properties in the area, and was more than adequate to account for a large percent of the variation in most soil chemical properties. For future sampling of the area it is possible to increase the sampling distance interval by two to three km and still account for a large percent of the variation in most soil chemical properties.

Using the spatial relationships of soil chemical properties, values for some properties were estimated at unsampled locations by the use of kriging and these values were mapped. Maps based on kriged values show trends in soil properties similar to those shown by isarithm maps based on raw or original data. However, contours in kriged maps are smoother and generally cover the sample area more evenly. Kriging does optimal interpolation, thus values are smoothed according to neighboring values and their importance of values based on spatial dependence as estimated by the semi-variograms. Furthermore, kriged values were estimated at a uniform distance from one another and cover the entire area of study. On the other hand, actual samples were taken at non-uniform distances from one another, and some parts of the area were sampled more intensively than others. Thus, gaps in the data were present. As a result, contours are cut off sharply at those gaps.

Large areas can best be sampled using information contained in detailed soil survey maps, along with the spatial relationships of soil properties revealed by semi-variograms. Using survey maps one is able to select sites where major soils of the area occur, to include most of the different types of soils, to determine areas which are not valid samples sites, and to determine, more or less, how accessible the locations can be. Using spatial dependence of soil properties an appropiate sampling distance can be determined and used for actual sampling.

One way this study can be used is to make general estimates of fertilizer requirements to bring soils of an area to levels that are adequate for crop production. It also can be used to determine what sort of crops should be grown in an area--matching the fertility of soils to crops that would be productive in those soils.

APPENDIX OF TABLES

Table 16. Mean, standard deviation, minimum, and maximum of chemical properties of surface soils belonging to the order Inceptisol.

Soil Chemical Property	Mean	Standard Deviation	Minimum	Maximum
pH	5.6	0.6	4.0	6.6
Ca (meq/100 g)	21	10.9	1.1	39.2
Mg (meq/100 g)	4.9	3.6	0.5	20.7
K (meq/100 g)	1.4	0.9	0.2	4.0
Na (meq/100 g)	0.3	0.2	0.1	0.8
Si in saturation extracts (ug/ml)	9.1	3.8	1.9	17.5
P in saturation extracts (ug/ml)	0.031	0.040	0.001	0.195
P sorbed at 0.02 ppm (ug/g)	88	136	-245	327
P sorbed at 0.2 ppm	614	362	150	1765
P buffering capacity (ug/g)	163	106	53	585
Olsen P (ug/g)	20.4	17.6	1.4	70.5
Bray No.1 P (ug/g)	9.6	9.6	0.4	44.8
Al (meq/100 g)	0.097	0.240	0.0	1.217
Extrac. S (ug/g)	89	52	39	264
S sorbed at 5 ppm (ug/g)	11	64	-262	102
Median annual rainfall	849	242	575	1750

n = 36

Table 17. Mean, standard deviation, minimum, and maximum of chemical properties of surface soils belonging to the order Mollisol.

Soil Chemical Property	Mean	Standard Deviation	Minimum	Maximum
pH	6.3	0.7	5.3	7.7
Ca (meq/100 g)	11.6	11.4	3.5	39
Mg (meq/100 g)	7.1	3.7	2.7	12.4
K (meq/100 g)	1.9	1.2	0.4	4.3
Na (meq/100 g)	1.6	2.1	0.2	5.8
Si in saturation extracts (ug/ml)	12.5	4.6	6.5	21.7
P in saturation extracts (ug/ml)	0.075	0.045	0.019	0.134
P sorbed at 0.02 ppm (ug/g)	-8	141	-300	201
P sorbed at 0.2 ppm (ug/g)	188	134	90	482
P buffering capacity (ug/g)	56	28	30	116
Olsen P (ug/g)	26.4	25.4	5.9	82.5
Bray No.1 P (ug/g)	12.8	8.2	3.1	23.6
Al (meq/100 g)	0.012	0.023	0.0	0.059
Extrac. S (ug/g)	65	24	37	105
S sorbed at 5 ppm (ug/g)	-10	18	-40	13
Median annual rainfall	570	199	325	900

n = 8

Table 18. Mean, standard deviation, minimum, and maximum of chemical properties of surface soils belonging to the order Oxisol.

Soil Chemical Property	Mean	Standard Deviation	Minimum	Maximum
pH	5.9	0.5	5.3	6.4
Ca (meq/100 g)	9.5	7.3	4.4	23.2
Mg (meq/100 g)	4.3	2.1	1.3	7.2
K (meq/100 g)	1.3	0.6	0.4	1.7
Na (meq/100 g)	0.7	0.6	0.1	1.8
Si in saturation extracts (ug/ml)	10.3	3.6	5.9	15.6
P in saturation extracts (ug/ml)	0.034	0.046	0.006	0.127
P sorbed at 0.02 ppm (ug/g)	68.5	29.5	40	102
P sorbed at 0.2 ppm	266	118	168	460
P buffering capacity (ug/g)	57	29	32	113
Olsen P (ug/g)	14.5	6.7	7.5	24.9
Bray No.1 P (ug/g)	8.7	4.8	4.3	15.8
Al (meq/100 g)	0.022	0.031	0.0	0.079
Extrac. S (ug/g)	70	46	37	158
S sorbed at 5 ppm (ug/g)	-21	51	-105	29
Median annual rainfall n = 6	570	94	475	700

Table 19. Mean, standard deviation, minimum, and maximum of chemical properties of surface soils belonging to the order Ultisol.

Soil Chemical Property	Mean	Standard Deviation	Minimum	Maximum
pH	4.4	0.9	3.2	6.7
Ca (meq/100 g)	4.4	8.5	0.2	29.9
Mg (meq/100 g)	0.9	1.4	0.05	5
K (meq/100 g)	0.4	0.5	0.07	1.9
Na (meq/100 g)	0.2	0.1	0.05	0.4
Si in saturation extracts (ug/ml)	4.6	1.8	1.8	8.7
P in saturation extracts (ug/ml)	0.016	0.017	0.003	0.069
P sorbed at 0.02 ppm (ug/g)	223	122	45	385
P sorbed at 0.2 ppm (ug/g)	712	252	375	1240
P buffering capacity (ug/g)	141	46	87	235
Olsen P (ug/g)	11.8	18.7	0.6	59.9
Bray No.1 P (ug/g)	7	8.8	0.1	23.6
Al (meq/100 g)	1.46	1.14	0.02	3.32
Extrac. S (ug/g)	279	207	35	659
S sorbed at 5ppm (ug/g)	25	49	-61	99
Median annual rainfall n = 13	1696	403	1200	2500

Table 20. Means of chemical properties of surface soils of the different soil series belonging to the order Histosol

Soil Chemical Property	Soil Series Kaimu means
pH	5.8
Ca (meq/100 g)	37.1
Mg (meq/100 g)	7.9
K (meq/100 g)	1.7
Na (meq/100 g)	0.4
Si in saturation extracts (ug/ml)	13.06
P in saturation extracts (ug/ml)	0.045
P sorbed at 0.02 ppm (ug/g)	-187
P sorbed at 0.2 ppm (ug/g)	235
P buffering capacity (ug/g)	109
Olsen P (ug/g)	19.6
Bray No.1 P (ug/g)	19.1
Al (meq/100 g)	0.0
Extrac. S (ug/g)	131
S sorbed at 5 ppm	-76
n	3

Table 21. Means of chemical properties of surface soils of the different soil series belonging to the order Inceptisol.

Soil Chemical Property	Soil Series						
	Io	Kula	Pane	Laumaia	Kaipoioi	Uma	Haliimaile
	means						
pH	6.1	5.8	5.5	6.3	5.2	5.5	4.7
Ca (meq/100 g)	31.9	26.5	14.1	26.7	14.1	35.7	6.6
Mg (meq/100 g)	9.5	4.9	5.4	5.15	4.6	3.6	1.7
K (meq/100 g)	2.2	1.4	1.5	0.5	0.8	0.4	1.1
Na (meq/100 g)	0.5	0.4	0.2	0.3	0.3	0.6	0.2
Si in saturation extracts (ug/ml)	14	8.7	7.0	9.7	4.3	14.8	7.3
P in saturation extracts (ug/ml)	0.061	0.037	0.015	0.017	0.015	0.009	0.018
P sorbed at 0.02 ppm (ug/ml)	-46	71	170	127	240	-15	153
P sorbed at 0.2 ppm (ug/ml)	281	670	821	785	1765	780	480
P buffering capacity (ug/g)	90	182	204	240	585	168	97
Olsen P (ug/g)	33	16	14	11	1.4	12	24.8
Bray No.1 P	13.4	8.2	5.7	17.2	0.3	11.5	9.9
Al (meq/100 g)	0.0	0.003	0.032	0.0	0.27	0.12	0.33
S (ug/g)	52	84	87	73	49	71	130
S sorbed at 5 ppm (ug/g)	-32	19	58	20	80	17	30
n	6	13	4	2	1	1	9

Table 22. Means of chemical properties of surface soils of the different soil series belonging to the order Mollisol.

Soil Chemical Property	Soil Series				
	Pala	Ewa	Walakoa	Kamaole	Pulehu
			means		
pH	5.4	6.3	6.5	6.4	7.7
Ca (meq/100 g)	5.7	6.0	11.1	39	8.3
Mg (meq/100 g)	3.2	8.2	4.9	11.7	12.4
K (meq/100 g)	0.8	1.5	2.2	4.3	2.3
Na (meq/100 g)	0.4	3.6	0.3	0.3	3.8
Si in saturation extracts (ug/ml)	8.2	14.3	11.7	10.1	21.7
P in saturation extracts (ug/ml)	0.019	0.085	0.076	0.134	0.112
P sorbed at 0.02 ppm (ug/g)	135	-26	11	-300	-5
P sorbed at 0.2 ppm (ug/g)	382	111	166	90	99
P buffering capacity (ug/g)	67	42	44	116	30
Olsen P (ug/g)	11.6	25.6	22.4	82.5	9.6
Bray No.1 P (ug/g)	6.6	17.4	12	23.6	6.6
Al (meq/100 g)	0.049	0.0	0.0	0.0	0.0
Sulfur	71	73	43	92	57
S sorbed at 5 ppm (ug/g)	11	-25	-2.5	-40	-6.0
n	2	2	2	1	1

Table 23. Means of chemical properties of surface soils of the different soil series belonging to the order Oxisol.

Soil Chemical Property	Soil Series	
	Keahua	Molokai
	means	
pH	5.7	6.2
Ca (meq/100 g)	11.7	4.9
Mg (meq/100 g)	3.5	5.9
K (meq/100 g)	1.1	1.7
Na (meq/100 g)	0.3	1.3
Si in saturation extracts (ug/ml)	8.3	14.4
P in saturation tion extracts (ug/ml)	0.039	0.023
P sorbed at 0.02 ppm (ug/g)	82	41
P sorbed at 0.2 ppm (ug/g)	315	168
P buffering capacity (ug/g)	68	36
Olsen P (ug/g)	17.4	8.7
Bray No.1 P (ug/g)	9.7	6.6
Al (meq/100 g)	0.033	0.0
Extrac. S (ug/g)	75	61
S sorbed at 5 ppm (ug/g)	-13	-37
n	4	2

Table 24. Means of chemical properties of surface soils of the different soil series belonging to the order Ultisol.

Soil Chemical Property	Soil Series		
	Makawao	Haiku	Pauwela
		means	
pH	5.3	4.0	4.7
Ca (meq/100 g)	14.5	1.4	0.6
Mg (meq/100 g)	2.6	0.4	0.6
K (meq/100 g)	0.7	0.4	0.2
Na (meq/100 g)	0.2	0.2	0.2
Si in saturation extracts (ug/ml)	4.7	4.9	1.8
P in saturation extracts (ug/ml)	0.034	0.009	0.023
P sorbed at 0.02 ppm (ug/g)	185	222	350
P sorbed at 0.2 ppm (ug/g)	715	680	985
P buffering capacity (ug/g)	157	129	202
Olsen P (ug/g)	23.4	9.3	0.6
Bray No.1 P (ug/g)	17.1	4	3.7
Al (meq/100 g)	1.16	1.58	1.21
Extrac. S (ug/g)	184	327	133
S sorbed at 5 ppm (ug/g)	16	20	99
n	3	9	1

Table 25. Mean, standard deviation, minimum, and maximum of chemical properties of subsurface soils belonging to the order Inceptisol.

Soil Chemical Property	Mean	Standard Deviation	Minimum	Maximum
pH	5.8	0.8	3.9	7.1
Ca (meq/100 g)	19.9	12.3	0.7	38.5
Mg (meq/100 g)	4.5	5.5	0.5	32.3
K (meq/100 g)	0.8	0.8	0.09	3.7
Na (meq/100 g)	0.5	0.4	0.07	1.7
Si in saturarion extracts (ug/ml)	5.8	3.5	0.6	15.2
P in saturation extracts (ug/g)	0.021	0.032	0.001	0.163
P sorbed at 0.02 ppm (ug/g)	239	247	-175	1080
P sorbed at 0.2 ppm (ug/g)	944	731	170	3760
P buffering capacity (ug/g)	217	169	55	840
Olsen P (ug/g)	12.9	16.4	0.6	73.8
Bray No.1 P (ug/g)	3.3	5.6	0.09	24.9
Al (meq/100 g)	0.17	0.04	0.0	1.54
Extrac. S (ug/g)	98	67	0.0	349
S sorbed at 5 ppm (ug/g)	49	67	-40	265

n = 33

Table 26. Mean, standard deviation, minimum, and maximum of chemical properties of subsurface soils belonging to the order Mollisol.

Soil Chemical Property	Mean	Standard Deviation	Minimum	Maximum
pH	6.5	0.8	5.2	7.6
Ca (meq/100 g)	10.1	6.4	3.2	24.6
Mg (meq/100 g)	6.1	3.5	1.2	11.8
K (meq/100 g)	1.4	1.7	0.1	5.4
Na (meq/100 g)	1.2	1.3	0.2	3.9
Si in saturation extracts (ug/ml)	6.2	2.7	2.0	10.1
P in saturation extracts (ug/ml)	0.024	0.021	0.001	0.063
P sorbed at 0.02 ppm (ug/g)	98	101	-15	275
P sorbed at 0.2 ppm (ug/g)	373	228	25	710
P buffering capacity (ug/g)	81	43	40	180
Olsen P (ug/g)	11.7	8.3	3.6	28.6
Bray No.1 P (ug/g)	5.2	6.2	0.4	18.6
Al (meq/100 g)	0.004	0.013	0.00	0.039
Extrac. S (ug/g)	75	38	44	164
S sorbed at 5 ppm (ug/g)	-1.7	19	-25	30

n = 8

Table 27. Mean, standard deviation, minimum, and maximum of chemical properties of subsurface soils belonging to the order Oxisol.

Soil Chemical Property	Mean	Standard Deviation	Minimum	Maximum
pH	6.0	0.7	5.3	6.9
Ca (meq/100 g)	8.3	7.2	2.6	22.3
Mg (meq/100 g)	3.6	2.0	1.6	6.3
K (meq/100 g)	0.7	0.5	0.2	1.2
Na (meq/100 g)	0.7	0.4	0.2	1.3
Si in saturation extracts (ug/ml)	4.8	3.7	1.4	11.3
P in saturation extracts (ug/ml)	0.020	0.025	0.001	0.071
P sorbed at 0.02 ppm (ug/g)	125	45	87	205
P sorbed at 0.2 ppm (ug/g)	364	63	261	445
P buffering capacity (ug/g)	75	20	56	110
Olsen P (ug/g)	14.5	6.7	7.5	24.9
Bray No.1 P (ug/g)	10.6	10.3	2.1	26.0
Al (meq/100 g)	4.46	4.83	1.40	13.75
Extrac. S (ug/g)	66	36	33	132
S sorbed at 5 ppm (ug/g)	8.3	52	-59	72

n = 6

Table 28. Mean, standard deviation, minimum, and maximum of chemical properties of subsurface soils belonging to the order Ultisol.

Soil Chemical Property	Mean	Standard Deviation	Minimum	Maximum
pH	4.2	0.8	3.1	5.7
Ca (meq/100 g)	2.4	3.5	0.1	9.8
Mg (meq/100 g)	0.5	0.7	0.03	2.5
K (meq/100 g)	0.3	0.4	0.04	1.4
Na (meq/100 g)	0.2	0.1	0.05	0.4
Si in saturation extracts (ug/ml)	3.7	2.4	0.6	7.6
P in saturation extracts (ug/ml)	0.007	0.007	0.001	0.029
P sorbed at 0.02 ppm (ug/g)	277	183	-140	530
P sorbed at 0.2 ppm (ug/g)	807	331	388	155
P buffering capacity (ug/g)	160	101	68	470
Olsen P (ug/g)	10.1	13.9	0.5	51
Bray No.1 P (ug/g)	5.6	6.3	0.4	18.7
Al (meq/100 g)	1.5	1.1	0.0	3.94
Extrac. S (ug/g)	324	206	92	687
S sorbed at 5 ppm (ug/g)	38	81	-110	165

n = 13

Table 29. Means of chemical properties of subsurface soils of the different soil series belonging to the order Inceptisol.

Soil Chemical Property	Soil Series means						
	Io	Kula	Pane	Laumaia	Kaipoioi	Uma	Haliimaile
pH	6.5	6.3	5.7	6.1	4.9	5.7	4.9
Ca (meq/100 g)	30.9	27.2	12.6	31.8	3.6	28.3	6.1
Mg (meq/100 g)	11.4	3.9	3.9	4.1	1.7	4.0	1.6
K (meq/100 g)	1.1	0.7	1.3	0.3	0.2	0.4	0.8
Na (meq/100 g)	1.1	0.5	0.3	0.3	0.2	0.4	0.2
Si in saturation extracts (ug/ml)	9.4	4.9	2.7	5.1	1.3	12.6	5.8
P in saturation extracts (ug/ml)	0.049	0.008	0.013	0.013	0.011	0.027	0.022
P sorbed at 0.02 ppm (ug/g)	21	355	300	227	1080	79	154
P sorbed at 0.2 ppm (ug/g)	372	1244	1145	1432	3760	779	499
P buffering capacity	104	269	337	320	840	200	90
Olsen P (ug/g)	17.5	5.3	8.3	1.9	4.7	18.5	23.3
Bray No.1 P	3.6	0.7	0.8	0.3	0.2	7.2	7.5
Al (meq/100 g)	0.0	0.0	0.37	0.0	1.21	0.0	0.32
S (ug/g)	52	96	95	76	81	80	141
S sorbed at 5 ppm (ug/g)	-6	56	108	68	265	15	29
n	6	10	4	2	1	1	9

Table 30. Means of chemical properties of subsurface soils of the different soil series belonging to the order Mollisol.

Soil Chemical Property	Soil Series means				
	Paia	Ewa	Waiakoa	Kamaole	Pulehu
pH	5.4	6.5	6.7	7.0	7.6
Ca (meq/100 g)	6.5	6.5	9.8	24.6	10.6
Mg (meq/100 g)	1.9	6.8	5.3	9.5	11.8
K (meq/100 g)	0.3	0.8	1.3	5.4	0.9
Na (meq/100 g)	0.5	1.8	0.4	0.4	3.9
Si in saturation extracts (ug/ml)	3.1	9.4	5.4	5.9	8.2
P in saturation extracts (ug/ml)	0.015	0.027	0.023	0.001	0.063
P sorbed at 0.02 ppm (ug/g)	200	8.5	138	105	-12
P sorbed at 0.2 ppm (ug/g)	500	98	424	710	235
P buffering capacity (ug/g)	72	47	85	180	62
Olsen P (ug/g)	9.4	20.2	6.1	16.3	6.1
Bray No.1 P (ug/g)	4.3	13.5	1.1	1.7	2.6
Al (meq/100 g)	0.019	0.0	0.0	0.0	0.0
Extrac. S (ug/g)	104	58	62	88	62
S sorbed at 5 ppm (ug/g)	13	-25	12	-1	-12
n	2	2	2	1	1

Table 31. Means of chemical properties of subsurface soils of the different soil series belonging to the order Oxisol.

Soil Chemical Property	Soil Series: Keahua (means)	Soil Series: Molokai (means)
pH	5.8	6.5
Ca (meq/100 g)	10.8	3.5
Mg (meq/100 g)	3.1	4.5
K (meq/100 g)	0.8	0.5
Na (meq/100 g)	0.5	1.2
Si in saturation extracts (ug/ml)	5.0	4.5
P in saturation extracts (ug/ml)	0.026	0.011
P sorbed at 0.02 ppm (ug/g)	131	113
P sorbed at 0.2 ppm (ug/g)	397	299
P buffering capacity (ug/g)	83	59
Olsen P (ug/g)	14.7	2.4
Bray No.1 P (ug/g)	5.9	1.6
Al (meq/100 g)	0.017	0.0
Extrac. S (ug/g)	71	58
S sorbed at 5 ppm (ug/g)	20	-15
n	4	2

Table 32. Means of chemical properties of subsurface soils of the different soil series belonging to the order Ultisol.

Soil Chemical Property	Soil Series means		
	Makawao	Haiku	Pauwela
pH	4.8	4.0	4.5
Ca (meq/100 g)	4.9	1.8	0.5
Mg (meq/100 g)	1.1	0.4	0.6
K (meq/100 g)	0.6	0.3	0.1
Na (meq/100 g)	0.2	0.2	0.2
Si in saturation extracts (ug/ml)	3.2	4.2	0.6
P in saturation extracts (ug/g)	0.008	0.006	0.016
P sorbed at 0.02 ppm (ug/g)	304	252	430
P sorbed at 0.2 ppm (ug/g)	966	705	1260
P buffering capacity (ug/g)	256	121	220
Olsen P (ug/g)	10.9	8.9	18.4
Bray No.1 P (ug/g)	7.2	3.8	17.4
Al (meq/100 g)	1.35	1.59	1.15
Extrac. S (ug/g)	327	323	324
S sorbed at 5 ppm (ug/g)	18	30	165
n	3	9	1

APPENDIX OF FIGURES

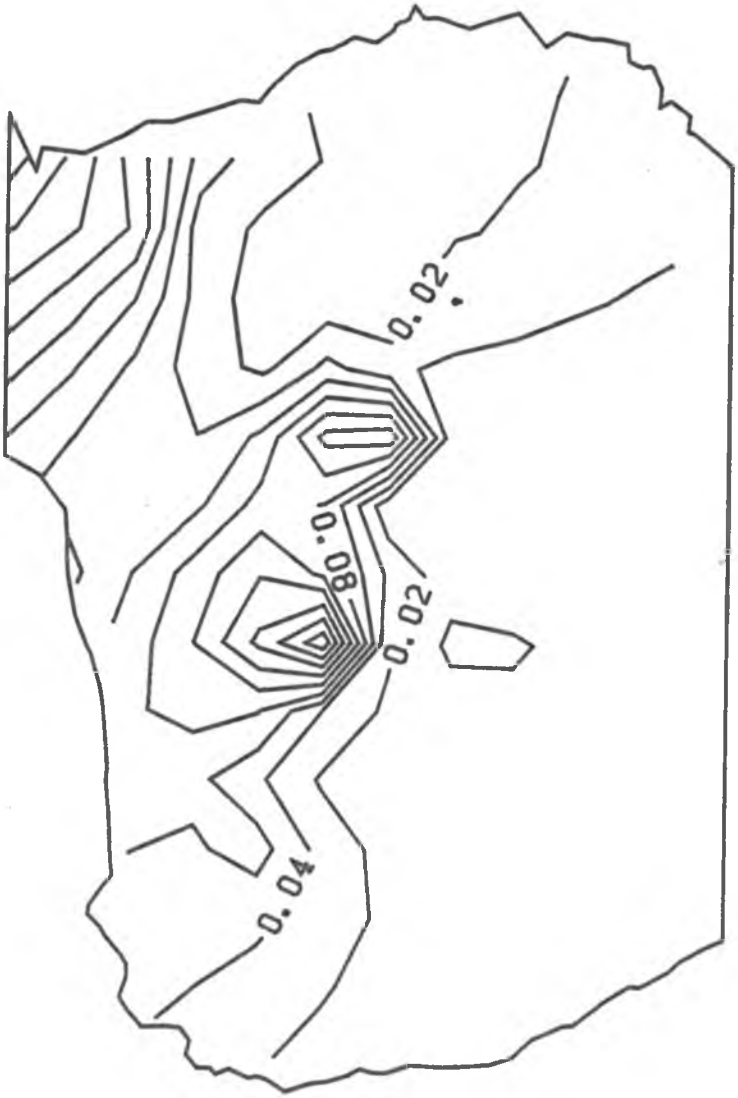

Figure 37. Isarithm map of P in saturation extracts of surface soils of the island of Maui.

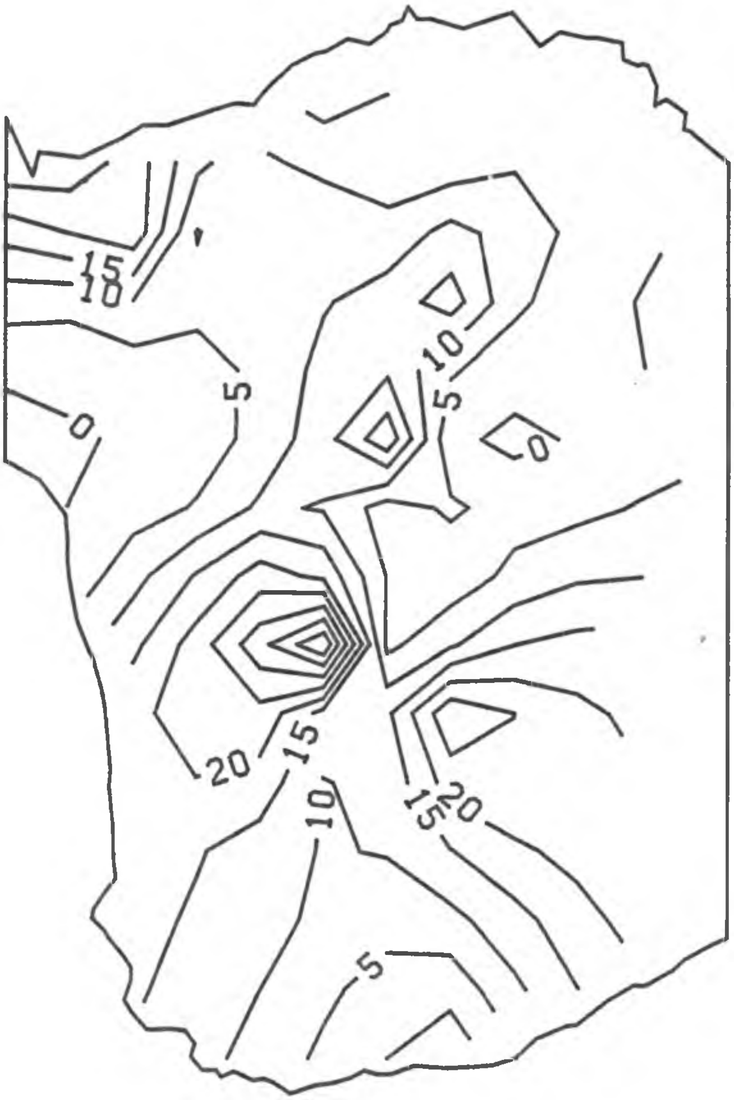

Figure 38. Isarithm map of acid fluoride extractable P of surface soils of the island of Maui.

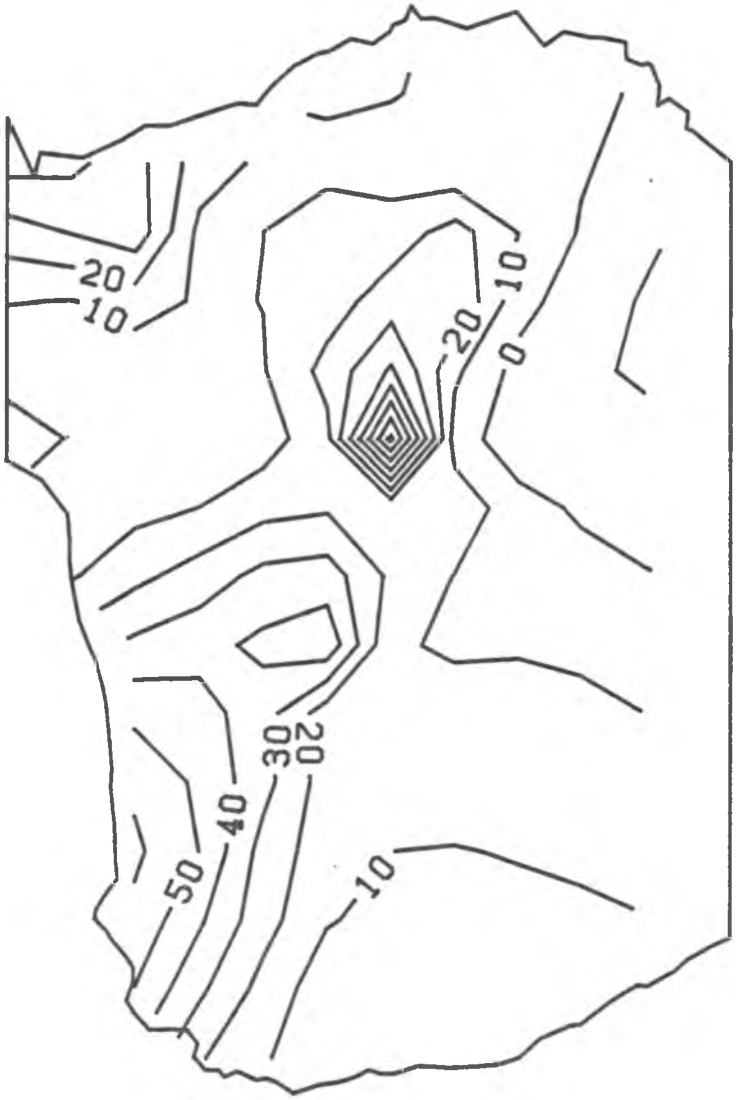

Figure 39. Isarithm map of $NaHCO_3$ extractable P of surface soils of the island of Maui.

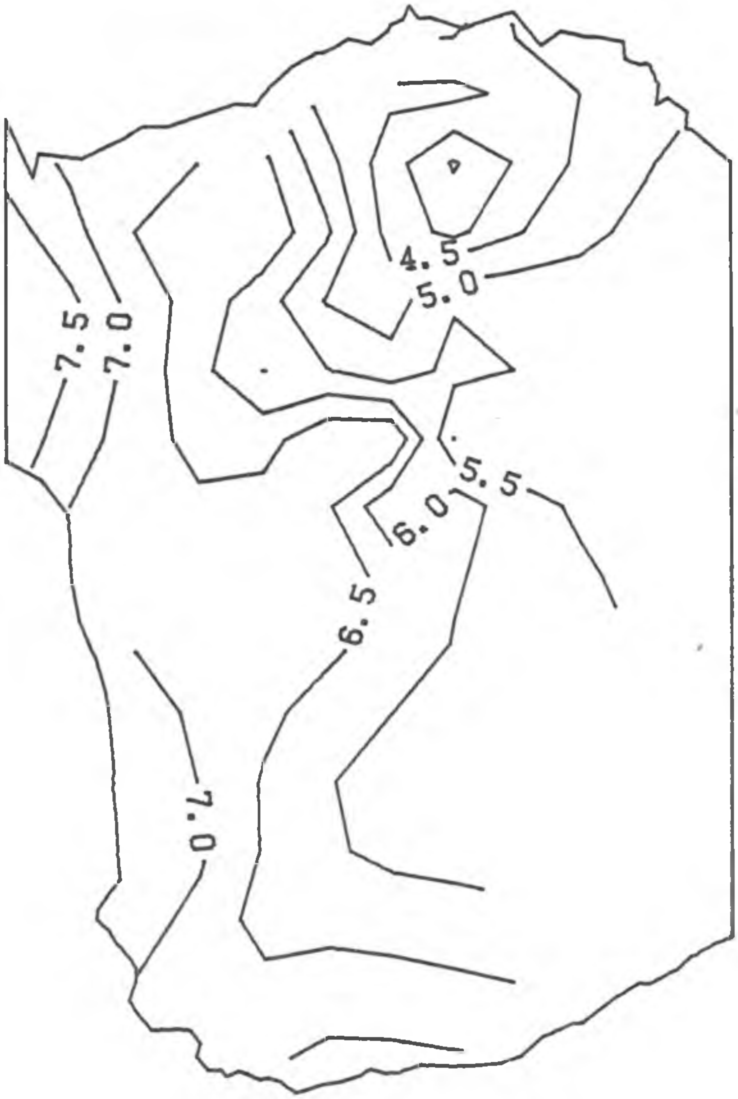

Figure 40. Isarithm map of pH of subsurface soils of the island of Maui.

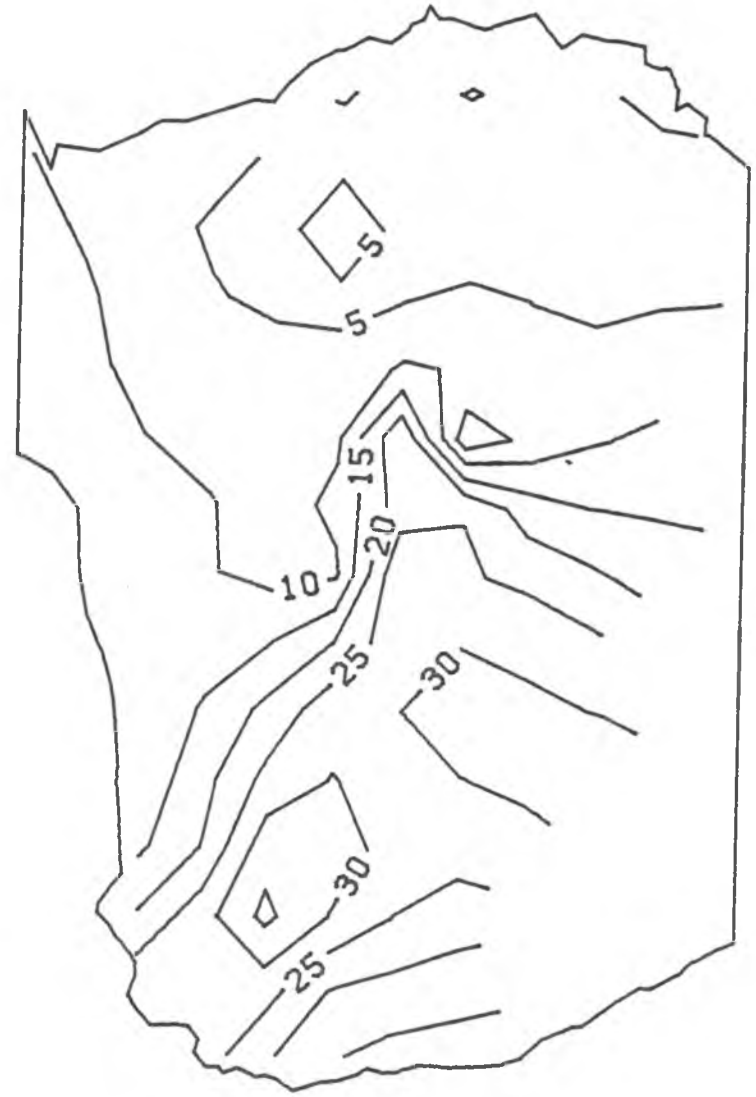

Figure 41. Isarithm map of exchangeable calcium of subsurface soils of the Island of Maui.

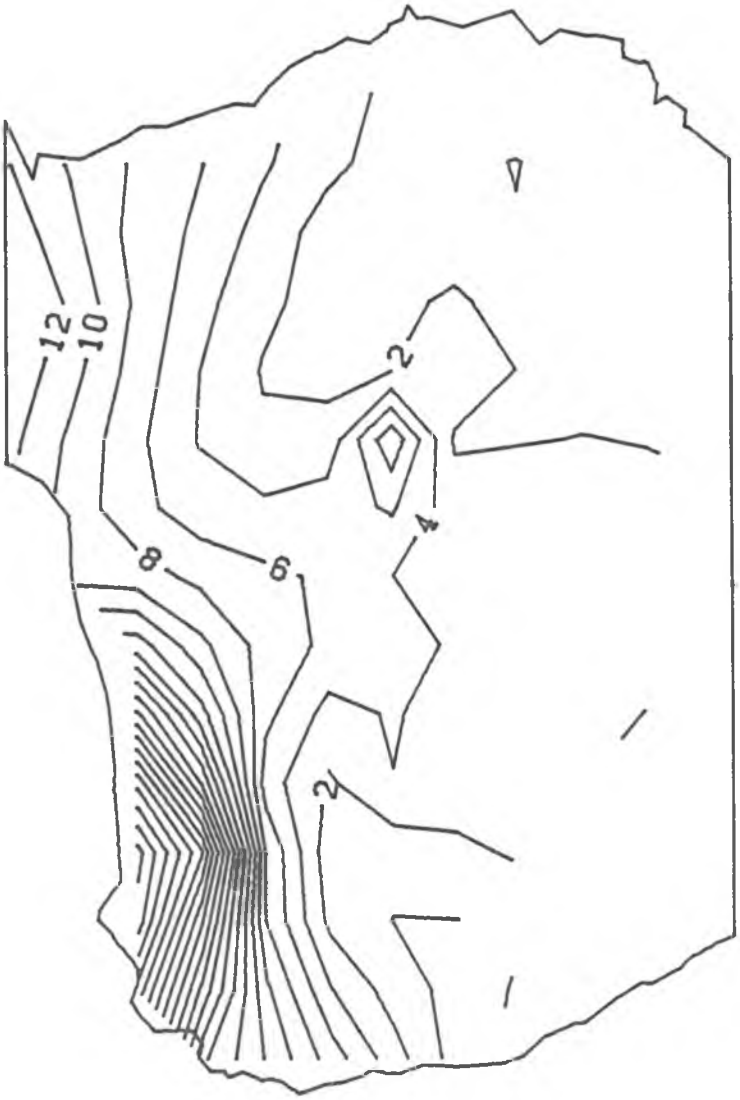

Figure 42. Isarithm map of exchangeable magnesium of subsurface soils of the island of Maui.

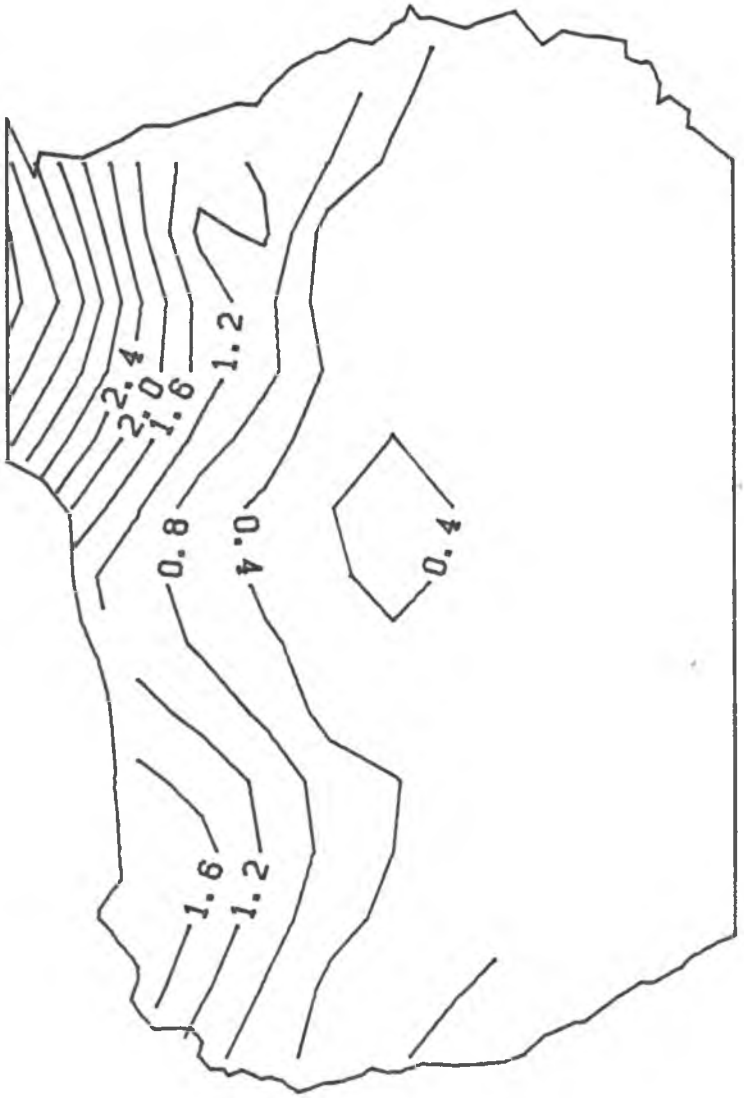

Figure 43. Isarithm map of exchangeable sodium of subsurface soils of the island of Maui.

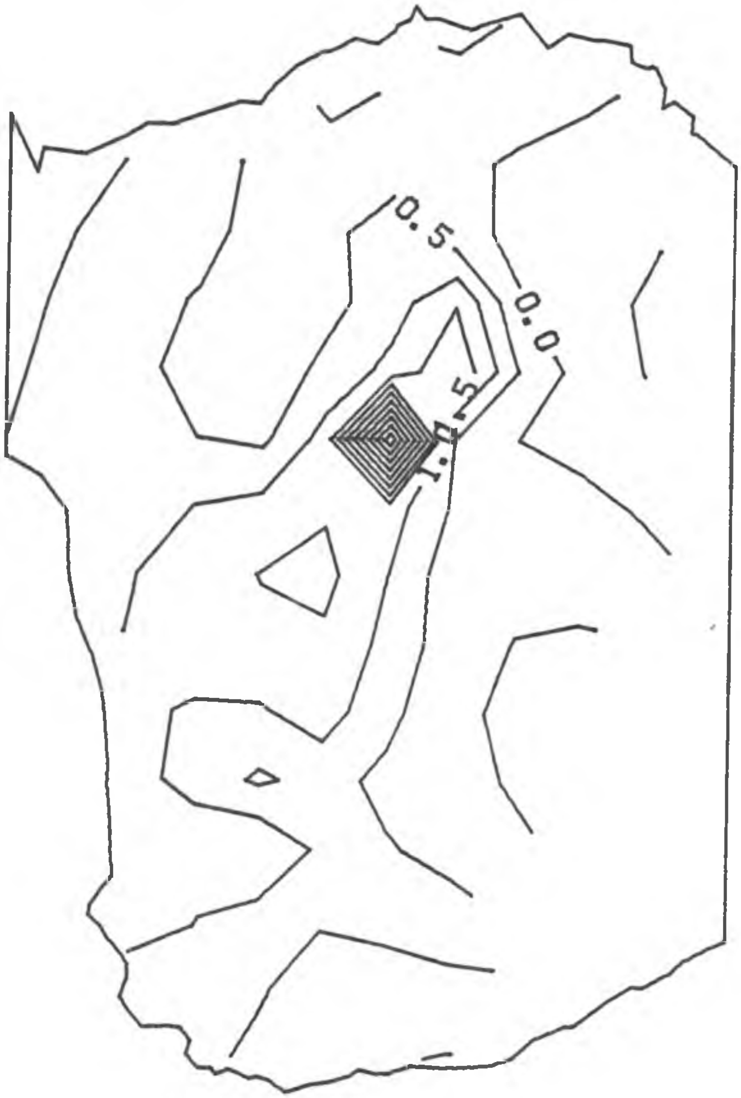

Figure 44. Isarithm map of exchangeable potassium of subsurface soils of the Island of Maui.

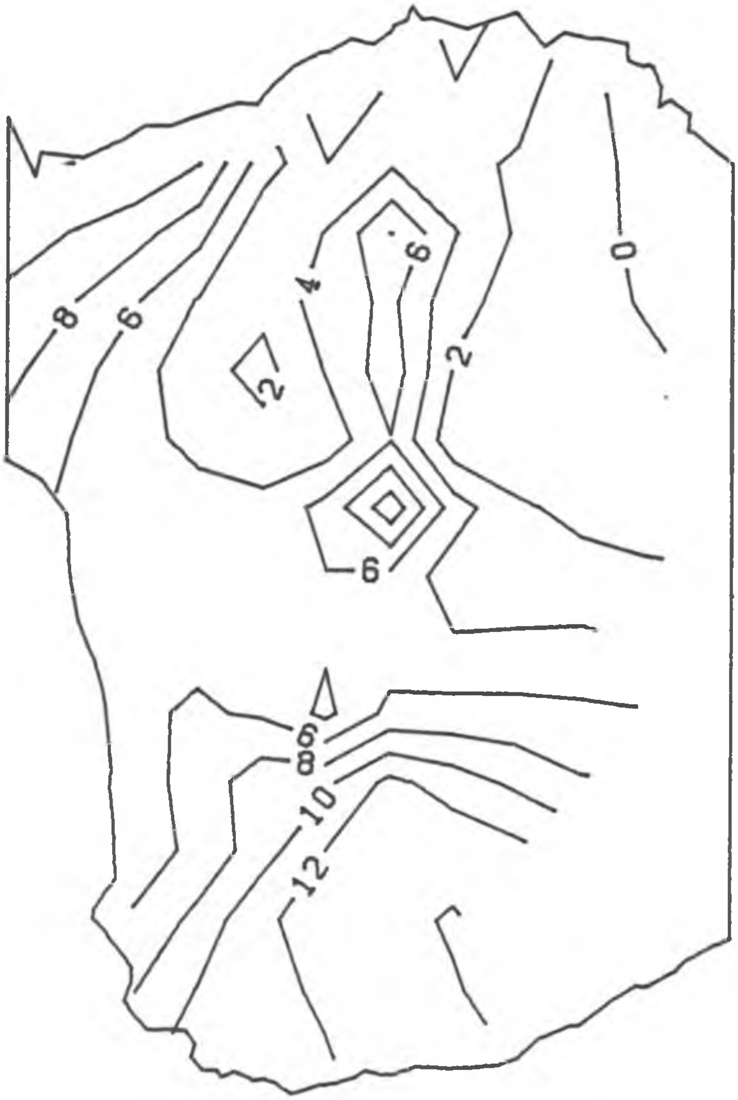

Figure 45. Isarithm map of silicon in saturation extracts of subsurface soils of the island of Maui.

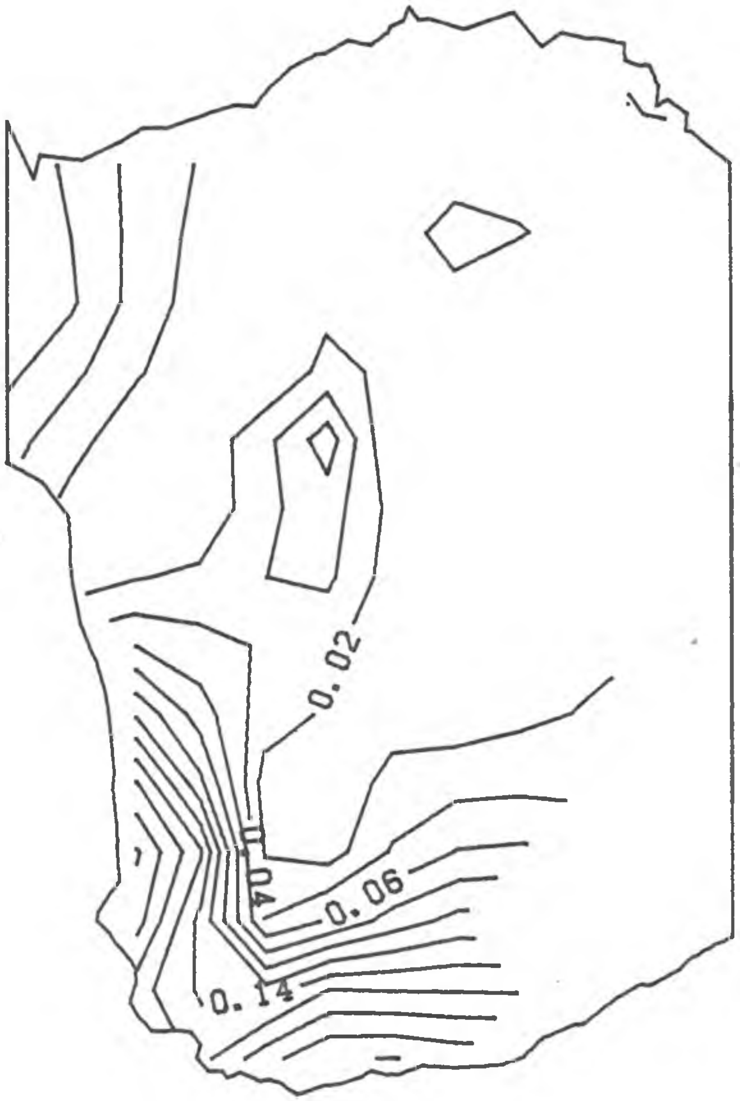

Figure 46. Isarithm map of P in saturation extracts of subsurface soils of the island of Maui.

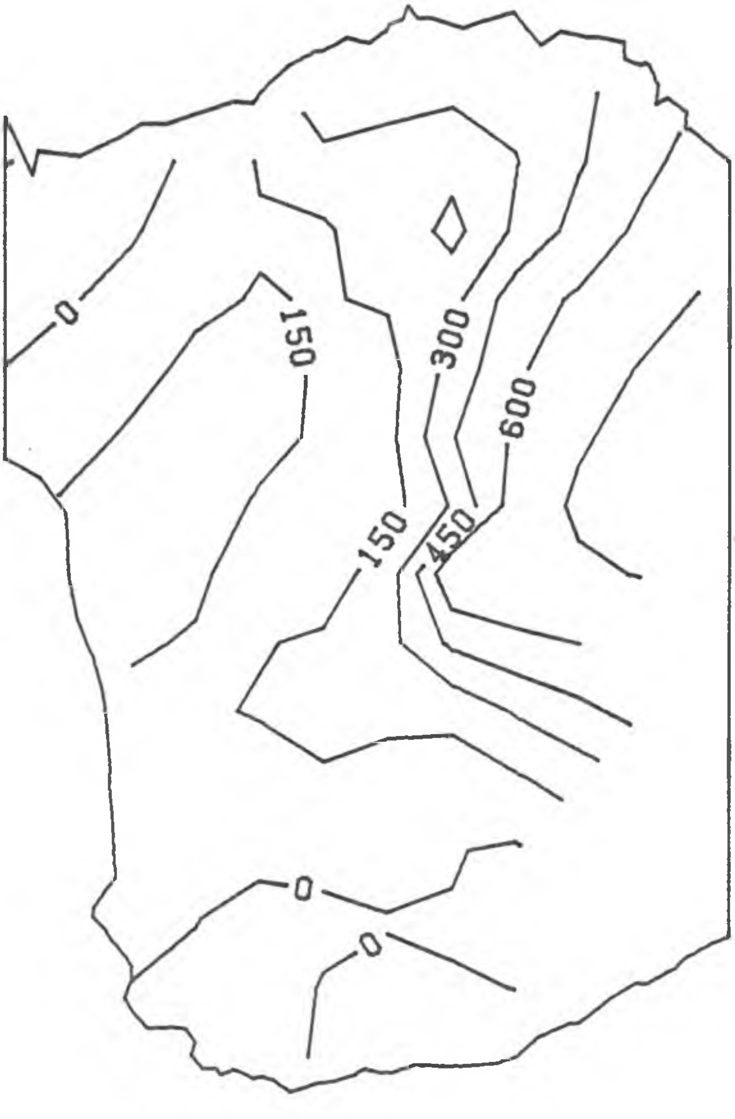

Figure 47. Isarithm map of P sorbed at 0.02 ppm by subsurface soils of the island of Maui.

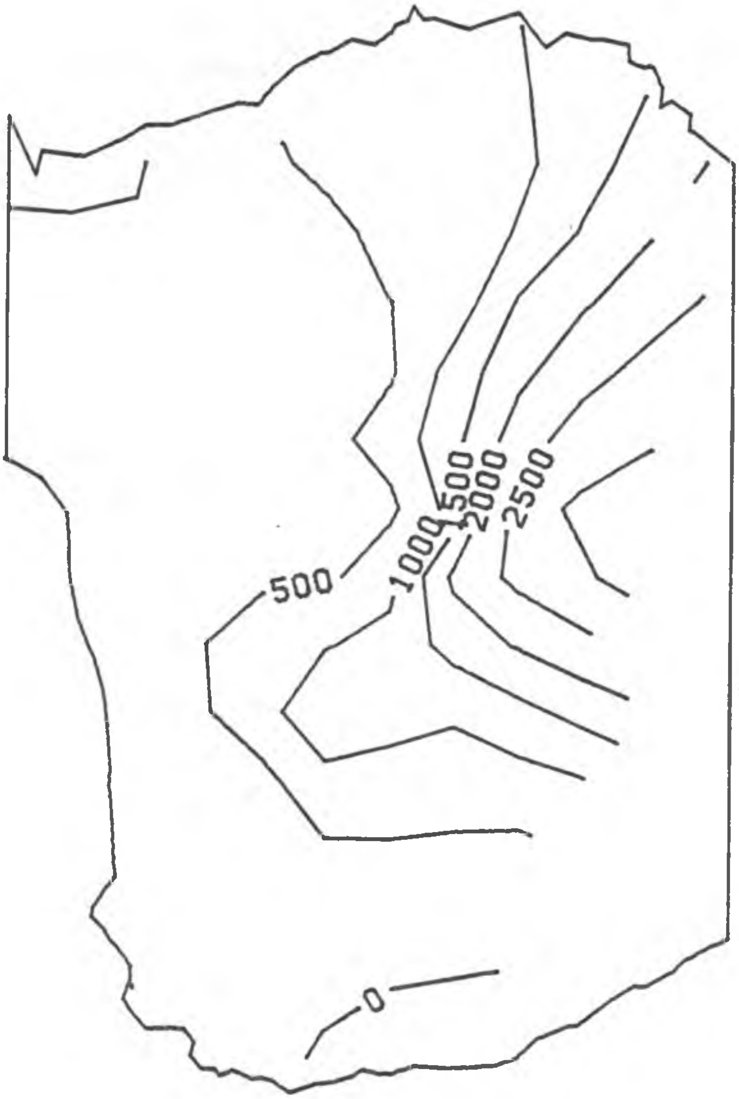

Figure 48. Isarithm map of P sorbed at 0.2 ppm by subsurface soils of the island of Maui.

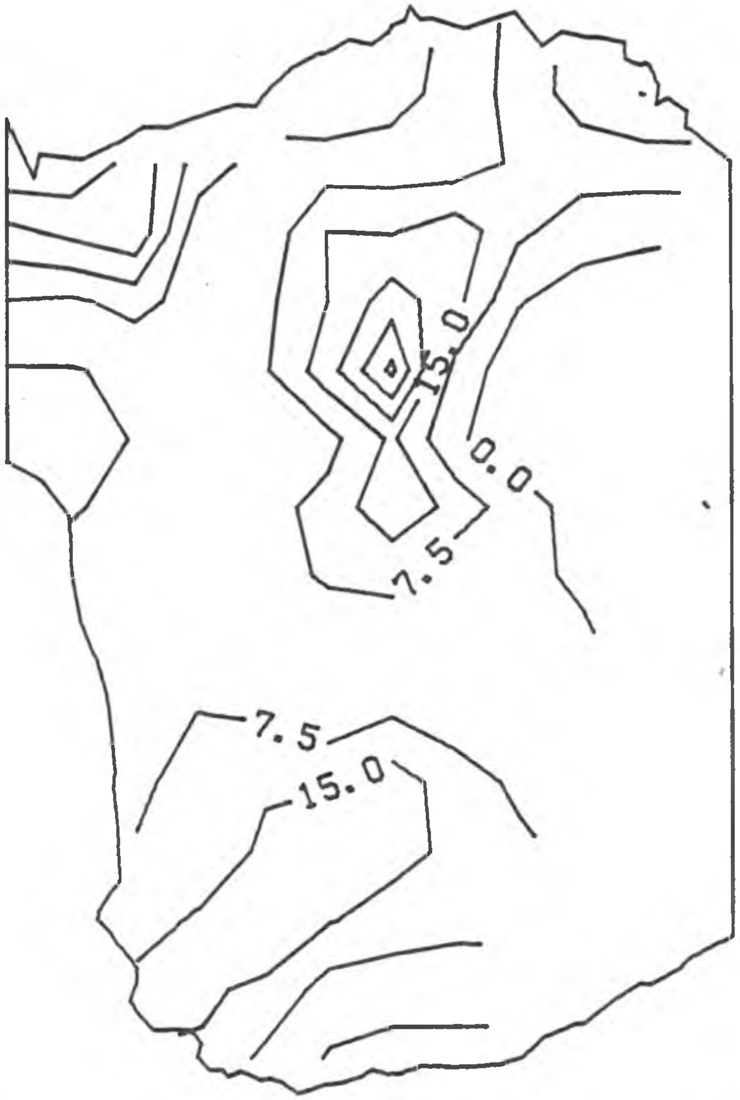

Figure 49. Isarithm map of NaHCO$_3$ extractable P of subsurface soils of the island of Maui.

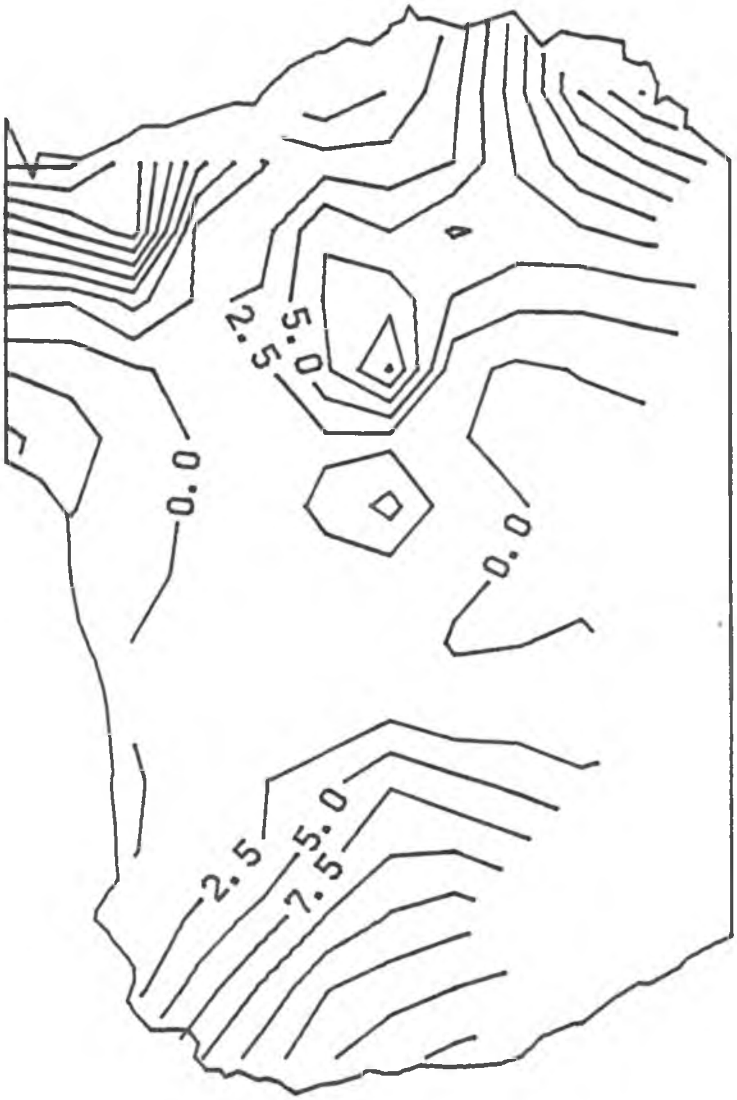

Figure 50. Isarithm map of acid fluoride extractable P of subsurface soils of the Island of Maui.

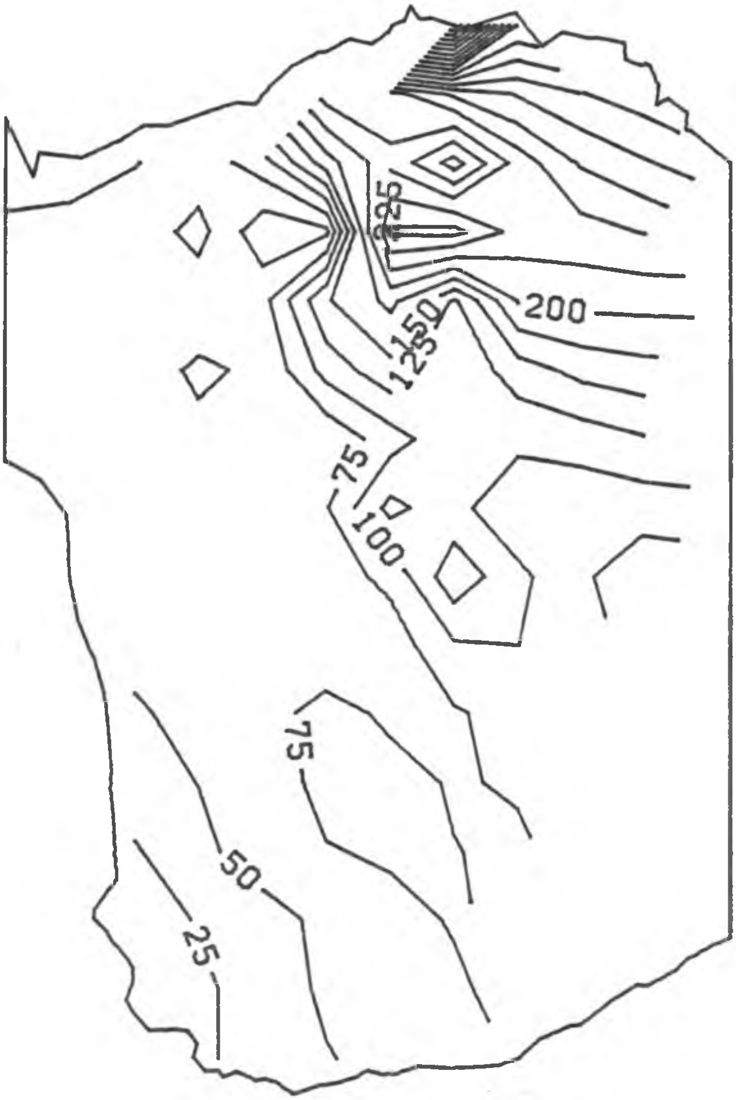

Figure 51. Isarithm map of extractable sulfur of subsurface soils of the Island of Maui.

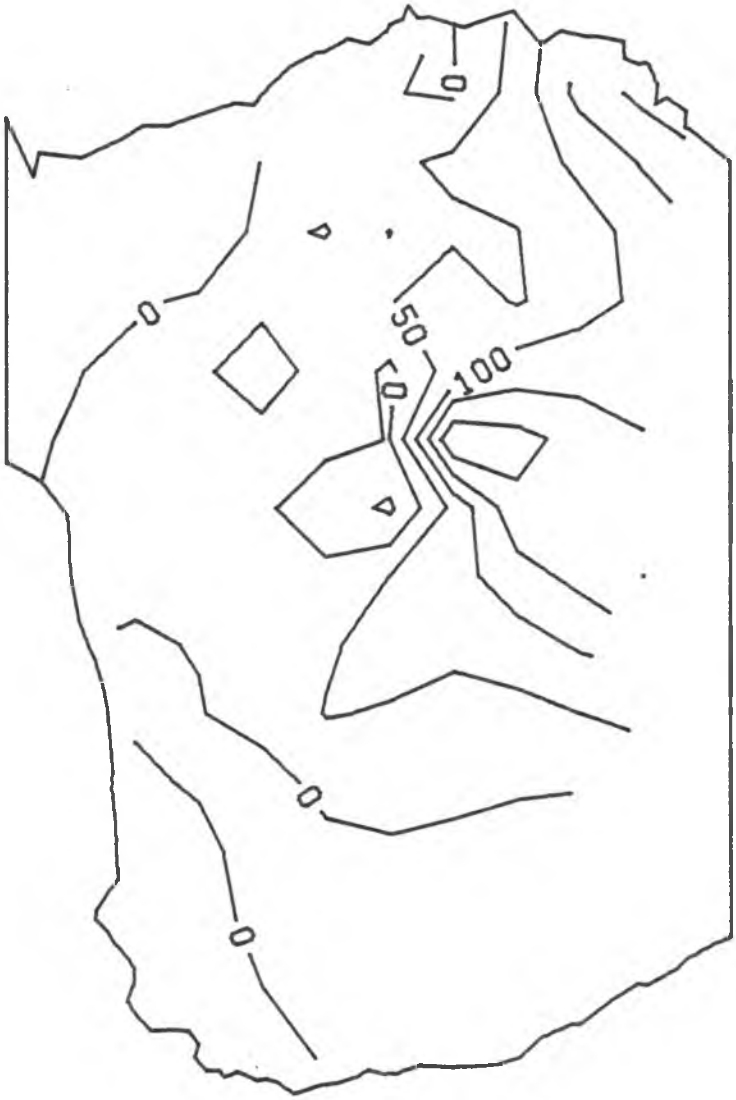

Figure 52. Isarithm map of SO_4-S sorbed at 5 ppm by subsurface soils of the island of Maui.

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