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ANALYSES

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MAPPING ZINC FERTILITY OF SOILS USING INDICATOR PLANTS
AND SOIL ANALYSES

A DISSERTATION SUBMITTED TO THE GRADUATE DIVISION OF THE
UNIVERSITY OF HAWAII IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

IN AGRONOMY AND SOIL SCIENCE

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by

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ABSTRACT

This investigation examined whether or not plant composition data, especially Zn contents of grains could be used to evaluate the Zn status of soils and crops and produce soil fertility maps. A possible role of Zn deficiency in Maui growth failure of sugarcane was also investigated. Maui growth failure has been an occasional disorder of sugarcane for over 50 years.

A series of greenhouse studies were conducted using two Zn deficient soils, Paaloa silty clay (clayey, oxidic, isothermic Humoxic Tropohumults) and Keahua silty clay loam (clayey, kaolinitic, isohyperthermic Torroxic Haplustolls). Paaloa soil was limed to pH 6.3. Its HCl-extractable Zn was 0.6 mg Zn/kg soil. Keahua soil pH was 6.6 and HCl-extractable Zn was 0.5 mg Zn/kg soil. Both soils were adequately supplied with nutrients, except Zn. Five levels of Zn, ranging from 0 to 27 mg Zn/kg, were applied as zinc sulfate. Eight indicator crops, corn (Zea mays L.), sorghum (Sorghum bicolor (L.) Moerch.), millet (Pennisetum americanum (L.) K. Schum.), rice (Oryza sativa L.), wheat (Triticum aestivum L.), sugarcane (Saccharum officinarum L.), soybean (Glycine max (L.) Merr.), and cowpea (Vigna unguiculata (L.) Walp.) were included in this study. All crops, except sugarcane, were grown to maturity to provide grains for Zn analysis. Sugarcane was harvested after 90-day growth. In addition

to studying the relative sensitivity of crop species to Zn deficiency, various plant parts, seedlings, foliar tissue, and grains, were evaluated for use as a diagnostic tissue.

Corn proved to be the most sensitive species to Zn deficiency. Without Zn fertilization, plants growing on both soils died after two weeks. In contrast, wheat, the most tolerant crop, produced about 90% of maximum grain without Zn fertilizer. The order of increasing responsiveness (in terms of grain yield for grain crops and dry matter yield for sugarcane) to Zn application was: wheat, sugarcane, sorghum, rice, millet, soybean, cowpea, and corn. The order of crop sensitivity to Zn deficiency was similar for both soils. The species included in this study fell into four groups with regard to their sensitivity to Zn deficiency. Corn was the most sensitive crop. Cowpea, soybean, and millet were highly sensitive and rice, sorghum, and sugarcane were moderately sensitive. Wheat was insenstive. Zinc deficient plants of sensitive crops developed severe deficiency symptoms that were not observed if Zn had been applied.

Zinc contents of all grains, especially wheat, were sensitive to the soil Zn status. Zinc contents in grain ranged from 6 mg Zn/kg (sorghum, no Zn added) to 71 mg Zn/kg (wheat, 27 mg Zn/kg soil). The ranges of Zn concentrations (mg Zn/kg) in grains of the various crops were: corn, 17 to 45; sorghum, 6 to 28; millet, 13 to 51; rice 12 to 44; wheat, 14 to 71; soybean, 23 to 68; and cowpea, 16 to 54. Zinc contents of sugarcane (90 day age) leaf blades ranged from 13 to 45 and leaf sheaths from 6 to 34 mg Zn/kg. Critical levels of Zn in different

plant parts, seedlings, foliar tissues, and grains were estimated. Fertilizer Zn requirement for near-maximum (95% of the maximum) grain yields was greatest for cowpea (7.5 mg Zn/kg soil) and least for wheat (0.5 mg Zn/kg soil). For grain crops, fertilizer Zn requirements for dry matter production was less than for grain production. Thus, Zn appears to be specifically involved in reproductive aspects of plant growth besides promoting vegetative growth.

In greenhouse studies, grains of cereals and legumes proved to be a good indicator tissue for evaluating the Zn status of soils and crops. This sensitivity was verified in a field study in Colorado. Wheat grains and associated soils were sampled from 41 locations. Seeds and soils were analyzed for Zn and other properties. A good correlation existed between grain Zn and soil Zn.

The Zn status of soils and wheat grain was mapped using geostatistical analysis procedures. Semi-variances were calculated and semi-variograms plotted. Appropriate semi-variogram models were fit to the semi-variances in order to estimate the vlaues of properties at unsampled locations. Interpolation of data was done by a block kriging procedure and isarithmic mapping was done using a Fortran program, SPLOT.

In greenhouse studies, sugarcane was moderately sensitive to Zn deficiency and Zn deficient plants developed symptoms similar to those of Maui growth failure. Application of K and Na salts depressed plant Zn and sugarcane growth and aggravated the symptoms. Sodium was more harmful than K. Applications of Zn increased foliar Zn, aleviated

symptoms and improved plant growth.

Maps were made of the Zn status of two sugarcane plantations on the island of Maui, Hawaii. One hundred plant tissue samples and associated soils were collected from Hawaiian Commercial & Sugar Company and Pioneer Mill Company. Soils, leaf blades, and leaf sheaths were analyzed for Zn and other parameters. Correlation analyses were used to examine variables related to soil and plant tissue Zn. Maps of soil and plant tissue Zn were constructed by geostatistical analysis procedures. Relationships between Zn status of plants and soils and other properties were observed by comparing their maps.

Zinc contents of leaf tissues coincided with soil Zn. Fields of sugarcane that were affected by maui growth failure in the past years were lower in soil and plant Zn than other fields.

A level of Zn that was adequate for every crop produced wheat grain that contained 43 mg Zn/kg and sugarcane leaf blades with 22 mg Zn/kg. Field grown sugarcane leaves contained 14 to 29 (median 19) mg Zn/kg; wheat grain (Colorado) contained 12 to 60 mg Zn/kg (median 24 mg/kg). The data suggest that grain and foliar analysis provide a valid basis for evaluating and mapping the Zn status of soils and crops.

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I. INTRODUCTION

Maximum crop production requires that all of the factors required for plant growth be at optimal values. To the extent that even one factor is below optimum, production will be depressed. The factors that are most amenable to control by man include those governing the ionic composition of the soil solution; its supply of plant nutrients, its acidity, and its salinity. Modification of soil properties by various means have, in many instances, given spectacular increases in crop yields and this has made fertilization and correction of unfavorable chemical and physical conditions familiar soil management practices.

Zinc deficiency in agricultural crops is one of the most common micronutrient disorders (Lindsay, 1972) and it is becoming increasingly significant in crop production as a result of use of high purity chemical fertilizers; abundent crop yields from the adoption of high-yielding crop varieties; use of large quantities of macronutrient fertilizers, particularly phosphates; expansion of cultivation to marginal lands; decreased use of animal manures, and consequent depletion of soil organic matter; erosion; and depletion of the soil supply of available nutrients. Areas of Zn deficiency are expected to increase with time.

Deficiency of Zn is most prevalent in alkaline and calcareous soils but it occurs as well in acid soils (Mortvedt et al., 1972)

including soils of the tropics (Sillanpaa, 1982; Kanehiro and
Sherman, 1967).

Various crops are not equally susceptible to Zn deficiency, some
are affected by Zn deficiency on soils where others are not (Chapman,
1966). Cereals such as oats, barley, wheat, and rye are rather
insensitive to Zn deficiency. Other crops such as potatoes and
tomatoes are only moderately sensitive whilst some crops including
corn, cotton, onion and field beans, are highly susceptible to Zn
deficiency (Viets et al., 1954). Species differ in their
susceptibility to micronutrient deficiency, either their requirement
differs or they have differing abilities to extract nutrients from
soils (Viets and Lindsay, 1973).

Total Zn contents in most soils greatly exceed crop requirement;
availability usually is the important limiting factor. However some
highly leached acid soils are very poor in Zn with total values of 10
to 30 mg/kg. In these soils, soil solution concentrations and labile
Zn level in particular are often low, and Zn deficiency may result from
the inherently low Zn content of the soil (Mengel and Kirkby, 1982).

A number of soil test procedures have been devised to determine
the availability of soil Zn for plant growth. In most of these
procedures, soil Zn has been correlated with Zn uptake by one or more
crops in a given area. No test is appropriate for all soil types. In
fact soil test procedures and critical levels may vary within a region
(Cox and Wear, 1977). Some soil test procedures that appear promising
in other respects may not be adaptable for routine use in soil testing

laboratories. Most methods of extraction increase the concentrations
of micronutrients in soil solution by creating artificial soil
environments with respect to pH, oxidation potential, exchange
characteristics, etc. Such methods have practical application but they
primarily were developed to overcome analytical problems associated
with detection of low concentrations of micronutrients normally present
in the soil solution.

Methods which measure the concentration of Zn in the soil solution
offer several advantages: (a) they have wide application; (b) results
can be compared with data from solution and sand culture experiments;
and (c) effects of different soil amendments and fertilizers practices
on solubility of Zn can be determined (Bradford et al., 1971). Soil
solution nutrient concentration is used as a criterion for assessing
the P supplying status of soils (Fox, 1981). A similar procedure for
Zn should be advantageous.

Interpretations of nutrient concentrations in plant tissue have
received much attention. Nutrient element contents of plants reflect
the soil's available nutrient status; conversely a plant's ability to
absorb micronutrients in an established environment is reflected by the
plant micronutrient concentration at any one time. A soil test does
not always provide a measure of soil-plant interactions. Therefore,
soil tests have limited usefulness, particularly for micronutrients
(Jones, 1972) because trying to duplicate by chemical means what a
plant will take up or "see" has been only partially successful. Plant
analysis remains the most important diagnostic tool although it is a

post-mortem (Yost, 1983). Although nutrient composition of foliar tissue at a particular growth stage, such as at silking for corn or early flowering for soybean, is widely used to estimate the nutrient status of crops, adding fertilizer to correct deficiencies is often ineffective at this stage of growth.

According to Jones (1972), seed usually is not a useful index tissue for estimating the nutrient status of plants. However, seed analyses have been used to determine the Mo (Reisenauer, 1956) and Zn (Shaw et al., 1954) supply for young plants and for evaluating Mo (Lavy and Barber, 1963) and N (Pierre et al., 1977ab; Goos et al., 1981) supply status of soils. Also data on Zn contents of seeds provide important information on animal and human nutrition (Scott, 1972).

Presumably Zn contents of seeds reflect differences among soils in the Zn supply and the ability of plants to accumulate Zn. Seed composition may be well related to Zn concentrations in other plant parts. Therefore, defining Zn "critical" levels in seeds should be practically and scientifically useful.

The use of seed as diagnostic tissue is expected to have the following advantages over samples of other plant parts.

1. Seed samples are easily secured, subdivided, and processed. The unprocessed seeds are usually easy to separate from foreign material and are easy to clean.

2. Analyzing mature seeds should minimize differences in Zn content due to differing stages of development. Unlike foliar samples, the time of sampling is not critical. Thus a large

number of samples can be secured over extensive areas during one cropping season.

3. The small amount of Zn in foliar parts, particularly in the case of severely Zn deficient plants, is difficult to measure. Using seeds rather than stems or leaves may be advantageous if, as in the case of Mo, seeds contain more Zn than vegetative parts.

A possible disadvantage is that whereas results of foliar analysis may be useful for current crop, seed analysis can only be used to diagnose past problems and plan for future action.

The use of soil analyses to construct maps of soil properties and to identify areas of particular interest or requiring separate management is important in soil science. Recent developments in geostatistics permit increased ability to summarize and interpret soil analyses (Yost et al., 1982b). Soil properties are spatially-dependent variables whose relative values differ according to their direction and distance of separation within the same region. Recent developments in statistical theory enable quantitative analysis of spatial dependence of soil characteristics and its use for optimal interpolation of soil properties at unsampled locations. Such analyses are achieved by application of geostatistics.

The widespread prevalence and severity of Zn deficiency has led to studies of Zn levels in soils and crops in many countries, mainly in the temperate zone. Although this nutritional disorder is recognized in the tropics, much remains to be learned about its extent and

severity in tropical areas.

This study was undertaken along lines that would make the results generally applicable by first determining critical levels of Zn in foliar tissues and seeds of crops common to both the temperate and tropical zones and then by using some of the results as criteria to map the Zn status of soils and crops in both zones. Five cereals, corn (Zea mays L.), sorghum (Sorghum bicolor (L.) Moerch.), millet (Pennisetum americanum (L.) K. Schum.), rice (Oryza sativa L.), and wheat (Triticum aestivum L.), one sugar crop, sugarcane (Saccharum officinarum L.), and two legumes, soybean (Glycine max (L.) Merr.) and cowpea (Vigna unguiculata (L.) Walp.) were the test crops. The objectives of the study were to:

1. Determine the sensitivity of seeds of grain crops to soil Zn status.

2. Determine the comparative Zn requirements of cereal, sugar, and legume crops.

The results of greenhouse investigations, regarding the use of seeds as diagnostic tissue, were verified in a field study in eastern Colorado wheat fields.

Isarithmic maps of wheat fields of Colorado and two sugarcane plantations on Maui Island, Hawaii were prepared based on soil, grain, and/or foliar Zn contents. The objectives of this study were to:

1. Determine the structure of spatial dependence of soil properties and plant tissue composition over relatively long distances.

2. Examine and interpret semi-variograms of soil properties and
   plant tissue composition.

3. Estimate and display isarithimic maps for Zn fertility of
   soils of Colorado and Maui.

Maui growth failure, an occasional disorder of sugarcane on Maui
has sometimes been attributed to Zn deficiency (Clements, 1980). A Zn
connection has never been proved even though Zn is low in many soils of
Hawaiian Commercial & Sugar (HC&S). Maui growth failure occurs only in
certain soil, cane variety combinations and even then it is usually
associated with dry weather and the use of saline basal ground waters
for irrigation. Besides determining the sensitivity of sugarcane to Zn
deficiency, the role of K and Na salts in Maui growth failure was also
evaluated. Maps of soil and foliar Zn status of two sugarcane
plantations on the island of Maui were prepared, using geostatistical
techniques, to investigate the possible role of Zn deficiency in Maui
growth failure.

The overall objectives of field studies were to:

1. Evaluate the feasibility of using seeds as a diagnostic tissue
   for studying Zn status of soils and crops.

2. Analyze spatial variabilty of soil and crop Zn and map levels
   of soil, foliar and grain Zn.

3. Investigate the role of Zn deficiency in Maui growth failure
   of sugarecane.

II. REVIEW OF LITERATURE

A. Zinc Deficiency - Its Extent and Severity

Zinc deficiency in crops has steadily increased in intensity and scope until it has become world wide. Deficiencies have increased for several reasons: interaction of fertilizers, especially phosphates, with Zn to decrease its availability to crops; increased crop yields; increased cultivation of marginal lands; and decreased use of animal manures. High levels of phosphate often induce Zn deficiency in corn, beans, and other importants crops. Superphosphates once sold in the Western States (USA) contained as much as 5000 mg/kg or 0.5 % Zn because they were manufactured from Zn-contaminated sulfuric acid. Today many fertilizer phosphates are produced in high purity and contain little or no Zn (Mortvedt et al., 1972. Lindsay, 1972; International Lead Zinc Research Organization (ILZRO), undated).

Deficiency of Zn in one or more crops has been recognized in more than 40 states in the United States. Zinc deficiency in corn has been reported from more than 30 states. Zinc treatment was used on citrus and vegetables in Florida as early as 1927. However, only in more recent years has the need for Zn supplementation been recognized in corn, beans, soybean, sugarbeet, cotton, peanuts and other major crops. Crops affected by Zn deficiency in Hawaii include corn, banana, coffee, citrus, cucumber, pineapple, pepper, legumes, potato and

macadamia nut (ILZRO, undated; Bauer, 1971; Warner and Fox, 1972).

Some comprehensive reviews dealing with the extent and severity of Zn deficiency in field crops are by Sillanpaa (1982), ILZRO (undated), Cox and Wear (1977), Lindsay (1972) and Mortvedt et al. (1972). No attempt has been made to review the subject beyond that provided by the above cited publicaions. The following paragraphs give an idea of Zn deficiency in crop species used as test crops in this study and a discussion of the magnitude of the problem in the tropics.

The intensity of Zn deficiency varies with soil conditions and with crops being grown. Availability of soil Zn to plants generally decreases as soil pH increases above neutral (Wear, 1956). Widespread deficiency occurs in calcareous soils of the corn growing states in the Mid-West; the calcareous, eroded, heavily irrigated and sandy soils of the Western states; poor sandy soils of Florida and the Coastal Plains (ILZRO, undated).

Zinc deficiency is probably the most widespread micronutrient disorder in tropical rice. It occurs in India, Pakistan, the Philippines, and Colombia under lowland conditions, where it is associated with calcareous soils and is accentuated by prolonged flooding. It also occurs in upland conditions of the Cerrado of Brazil (Sanchez, 1976). In acid Oxisols of Brazil, Zn deficiencies are widespread in upland rice. The solubility of Zn is high at low pH. Apparently these soils are so low in total Zn or so weathered that deficiencies occur in spite of high solubility.

Zinc deficiency in soybean most often occurs on calcareous land

that has been excavated for leveling, drainage, terracing or other purposes. Beans grown on sandy soils and soils of low organic content, low cation exchange capacity, or high P and lime contents can also be affected by insufficient Zn (ILZRO, undated).

Zinc quantity and distribution within soil profiles has been tabulated for several Hawaiian soils by Kanehiro and Sherman (1967). Total Zn varied between 64 and 288 mg/kg which is within the 10 to 300 mg/kg range reported by Lindsay (1972). Plots of both total and 0.1 N HCl-extractable Zn as a function of rainfall indicate decreasing contents of Zn with increasing rainfall with the notable exception of the Hydrandept great group. The Hydrandepts have higher levels of HCl-extractable Zn at a particular rainfall level than did the other soils they analyzed. This could have been expected from high organic matter contents and its ability to complex micronutrients. Such soils are also gel-like and such physical conditions may help in enhanced extractable Zn contents. With such comparisons it is important to remember that the bulk density of Hydrandepts can be less than 50 % that of Vertisols, which means a given volume of soil explored by the plant will have proportionately less nutrients than on soils of high bulk densities. The Vertisols had much less 0.1 N HCl-extractable Zn relative to total Zn, probably because of lower Zn solubility at high soil pH, possible neutralization of acid extractant with free $CaCO_3$ and sorption of Zn on $CaCO_3$. Regressions of total and 0.1 N HCl-extractable Zn on rainfall were significant when the Hydrandepts and Vertisols were excluded from the sample (Yost, 1983).

B. Sensitivity of Crops Species to Zinc Deficiency

Crops are not equally susceptible to Zn deficiency; some are Zn deficient whereas others on the same soil are not. Neither are they equally responsive to available Zn. They also differ markedly in the frequency with which they exhibit Zn deficiency symptoms. They differ characteristically in their extracting power - namely, in their ability to extract Zn from soils and absorb and translocate it from roots to tops (Brown and Tiffin, 1962; Gladestone and Loneragan, 1967).

The capacity of crops for selective absorption of essential nutrients may be utilized to develop suitable crop combinations and sequences to help maintain balance among nutrients in soil and thereby enhance soil productivity. This capacity can also be exploited to develop new varieties that require less Zn and therefore can be successfully grown in soils where Zn deficiency cannot be corrected for one reason or another.

Fruit trees, particularly citrus and peaches, are good indicator crops, and are frequently affected by Zn deficiency in soils where field and garden crops grow normally (Chapman, 1966). Alfalfa and wheat obtain adequate Zn from soils that produce deficiency symptoms in corn and rice (Brown et al., 1964; Kausar et al., 1976). Corn and soybean are particularly sensitive to insufficient Zn. Other sensitive crops are field bean, cotton, onion, sorghum, and tomato plants. Barley, oats, rye, and wheat are relatively insensitive to Zn supply (Viets et al., 1954; ILZRO, undated). Several reasons have been

proposed for this. Genetic variability of species and cultivars may be a controlling factor (Halim et al., 1968) or plant capacities for higher Fe and P absorption may be responsible (Chaudhry et al., 1977b; Boawn and Leggett, 1963). Lucas and Knezek (1972) and several other workers (Viets, 1966; Chapman, 1966; Gladestones and Loneragan, 1967) have listed various plant species according to their susceptability to Zn deficiency. These ratings may differ for different conditions. However, the similarity of rankings from several regions indicates that some guidance can be obtained from these ratings for identifying deficient areas. If incipient Zn deficiency in an area is suspected, sensitive crops may first be checked to see if the suspicion can be confirmed.

Chapman (1966) and International Lead Zinc Research Organization (ILZRO) (undated) grouped many crops according to their sensitivity to Zn deficiency. Corn and soybean are listed as very sensitive. Sorghum was categorized as sensitive to mildly sensitive and small grains, including wheat, as insensitive to Zn supply. Morgan (1984) compared five crop species for their sensitivity to Zn deficiency on a Zn deficient alkaline soil. According to his study, soybean was more sensitive than corn. Wheat was, however, the least susceptible of the crop species tested.

In a recent investigation, Moraghan (1984) grew five crop species, corn, flax, navy beans, soybean, and wheat, on an alkaline soil with 0.4 mg/kg DTPA-extractable Zn. All crops except wheat responded to Zn application. The order of their sensitivity to Zn

deficiency was: navy beans> flax > soybean > corn > wheat. Safaya and Malakondaiah (1981) also reported that wheat did not respond to Zn fertilization even on a soil in which DTPA-extractable Zn was exceedingly low, 0.28 mg/kg.

Millet is perhaps one of the most rarely studied crops for its sensitivity to Zn deficiency. Brown and Tiffin (1962) reported that millet was not Zn deficient on a Tulare soil which was Zn deficient for beans and corn. In a recent investigation of the comparative response of wheat and pearl millet to Zn fertilizers on two Indian soils, both of these crops produced higher grain yields with Zn fertilization (Singh and Singh, 1982). Zinc concentration in wheat grain on one soil was increased with Zn fertilization. In pearl millet various Zn sources did not affect Zn concentration but significantly modified Zn uptake. No information is given on the Zn status of the soils or plants in this report.

There are not many reports of Zn deficient sugarcane. In areas where coffee, citrus, gardenia, and some other plants were seriously affected if Zn was not added, sugarcane was not noticeably deficient (Clements, 1980).

Studies of Zn nutrition of cowpea are also rare in the literature. Safaya and Malakondaiah (1981) have recently reported that cowpea is even more sensitive to Zn deficiency than corn and sorghum. Andrew et al. (1981) in a study on 10 tropical and sub-tropical pasture and forage legumes, ranked legume species in the order of their susceptibility to Zn deficiency problem. Whereas species such as

Desmomium and Centrosema were highly sensitive, cowpea came in 6th

position and Medicago was least sensitive to low Zn.

Varieties of crops also vary widely in their sensitivity to low

levels of Zn (Brown et al., 1972). For example, the IR-6 variety of

rice is highly susceptible to Zn deficiency whereas the Basmati-370

variety is quite tolerant (Chaudhry et al., 1977b). Similarly, Russet

Burbank potatoes developed Zn deficiency under field conditions where

variety White Rose showed no symptoms (Boawn and Brown, 1968).

Crops also vary in their sensitivity to excess Zn. Such

excesses occur naturally in some areas or can be produced artificially

by overfertilization. Field crops that are sensitive to excess Zn

include carrot, corn, cowpea, oats, spinach and sugarbeet (Chapman,

1966). Although Chapman has included corn in the list, experience

indicates that this crop is not particularly sensitive to excessive

levels of Zn.

C. Zinc Requirements of Specific Crops

The nutrient requirements of crops can be expressed as internal

requirements and as external requirements. Pertinent information is

reviewed regarding Zn requirements of the test crops used in this

study.

1. Internal Zinc Requirements

The term "internal nutrient requirement" according to Fox

(1981), may mean the minimum uptake of nutrient (a quantity factor in

plant nutrition) that is associated with a specified yield, usually 95%

of maximum. The internal requirement can also be defined as the

concentration of a nutrient in the plant (an intensity factor in plant

nutrition) that is associated with near-maximum yield, usually named

the "critical concentration". The nutrient element content of the

plant is a reflection of the soil's available nutrient status. The

plant's ability to absorb a nutrient in the established environment is

reflected by the plant nutrient concentration at any one time (Jones,

1972).

A normal Zn concentration range in plants is 25 to 150 mg Zn/kg

dry matter with toxicities occurring when the Zn leaf levels exceed 400

mg/kg (Jones, 1972). Zinc content is generally highest in very young

seedlings and decreases with age (Carroll and Loneragan, 1968).

Reported decreases in Zn content with age often reflect depletion of

available Zn in the soil or nutrient solution (Lindsay, 1972).

Levels of Zn in plant material generally do not exceed 100

mg/kg dry matter and the internal Zn requirement of plants is even

less. Boehle and Lindsay (1969) have proposed 20 mg Zn/kg as the

critical deficiency level in corn leaves, soybean tops, tomato leaves,

and lucerne tops. In many plants Zn deficiency occurs if leaf

concentration is appreciably less than 20 mg/kg dry matter (Jones,

1972). For a great number of crops, a Zn level of 15 mg/kg or less in

dry leaves appears to be associated with deficiency symptoms (Thorne,

1957; Chapman, 1966). In the Indian Punjab, the critical limits of Zn

in the leaf tissue of rice, wheat and maize as determined by (Randhawa

and Takkar, 1975) were 16, 15-20, and 17mg/kg, respectively.

Internal Zn requirements may differ drastically among crops. Lo and Reisenauer (1968) for example, reported that maximum alfalfa production was obtained with leaf Zn levels approximately one-third to one-half that required for most other crops. Zinc requirements are also known to differ for different varieties of the same crop (Brown et al., 1972).

From a study of 25 annual crop and pasture varieties, representing 21 species, Gladstones and Loneragan (1967) concluded that species differ characteristically in their feeding power for Zn. Brown and Tiffin (1962) grew 14 plant species or varieties on a calcareous, Zn-deficient soil; seven developed Zn deficiency, two developed Fe deficiency, and five did not develop micronutrient deficiency.

Jones (1972) reported a sufficiency range of Zn for corn as 20 to 50 mg/kg dry matter. In an earlier paper (Jones, 1966) he listed 20 to 70 mg/kg as the sufficiency level of Zn in corn leaves. Zinc apparently concentrates in the nodes and ears of corn plants; Zn concentrations are generally highest in leaves from the top portion of corn plants and in leaves during early stages of growth (Gorsline et al., 1965).

Melsted et al. (1969) determined the critical concentrations of Zn to be 15 mg/kg for corn leaf at, or opposite and below, ear level at tassel stage, the youngest mature leaves and petioles of soybean after first pod formation, whole wheat plants at the boot stage, and upper stem cuttings of alfalfa in early flower stage. These levels are

based on field experiments at a number of locations for several years.

a. Corn

The internal Zn requirement is higher for corn than for other grain crops. In other words, corn is more sensitive to the lack of Zn and needs higher levels of Zn for healthy growth and good yield (ILZRO, undated). In several areas in the United States, corn produces deficiency symptoms when leaves contain less than 15 to 20 mg Zn/kg. In Michigan, the critical range is set somewhat higher, 16-25 mg/kg. The critical value depends on the source and age of the tissue being tested. For example, corn was deficient in Zn when the lower leaves contained 9 mg Zn/kg at tasseling or when the sixth leaf from the base contained 14 to 15 mg/kg Zn at silking time (Chapman, 1966). The plant Zn critical level in the ear leaf at early silking stage was 15 mg/kg. The Zn critical level in young corn plants, five to six leaf stage, was slightly higher, approximately 20 mg/kg (Cox and Wear, 1977).

b. Sorghum

Reported critical levels of Zn in sorghum tissues are in a similar range with other grain crops, 15 to 20 mg Zn/kg (ILZRO, undated). However, Chapman (1966) listed a value of 10 mg Zn/kg in the 2nd leaf from the top of sorghum at heading.

In field experiments over three years, Zn levels in grain sorghum plant samples exhibited a curvilinear relationship with grain yield (Lockman, 1972). At low yield levels correlations were positive, but as yields increased beyond 100 to 120 bushel, correlations became negative. Field data indicated the critical Zn level values were

approximately 30 mg/kg for seedlings, and 15 mg/kg for third-leaf at bloom growth.

Critical Zn deficiency and toxicity levels were estimated for grain sorghum by Ohki (1984) using a solution culture technique. The Zn deficiency value in blades was 10 mg/kg for blade no. 1 (top) and no. 2. Toxicity values in blades no. 1 and 2 were 64 and 68 mg/kg. The recommended sampling tissue was blade no. 1 at 49 days age.

c. Rice

Critical Zn concentration in Basmati-370 rice plants at preflowering stage was 17.4 mg/kg (Kausar et al., 1976). The estimated critical level of Zn in rice leaves when panicles were 2 mm in length, 15 mg/kg (Cox and Wear, 1977). Critical levels, however, differ considerably for different cultivars of rice. For example, Chaudhry et al., (1977b) reported critical Zn concentrations in ear leaves of rice as follows; Basmati-370, 16.9 and IR-6, 25.0 mg/kg. An earlier report (IRRI, 1969) listed 10 mg Zn/kg in leaf blades of rice as the critical Zn concentration.

d. Wheat

On the basis of a large number of field experiments on wheat in India, Randhawa et al. (undated) concluded that wheat exhibited acute deficiency at <8, moderate deficiency at 8 to 12, hidden hunger at 12 to 20 and lack of response at >20 mg Zn/kg. Shukla and Raj (1974) studied the relative susceptibility of 21 wheat varieties to Zn deficiency and estimated a Zn concentration of 19 mg/kg as a tentative critical level in eight week-old wheat shoots. Radjagukguk et al.

(1980) reported that in a greenhouse experiment only 1.2 to 3.7 kg

Zn/ha, as zinc sulfate, was sufficient to achieve maximum or

near-maximum yields of wheat tops grown on 12 Zn-deficient Darling

Downs black earth soils of Australia. The estimated critical Zn

concentration in the 42 day old wheat tops associated with 90% of

maximum dry matter yield was 20 mg/kg. Kausar et al. (1976), however,

reported a much lower value (14.5 mg/kg) as the critical Zn

concentration in wheat plants before flowering. Zinc determinations

were based on nitric-perchloric acid digests in both cases.

e. Sugarcane

Only a few reports list critical levels of Zn in sugarcane.

Bowen (1983) statistically analyzed leaf Zn data collected over a

period of 8 years pertaining to more than 2,000 commercial sugarcane

fields on the Island of Hawaii. Maximum yields of millable cane and

sugar were obtained when the tissue Zn concentration was 10 mg/kg dry

weight of leaf sheath nos. 3, 4, 5, and 6, sugar-free basis. Clements

(1980) also suggested previously that the critical level of Zn in leaf

sheaths should be 10 mg/kg. In both of these reports, Zn analyses were

based on a dry ashing procedure.

Because most sugarcane researchers have advocated the use of

leaf sheaths for diagnostic purposes, reports on Zn contents of leaf

bledes are rare. Elaward et al. (1982) in a silicon study estimated

that Zn concentrations of top-visible-dewlap leaf blades of plant-crop

and ratoon-crop cane ranged from 23 to 34 and 13 to 17 mg/kg,

respectively. These Zn values pertained to whole leaf blades,

excluding midribs, analysed by nitric-perchloric acid digestion. In a
subsequent study, which compared soil testing, foliar analysis, and
Diagnosis and Recommendation Integrated System (DRIS) as guides for
sugarcane fertilization, Elwali and Goscho (1984) used the top-visible
dewlap leaf laminae as index tissue. Zinc concentration, analysed by
nitric-perchloric acid digestion, in 1600 leaf samples ranged from 13
to 20 mg/kg.

f. Soybean

Zinc deficient soybean contained about 16 mg Zn/kg in young
mature leaves; similar leaves with no deficiency symptoms contained 19
to 24 mg/kg Zn (Viets et al., 1954). Jones (1966) suggested 21 to 50
mg/kg as the sufficiency level of Zn in top mature leaves of soybean at
initial bloom growth stage. The critical Zn level of soybean was also
estimated by Ohki (1977, 1978) by growing plants in nutrient solution.
The critical Zn level at 90 percent of maximum yield in blade 3 from
the top at 41 day age was 15 mg/kg and at 36 day was 12 mg/kg. Earlier
Melsted et al. (1969) reported 15 mg/kg as the critical Zn level for
the youngest mature leaves and petioles after first pod formation in
soybean. However, Small and Ohlrogge (1973) reported 21 to 50 mg/kg Zn
as the sufficiency range for soybean leaves, a value developed on the
basis of their work.

g. Cowpea

Safaya and Malakondaiah (1981) determined the critical Zn
concentration in 67-day old cowpea shoots as 40 mg/kg. They used
nitric-perchloric acid method for plant digestion. Critical levels for

corn and sorghum were much lower than for cowpea. The concentration of
Zn in leaves of Zn-deficient plants was in a range which is considered
adequate for several other species (Jones, 1972). On the other hand
Andrew et al. (1981) estimated 17 mg/kg to be the critical Zn level in
cowpea tops at preflowering stage. They did not mention the method of
ashing used for Zn analysis.

Viets et al. (1954) classified 26 field and vegetable crops
into three categories based on their Zn concentrations and
responsiveness to foliar and soil-applied Zn. Chapman (1966) listed
the ranges in Zn concentration from deficiency to toxicity for 17 crops
indicaing that deficiency levels are characterized by Zn levels of <20
to 25 mg/kg in the dry matter. Bauer (1971) also reported average Zn
concentration data for a number of field and vegetable crops. The
deficiency levels in his report are characterized by Zn levels of <20
to 25 mg/kg in dry matter.

2. External Zinc Requirements

"External nutrient requirement" can be defined as the quantity
of nutrient (or some proportional part of that quantity) that
constitutes a minimum pool for adequate crop nutrition. But the
external requirement can also refer to the intensity of nutrition, the
concentration of the nutrient in the soil solution which is associated
with adequate nutrition (Fox, 1981).

There are a number of extraction procedures used to assess the
Zn availability status of soils for various soil-plant combinations.

Some recent literature reviews concerning soil tests for availale Zn are by Cox and Kamprath (1972), Viets and Lindsay (1973) and Lindsay and Cox (1985). Lindsay (1972) has reviewed the literature showing how Zn solubility in soils affects the availability of Zn to plants. Three extraction procedures, HCl, DTPA, and AB-DTPA, have been used for measuring Zn in these studies. Literature regarding these three methods, relevant to the test crops of this study, is presented in the following paragraphs.

The extractants most frequently used to extract "available" Zn include DTPA and 0.1 N HCl. In a study involving 77 Colorado soils, Lindsay and Norvell (1978) determined a critical value of 0.8 mg Zn/kg for corn and 0.6 mg Zn/kg for sorghum by a DTPA soil extraction method. A comprehensive micronutrient investigation was conducted by Sillanpaa (1982) in cooperation with scientists from 30 countries. The study included many tropical countries and 7500 soil and plant samples. It provides valuable data on the correlation between Zn concentrations in plants growing on these soils and extractable soil Zn by several extractants. Wheat and corn were sampled at original sites where the soils were taken; then wheat was also grown under uniform greenhouse connditions. The tentative critical range for Zn was <0.4 to 0.6 DTPA-extractable Zn.

Cox and Wear (1977) reported critical Zn soil test levels for corn and rice based on experiments conducted as a part of a joint regional project that included the Southern states, Pennsylvania and Puerto Rico. The critical soil test levels (mg Zn/kg soil) were as

given in the following text table:

	DTPA	0.1 N HCl
corn	0.5	1.4
rice	0.7	1.8

These critical values may not apply to extremely high CEC
soils, high P soils, or very acid soils. Acid extractants are not
recommended for calcareous soils. The DTPA extractant was developed
for use on near-neutral and calcareous soils, but by inclusion of soil
pH in the interpretation of results, the soil test has been extended to
acid soils well below the pH range for which the test was originally
intended (Haq and Miller, 1972). A level of 2.5 mg/kg HCl-extractable
Zn is barely sufficient for proper growth of corn or sorghum in the
absence of lime. With about 5 % free $CaCO_3$, at least 6 mg Zn/kg is
required. High levels of P further increase the minimum requirement
for Zn (Olson et al., 1962; Ward et al., 1963). Critical levels of
DTPA-extractable Zn in India have been determined as follows: corn,
0.60 to 0.75; wheat, 0.50 to 1.00; and rice, 0.83 mg/kg. Critical
levels of 0.1 N HCl extractable Zn for wheat was much higher, 4.5 mg/kg
(Randhawa et al., undated).

DTPA-extractable Zn values are closely related to rice response
to applied Zn fertilizers. Yield responses are usually obtained when
soil Zn levels are less than 0.5 mg Zn/kg soil (Reisenauer, 1983).

Critical soil Zn levels extracted with ammonium

bicarbonate-DTPA (AB-DTPA) in Colorado are 1.5 mg/kg for sensitive

crops, such as corn, sorghum, beans, and potatoes, and 0.5 mg/kg for

other crops (Soltanpour et al., 1979). The critical level of

DTPA-extractable Zn for wheat was 0.3 mg/kg (Radjagukguk et al., 1980).

This value is lower than other values reported in the literature. It

is substantially below the critical value of 0.8 mg/kg reported

previously for alkaline black earths of the Darling Downs (Whitehouse,

1973) and lower than the critical value of 0.5 mg/kg reported by Brown

et al. (1971) for 92 California soils.

Safaya and Malakondaiah (1981) determined a DPTA-extractable

critical Zn level of 0.9 mg Zn/kg for cowpea in a calcareous soil of

India. A much lower DTPA-Zn concentraion of 0.35 mg/kg in the same

soil was adequate for near-maximum yields of corn and sorghum.

In a field rice experiment in Arkansas, Zn content in the rice

plant Y leaf (the most recently mature leaf) followed soil solution Zn

levels (Yoon et al., 1975). The soil solution was extracted from soil

samples collected from a flooded field using 50 psi N_2 gas pressure

in a "Baroid" press. The extract was acidified with HCl and analysed

by atomic absorption spectrophotometry for Zn and other micronutrients.

Soil solution Zn concentration was 0.22 mg/kg 2 weeks after flooding

but decreased to 0.09 mg/kg 67 days' after flooding. Similarly Zn

concentration in rice Y leaves was 44 mg/kg 16 days after flooding and

decreased to 24 mg/kg 66 days after initial flooding.

Sinha and Prasad (1982) reported a significant linear regression

between concentration of soluble Zn in soil and Zn uptake by wheat.

Zinc is only sparingly soluble in soils. Solid phase minerals and adsorption reactions prevent a high concentration of Zn from persisting. Hodgson et al. (1966) measured total soluble Zn in several New York and Colorado soils. They reported an average of about 0.075 mg Zn/kg in several New York soils and <0.002 mg Zn/kg in 20 Colorado soils. They interpreted these results as indicating one reason why Zn deficiencies are more common on alkaline than on acid soils.

Carroll and Loneragan (1969) obtained maximal or near maximal yields of 8 different plant species, in flowing water culture experiments with Zn concentrations in the range of 0.01×10^{-6} M (0.00065 mg/L) to 2.5×10^{-6} M (0.163 mg/L).

Ohki (1977, 1984) estimated critical levels of Zn for soybean and sorghum tissue using solution culture techniques. The Zn requirement was 0.1 mg/L for soybean and 0.00005 mg/L (0.76 nmol/L) for sorghum to obtain 90% of maximum yields. The difference in solution Zn requirements is so great that it is easy to believe that some mistake was made.

To study soluble Zn in soils, Jeffery and Uren (1983) extracted soil solutions using a centrifugation method similar to that described by Gillman (1976). As the pH of the soil increased from 4.4 to 7.5, the total concentration of Zn decreased about 100-fold. (i.e.from 1.8 to 0.012 mg/L). The relationship between Zn concentration (log) and pH was essentially linear over the pH range studied. For each unit

increase in pH, Zn solubility decreased about five-fold.

Saturation extracts of 68 soil samples representing 30 soil series of California were analyzed by Bradford et al. (1971) for trace and major element contents. Zinc concentration in saturation extracts ranged from 0.01 to 0.4 mg/kg with a mean of 0.07 and median of 0.04 mg/kg. Oliver and Barber (1966) reported 0.31 micromolar Zn (0.02 mg Zn/kg) in a saturation extract of Sidell silt loam subsoil.

D. Diagnostic Criteria for Zinc

Although crop yield is the ultimate test of the availability of nutrients in a soil, other diagnostic techniques, when calibrated with yield data, are helpful in predicting the deficiency status. Early methods used to detect Zn deficiencies were visual observations of deficiency symptoms and response to foliar application of Zn. Plant analysis and soil tests for Zn are now becoming more widely used. Atomic absorption spectrophotometry and direct reading emission spectroscopy have simplified the analytical procedure for Zn and have largely replaced other methods (Lindsay, 1972). Soil and plant analyses supplement each other as tools in predicting the need for Zn fertilizers, although the amounts of fertilizer required for crops is usually based on local experimentation. Soil testing is most often used as a means of predicting whether or not remedial treatment is required for the current year, whereas plant analysis is used to monitor nutrient levels during the growing season. In these ways soil and plant analyses complement each other.

1. Soil Analysis

Soil analysis has proved to be an effective means of identifying soils where Zn deficiency is likely to be a nutritional problem (Reisenauer, 1983).

The first requirement for a reliable soil tests is a good sample. Deficiencies of Zn and other micronutrients occur most commonly in small areas of fields and only rarely a field is uniformly deficient (Reisenauer, 1983). Deficiencies of Zn are encountered most often in areas where surface soil has been removed by land-leveling or by erosion (Kanehiro and Sherman, 1967). Hence, soil samples should be taken to represent areas suspected (by noting crop growth or appearance) of being deficient, or to represent the entire field if an assessment of the field is desired.

Several methods for estimating "available" levels of Zn in soils have been proposed. The most promising appears to be a DTPA extraction method developed by Lindsay and Norvell but it is not suitable for acid soils of the tropics (personal investigations, data not reported). The 0.1 $\underline{N}$ HCl method was developed by Nelson et al. (1959) and has been used extensively for predicting soil Zn availability. The method works quite well for most acid soils but is not suitable for predicting Zn availability in soils above pH 7 unless additional measurements are made (Baker and Amaracher, 1982).

Soltanpour and Schawab (1977) combined the DTPA soil test, with the bicarbonate soil test for P, into what they term the ammonium bicarbonate-DTPA (AB-DTPA) soil test. The AB-DTPA soil test was

developed to simultaneously extract P, K, Zn, Fe, Cu, and Mn. The method can also be used to evaluate the availability and toxicity ot trace elements such as Pb, Ni, Cd, Mo, B, As, and Se.

2. Visual Symptoms of Zinc Deficiency

Deficiency symptoms exhibited by plants are valuable guides in application of fertilizers during crop growth and may also indicate fertilizer needs for future crops. Zinc deficiency sometimes occurs without any visual symptoms and is shown only by low production. For many species, Zn deficiency can be identified by distinctive visual symptoms. They occur most often in the leaves, but sometimes also appear in the fruit or branches or are evident in the overall development of the plant. The severity of the symptoms can be used as a guide to the degree of deficiency.

In acute form, Zn deficiency causes easily recognizable diseases in crops; for example, white bud of corn, little leaf of apple or pear, rosette of pecans, or mottle leaf of citrus. Yields are low, seeds do not form, and the crops may be a total failure. Symptoms common to many crops include:

- The appearance of light green, yellow, or white areas between the veins of leaves, particularly the older, lower leaves - a condition known as cholorosis.

- Death of tissue in this discolored, cholorotic leaf areas.

- Shortening of the stem or stalk internodes resulting in a bushy, resotted appearance of the leaves.

- Small, narrow, thickened leaves.

- Early loss of foliage.

- Stunted growth.

- Malformation of the fruit, often with little or no yield at

all.

The visual symptoms are quite distinct and characteristic in corn, sorghum, grapes, and in nut and fruit trees. In other crops, Zn deficiency can easily be confused with disorders caused by lack of other micronutrients or by plant diseases, micro-organisms, or pesticides. For example, Mn or Fe deficiency can produce a chlorosis of fruit trees similar to that resulting from Zn starvation. However, only Zn deficiency causes the characteristic 'little leaf' and 'resetting', the clustering of leaves at the top of the branch while the stem is largely bare. Chemical analysis of soils and plants is useful to confirm a Zn deficiency when visual symptoms are not conclusive.

Corn shows characteristic deficiency symptoms, stunted growth, and often reduced yield when grown in soil low in available Zn. Severely deficient plants are also stunted, and have short internodes (Chapman, 1966; ILZRO, undated). Generally the plants remain green during the first month, but have a stunted growth. Older leaves develop light yellow streaks or chlorotic striping between veins; this may show as a broad band of white or yellow tissue between the midrib and edge of the leaf, occurring mainly in the lower half of the leaf, and is visible when the young leaf is coming out of the whorl. Later

the tissue dies in these streaks. In severe cases, the unfolding young

leaves may be white or yellow - hence the name 'white bud' for acute Zn

deficiency in corn. Silking and tasseling are delayed. These stripes

extend from the base to the top of the leaf and often occur in an

irregular pattern. First affected are the older lower leaves, which

are striped and comparatively narrow. The younger upper leaves may

remain green unless the deficiency is severe (Gunderson et al., 1965).

Deficiency symptoms in grain sorghum are similar to those in

corn, but less pronounced. Although sorghum is not as susceptible as

corn, Zn deficiency appears to retard the development and maturation of

the heads (Welch et al., 1967). Initiation of Zn deficiency symptoms

in sorghum, according to Ohki (1984), occurs at the base of young

developing leaves within the whorl. Very slight interveinal chlososis

first develops at the base of young leaves near the midrib and

progresses to larger areas with occasional collapsed areas that become

necrotic. The top view shows diffused interveinal chlorosis in the

vicinity of the midrib at the base of young developing leaves within

the whorl. Under severe Zn deficiency conditions, the plant shows an

overall pale yellow appearance with diffused interveinal chlosoris.

The older leaves exhibit marginal necrosis of the tip with reddish

purple coloration of interveinal areas in the tip half of the leaf and

interveinal chlorosis in the basal portion of older leaves.

Zinc deficiency symptoms of rice are sometimes difficult to

diagnose. Cox and Wear (1977) and Chaudhry et al. (1977a) have

described Zn deficiency symptoms of rice in detail. Zinc-deficient

young seedlings wither and die from the tops downward toward the roots. After true leaves have developed, Zn deficiency symptoms generally appear as light yellow or rusty brown lesions on the stems and leaves. In the tillering stage, Zn deficient plants appear to be infected with rust because of these lesions. The midribs of young leaves first become chlorotic and later brown spots or streaks develop in lower leaves, resulting in stunted growth. Zinc deficiency symptoms in rice usually are described by the term "bronzing". Under flooded conditions, Zn deficient plants appear very listless with the bottom leaves floating on the water surface away from the stem. All leaves of such plants have a rather pale yellow-green color. In severe cases, plants remain extremely stunted and adopt a rusty and burning appearance.

In wheat, the chlorotic and necrotic stripes on each side of the midrib are charactericstic of mild Zn deficiency. These symptoms begin as small white irregular patches in the interveinal areas of lower leaves (generally third or fourth leaf) which later enlarge and coalesce resulting in white-green mottling spread down the blade of the already affected leaves, and may also appear in the leaves immediately above them.Where Zn deficiency is more severe, the leaves tend to be totally chlorotic and short but of normal width. In severe cases, the chlorotic areas also spread to the leaf sheaths down the next node. Sometimes they have an oil-soaked appearance. As necrosis proceeds, the leaves often collapse across the midrib along the severly affected areas and become flaccid and dried while the distal portions may remain

green (ILZRO, undated; Shukla and Raj, 1974).

Not many reports describe Zn deficiency symptoms in sugarcane. Evans in 1960 claimed he had developed certain Zn deficiency symptoms. Clements (1980) obtained a sheath level of 4.0 mg/kg Zn by using "fourth generation" minus-Zn setts. These plants were not only poor in growth but showed the symptoms of Zn deficiency. The bottom leaf showed a single broad, lightly colored stripe taking up the middle third of left half of the blade. It was not a chlorotic situation, but only a lighter green color. The spindle exhibited the most severe symptom. It emerged but growth was defective, with edges of young leaves almost white edges from the tip downward about a third of the leaf length. The edges of the two top blades showed a tendency to become torn, and young leaves tended to furl.

Unlike corn, fruits and nuts, soybean does not develop highly specific Zn deficiency symptoms. Rather the symptoms often resemble those of Fe, Mg, or Mn deficiencies. In general, the stems and leaves of Zn deficient plants fail to develop to normal size and the tissue between the leaf veins turns yellow. This yellowing, known as interveinal chlorosis, is usually worst on the lower leaves of the plant. Chlorotic leaves may turn brown or gray and die prematurely. Symptoms are more common and more severe in earlier stages of growth. Deficient plants are frequently stunted and give low yields (Chapman, 1966; ILZRO, undated).

Symptoms of Zn deficiency in cowpea can appear within 12 to 15 days after sowing (Safaya and Malakondaiah, 1981). Primary leaves

develop chlorotic spots in the interveinal areas which turn rust-brown

with time. All the trifoliate leaves are considerabley reduced in size

with necrotic apots appearing first on the margins of the leaflets and

later invading most of the areas between the main and lateral veins.

All major veins, including midribs, may lose their green color, turning

yellowish white. The affected leaves abscise resulting in premature

loss of foliage.

3. Plant Tissue Analysis

Plant analysis as a guide to the fertilization of crops is

based on the concept that "what is in the plant is related to growth".

When plant analysis is used as a means of evaluating nutrient status of

the crop, changes in the fertilizer program can often be made

immediately, or if that is impossible, in time for the next crop. In

this way a good plant analysis program evaluates current nutrient needs

and anticipates those of the next crop on the same field. Crop yield

and quality measurements, as well as appropriate soil tests, are also

essential features of a good plant analysis program (Reisenauer, 1983).

Plant analysis has, however, limited use for fertilizer

recommendations in annual crops like wheat, barley, and corn. This is

due to the relatively short growing season for these crops and the time

required for laboratory analysis and corrective action. Plant tissue

analysis can, however, be used more successfully for long term crops,

and an excellent example of the use of plant analyses in crop

production operations is the crop logging carried out for sugarcane in

Hawaii (Clements, 1980). The crop log, which is a graphic record of the progress of the crop, contains a series of chemical and physical measurements. The measurements indicate the general condition of the plants and suggest changes in management that are necessary to produce maximum yields.

It is essential to select a plant part for chemical analysis that reflects the nutritional status of the plant for most or all of the growing season. For best results, the plant part selected should remain relatively constant in nutrient concentration in the zone of deficiency and then increase rapidly in concentration as the plant becomes well supplied with nutrients. The transition zone from deficienty to adequacy should also be relatively a narrow (Reisenauer, 1983).

Efforts have been made to determine critical levels of Zn in a number of crops. Literature regarding critical levels of Zn for various crop species has been presented earlier under internal zinc requirements.

Halim et al. (1968) obtained evidence of genetic control of Zn utilization and suggested that critical levels of Zn in tissues might be different for some genetic lines. Leaves of single and double crosses of corn plants vary widely in the Zn contents at which deficiency occurs. Therefore, plant parts, stages of plant growth, and varietal differences must be taken into account in studies to determine critical levels of Zn in plants.

In using plant analysis to diagnose the nutrient status of

annual crops, knowledge of the environmental conditions under which the

crop is growing is also essential for proper evaluation of the test

data. The following may influence test results: 1) the plant itself;

e.g. species, age, and part analyzed, 2) environmental conditions;

e.g. deficiencies or toxicities of elements not being tested, drought

, high or lower temperatures, disease, plant defoliation, and 3) type

of crop culture, i.e. field versus potted soil versus nutrient

solution). Any factor that limits plant growth more than the element

tested will likely increase the concentration of the tested element in

the plant. Usually, lower critical concentrations have been obtained

in pot and nutrient solution experiments than in the field (Jones,

1983).

Then there is controversy in the literature regarding the

suitability of method of ashing for Zn analysis in plants. Many

reports indicate that some of the Zn in plant tissue is not solubilized

by dry ashing procedure. Therefore wet combustion (Reisenauer, 1983)

is the preferred method for Zn and many other elements. Piper (1942)

has written that regardless of the dry ashing procedure used, the

siliceous residue may retain small portions of some of the

consititiuents. This retention causes an error that is claimed to be

especially noticeable for micronutrients, and complete recovery of

these elements is reportedly attained only by solution of the silica in

hydrofluoric acid or by alkaline fusion.

Some workers believe that errors from silica retention are

negligible for most elements. Gorsuch (1959) reported results from an

excellent study of several wet- and dry-ashing procedures in both of which he added radioisotopes to 2 grams of cocoa before ashing. After wet ashing, the samples were diluted with water and counted. The residues from the dry-ashed samples were digested with dilute HCl (acid:water ratio 1:1) and counted. In addition, the ashing containers (usually vitreous silica) were counted to evaluate their metal retention. Ashing with nitric and perchloric acids was satisfactory for almost all elements including Zn. Dry ashing with or without added reagents was unsatisfactory for elements like Hg, Se, Cu, and Cd but was satisfactory for many elements including Zn.

Greweling (1976) compared results of several variations of the dry-ashing procedure for plant materials including orchard leaves, orchard grass, alfalfa, Ladino clover, white pine, corn leaves, corn grain, and sugar beet leaves. Dry ashing was done at 500 $^{\circ}$ C and ash was treated or not treated with HNO_3 and/or HCl before finally dissolving it in 1 N HCl. No differences due to treatment were found for Ca, Mg, K, Na, Cu, Zn, P, and Pb. Their data also indicated that for atomic absorption determination of metals, the presence of some organic matter is inconsequential and the HNO_3 treatment is unnecessary. In Greweling's report, however, dry ashing procedures were not compared with wet ashing.

E. Seed Analysis as a Diagnostic Tool

Historically, seed composition has been considered a poor indicator of the nutritional conditions which grew a crop. A generally accepted opinion presented by Small and Ohlrogge (1973) is that the

"quantity of seed produced by a plant is adjusted to maintain viability in part through constant composition". According to Small and Ohlorogge, the concept is true in general, but there may be exceptions, particularly at very high yields or as changes brought about by plant breeding result in plant types which do not conform to the accepted theory.

In fact, there are many reports contradicting the concept. Seed analyses were valuable for determining the Mo and Zn supply for young plants developing from that seed (Reisenauer, 1956; Shaw et al., 1954), and evaluating Mo, N, S supplying status of soils (Lavy and Barber, 1963; Pierre et al., 1977a, b; Fox et al., 1977).

Shaw et al. (1954) grew corn plants, from seeds that contained radioactive Zn, in a Zn deficient soil to which 0 and 10 mg Zn/kg had been applied. The plants grown on low Zn soil contained more seed Zn than did plants grown on soil to which Zn fertilizer was added. After 17 days growth, seed Zn represented 73 percent of total Zn in untreated soil and 25 per cent in treated soil. After 44 days growth, the fractions of plant Zn originating from the seed were 15.7 and 4.8 per cent for the untreated and treated soils, respectively. Thus Zn supplied by the corn seed furnished an important part of the plant's Zn, particularly when the soil Zn supply was low. The Zn concentration in corn seeds used for this study was not reported.

Molybdenum content of soybean seeds was reported as a suitable indicator of the available Mo status of a soil by Lavy and Barber (1963). In their study, yield increases from Mo fertilization occurred

when the soybean seeds on the untreated plots contained 1.6 mg/kg or less of this element. Harris et al. (1965) similarly reported that the progeny of Hill soybean seed samples obtained from six different states containing 2.6 mg/kg or less of Mo responded to Mo addition when grown in soils deficient in this element. Another study in Georgia (Gurley and Giddens, 1969) also demonstrated that foliar-applied Mo to deficient plants raised concentrations of this nutrient in the seeds so that progeny from these seeds did not develop Mo shortages when grown on Mo deficient soil. These and other studies clearly show the value of chemical analysis of soybean seeds as an indicator of Mo status of the plants which produced them.

Encouraged by the above-cited research, Tisdale et al. (1985) also suggested that the micronutrient content of seed of crops may be an indicator of soil fertilizer needs, as determined with Mo on soybean.

Pierre et al. (1977a, b) evaluated the N content of corn grain as a measure of N sufficiency of the crop for maximum yield. This was done by studying the relationship between yield, expressed as a percentage of maximum, and the N percentage in grain. The relationship was determined from the data of 13 site-years of six N-rate experiments in Iowa and from data reported in the literature pertaining to four US states and one Canadian province. Grain N percentage from all the experiments ranged from 0.94 to 1.60 percent and mean critical N-value was 1.53 percent for 90% relative yield. They concluded that N contents of corn grain can be used to determine N sufficiency of crop

and to estimate the amount of N needed for subsequent crops grown under similar management and growth conditions. The range between minimum and critical N percentage was greater in leaves than in grain, but the precision of results may be more important than the range in values for determiming the most suitable plant part or stage of plant development for nutrient deficiency diagnoses. Probably the greatest advantage of grain is the ease of obtaining and handling representive samples, especially samples representating large areas.

The relative yield – percent N relationship obtained for corn grain offers a promising basis for estimating N sufficiency and N requirements for corn. Probably the technique also applies to other nutrients and for other crop species. But like other diagnostic methods involving plant analysis, its greatest value probably is in supplementing other methods and sources of information regarding N needs (Pierre et al., 1977a). Grain analysis is in fact a recommended method for developing N fertilizer recommendations for wheat in Colorado (Goos et al., 1981). If wheat grain contains less than 12 percent protein (1.92 percent N), the crop is considered deficient in N and fertilizer application is recommended for the next year crop in that field. This criterion is called the "12 percent protein rule" by Colorado State University agronomists.

Grains of cowpea proved good index tissue to evaluate the S supplying status of Nigerian soils (Fox et al., 1977). Sulfur contents of cowpea grains, grown on soils with varying soil S status, ranged from 0.12% to 0.36%. The S percentage of cowpea grains was 0.26% when

yield was 95% of maximum.

Contrary to general belief expressed in the literature, wide variations in nutrient composition of seed is fairly common. For example, samples of soybean seed collected from 152 Indiana certified seed growers were analysed for elemental contents (Small and Ohlrogge, 1973). Nitrogen and K contents of these seed samples were remarkably constant, with means and standard deviations as follows: N, 6.3 $\pm$ 0.2%; K, 1.9 $\pm$ 0.2%. The nutrient means and standard deviations, respectively, for other elements were: Ca, 0.33 $\pm$ 0.13%; Mg, 0.35 $\pm$ 0.06%; Fe, 103 $\pm$ 64 mg/kg; Mn, 24 $\pm$ 9 mg/kg; Zn, 41 $\pm$ 4 mg/kg; Cu, 15 $\pm$ 2 mg/kg; Mo, 6.2 $\pm$ 4 mg/kg; and B, 34 $\pm$7 mg/kg. The range of Mo concentration in soybean seeds also appears quite wide, because a high level of 22.4 mg Mo/kg was reported in a seed sample from Texas (Small and Ohlorogge, 1973). The variation in these samples was sufficiently great to conclude that seed analyses could be helpful in diagnosing the nutritional conditions under which a crop was grown (Small and Ohlrogge, 1973).

The data of White et al. (1981) for one cultivar of wheat, three cultivars of narrow leaf lupin and one cultivar of white lupin grown under a range of soil and climatic environments demonstrated that micronutrient concentrations do vary although Zn content seems more stable than Cu, Mn, Co, or Se. Standard errors were very low in general, and for Zn in particular. Zinc concentration in nitric-perchloric acid digests of kernels of 29 inbred corn lines ranged from 16 to 38 mg Zn/kg (Massey and Loeffel, 1966). Zinc

concentration in the kernel was, however, not closely related to the weight of the kernel or to the total weight of kernels per plant. Zinc contents of in grain differed for corn inbred lines. Data regarding Zn content of other plant parts was not reported.

In subsequent greenhouse studies with 32 corn inbreds, Massey and Loeffel (1967) found that Zn concentration in the kernel was not correlated with Zn uptake by the plant from those kernels or with the Zn concentration in plants grown on either Zn deficient or Zn-fertilized soil. In field experiments, however, variation in concentration of Zn in kernel of inbred lines did appear to be related to the general level of Zn in plants, but this factor was greatly modified by the extent to which inbreds were able to transfer Zn from stalks and leaves to ears. The effectiveness of this transfer was related to the general Zn content of the plant, because a plants with high Zn concentrations have more Zn available for transfer.

Rehm et al. (1983) in a 5-year field study with corn did not obtain any yield response to Zn application when grain Zn concentrations from control treatments ranged from 14 to 25 mg/kg. Grain Zn concentration, however, increased about 1.5 times from applications of 13.4 kg Zn/ka The ear leaf Zn concentration in control treatment ranged from 24 to 38 mg/kg, which were above the generally reported critical Zn values for this tissue (Melsted et al. 1969; Chapman, 1966).

Summerfield and Muehlbauer (1982) reviewed the information already published about mineral nutrient composition of lentil seeds

pertaining to different genotypes and locations. The summarized data differ widely for all elements investigated. Zinc concentration of lentil seeds represented by 16 determinations ranged from 21 to 330 mg/kg , more than a 15-fold variation. Nitrogen concentration varied less than 2-fold, P varied more than 7-fold, K 2.5-fold, Ca 8-fold, Mg 4-fold, Fe 3.5-fold, S 2-fold, Cu 3.5-fold, Mn 2.4-fold, and Na 65-fold. On the basis of the publications from which these data were compiled, these authors tentatively concluded that the chemical composition of lentil seeds varies with genotype and location and depends on the availability of various inorganic nutrients during both vegetative and reproductive growth of mother plants.

In a three-year sewage sludge experiment, Zn concentrations of corn leaves and grains increased from 18 to 153 and 16 to 34 mg Zn/kg with increasing levels of sludge-irrigation rates (Hinesly et al., 1982). The Zn content of soybean seed has been reported to increase from 14 to 46 mg/kg as Zn in nutrient solutions increased from 0.066 to 0.262 mg Zn/L (Welch and House, 1982).

In a field experiment conducted at the University of California, cowpea seeds contained from 54 to 57 mg Zn/kg (Labanauskas et al., 1981). Zinc was a uniform treatment in this experiment.

The wide range in the Zn concentration of seeds of many crops, and the demonstrated value of the usefulness of Mo and N composition of soybean and corn seeds in evaluating the nutritional status of these crops strongly suggest that the use of grain as an index tissue is a valid idea.

F. Spatial Variability Studies Using Geostatistics

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

Spatial variability can be divided into two broad categories: systematic and random (Wilding and Drees, 1978). Random variability is often complex, difficult to discern, and impossible to express analytically. Historically, pedologists have concentrated their efforts on systematic changes in soil with less emphasis on identifying random changes.

The use of soil analysis to construct maps of soil properties and identify areas of particular interest or requiring separate management is important in soil science. Recent developments in geostatistics permit increased ability to summarize and interpret such soil analyses (Yost et al., 1982b).

Soil properties are usually studied by taking samples on a grid or other pattern (Petersen and Calvin, 1965) with the assumption that properties measured at a point also represent the unsampled neighborhood. The extent to which this assumption is true depends on the degree of spatial dependence existing among samples. Geostatistical methods have been applied to soil studies over distances

of meters or tens of meters (Vieira et al., 1981) and even over kilometers (Yost et al., 1982a). For example, Yost et al. (1982a) concluded that soil chemical properties commonly have spatial dependence and understanding such structure may provide new insights into soil behavior over the landscape.

1. Semi-variograms

The importance of structural analysis using semi-variograms lies in its definition of parameters to be kriged (estimated), such as the degree of continuity and isotropy of the regionalized variable, the presence of trends (or drift), and range of spatial dependence. The application of regionalized variable theory assumes that semi-variance depends only on the direction and distance of separation between two sample sites and not on the actual locations of the sample sites. If this assumption is valid, then the semi-variogram for a region can be estimated from a single set of data (McBratney et al., 1982).

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

$$\gamma(a,h) = \varepsilon\{[z(x) - z(x+h)]^2\} / 2N$$

Where the semi-variance, $\gamma(a, h)$, is a measure of the similarity of the data, on the average, between points a given distance, h, apart. a is the angle or direction. 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). The semi-variance can also be

represented as $\gamma(h)$. The more alike the points are, the smaller $\gamma(a,h)$ 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 ideal case, the semi-variance of a property increases as distance increases and eventually attains a constant value (Fig. 1).

The value of the semi-variance at which the graph levels off is called the sill of the semi-variogram and is denoted by 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 by a. Within this range there is a systematic relationship or dependence between $\gamma(a,h)$ and h, and an empirical equation can be fitted to this relationship (Clark, 1979). Another important feature of the semi-variogram is the intercept, C_o, which in geostatistics is known as the nugget variance or nugget effect. C_o is the estimate of $\gamma(h)$ at h=0 and provides an indication of short distance variation - variation that occurs at distances shorter than the sampling interval (Yost et al., 1982a, b).

Burgess and Webster (1980a) suggested that range in soil surveys will usually be a few hundred meters, and, exceptionally, two or three kilometers. However they point out that range depends on the sampled area size. For example, over a large landscape on the island of Hawaii, Yost et al. (1982a) observed that the range for pH was 14 to
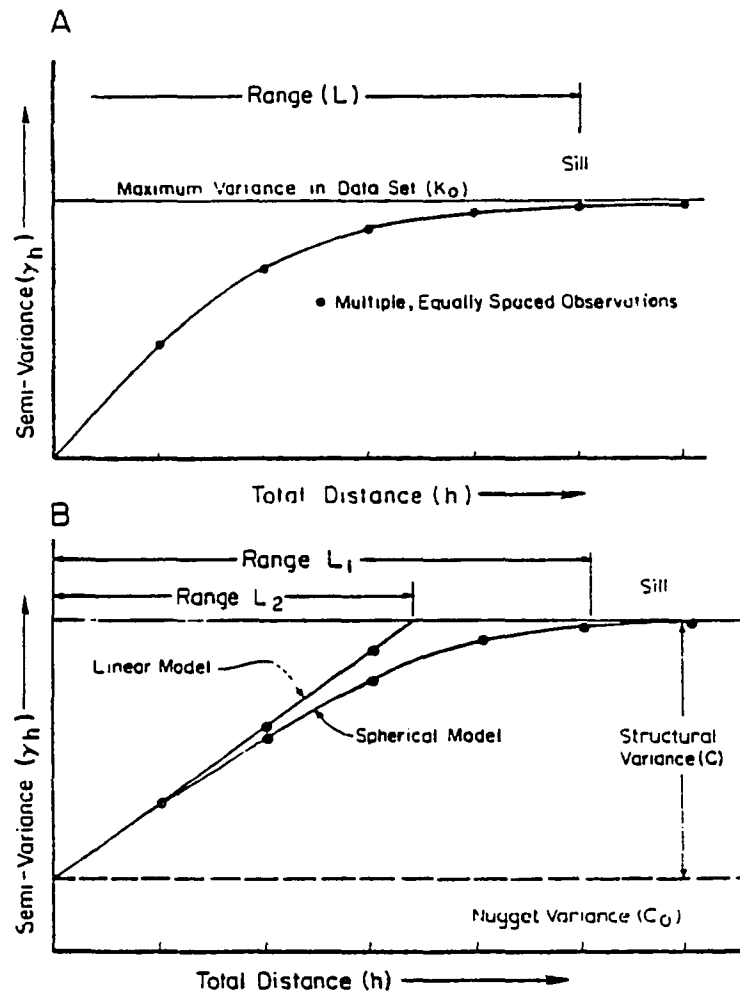
Fig. 1 A. Idealized semi-variogram with zero
nugget variance.
B. Observed semi-variograms for soil
properties with nugget variance.
(Source: Wilding and Drees, 1983).

32 km. Interpolation should preferably use points closer than the range.

Semi-variograms have been used to characterize spatial dependence of soil properties over many different scales of sampling. In a study in which P uptake by a sorghum crop was measured on a 1.5 m grid, the range of modified Truog P was 5.6 m and that of leaf P was 6.1 m (Trangmar, 1982). On plots to which 45 kg P/ha was applied, spatial dependence of soil P decreased to 5 m and variance of leaf P became nonstationary as a result of trends in P uptake across the plots. The results suggest that soil management affects micro-variation of soil properties which, in turn, affects nutrient uptake and variation in crop yield.

Viera et al. (1981) reported a range of 50 m and small nugget variance for a semi-variogram of water infiltration rates in a Typic Xerorthent. They used the range of spatial dependence to determine that future sampling intervals should be 20 m to allow for local variation and enable low estimation variance for kriging. This distance was larger than that indicated by autocorrelograms computed along the major axis of the field. The semi-variogram was averaged over all directions and tended to be less sensitive to local detail than autocorrelograms.

Using a sampling interval of 10 m, Campbell (1978) found that sand content was spatially dependent over distances of 30 and 40 m, respectively, in two adjacent soil mapping units. McBratney and Webster (1981b) sampled soils at 20 m intervals along a transect in N.

E. Scotland and identified spatial dependence up to 360 m for soil color, pH, and little or none for particle size fractions and organic matter content. Nested semi-variograms for some properties indicated soil variation at two different scales.

Yost et al. (1982a) observed that exchangeable Ca, Mg, K and P sorption was more variable in subsoils than topsoils as indicated by smaller zones of influence and larger nugget variances of the semi-variograms. This reflected greater variability in age and weathering of parent material and the effects of rainfall in reducing topsoil variation of these chemical properties.

The soil property is isotropic if it varies in a similar manner in all directions, in which case the semi-variance depends only on the separating distance, h. Isotropy rarely occurs in practice and by computing V(h) in various directions it is possible to determine any anisotropy that exists.

McBratney et al. (1982) found that regional variation of extractable Cu and Co in S. E. Scotland was isotropic and combined three components of variation; a long range or geological component extending to 15 km, a field-to-field component extending up to 3 km and a nonspatial or nugget component which accounted for 69% of the variance in Co. Trangmar et al. (1982) reported spatial dependence of about 4.0 km for exchangeable sodium percentage in an area of Vertisols in Sudan. Vander Zaag et al. (1981) used geostatistics to map selected soil properties in Rwanda and found zones of spatial dependence ranging from 37 km for pH to 62 km for log transformed silicon.

Trangmar et al. (1984) studied regional variation of selected topsoil properties in Sitiung, Indonesia. Geostatistical analysis of spatial variation identified the presence of distinct directional trends in sand, silt, and clay in relation to depositional patterns of soil parent materials. Similar, but weaker trends were also apparent in semi-variograms for pH, exchangeable Ca, Mg, Al saturation, and total P. Sand content of topsoils contained a distinct geological variation component with a range of spatial dependence of about 16 km. Ranges of spatial dependence were shorter (<0.4 km or 3-5 km) for most chemical properties due to their sensitivity to short-range features, including leaching, erosion, and soil management.

Clearly, the range of spatial dependence, the size of the nugget variance and isotropy characteristics are functions of both soil properties and scale of sampling. Differences in these parameters as a function of sampling scale indicates the "nested" nature of soil variability caused by interactions of soil forming factors and, to a lesser extent, by differences in soil management over space.

2. Interpolation by 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 statistical bias and with minimum variance. Many soil scientists have used kriging in recent years (Campbell, 1978; Burgess and Webster, 1980a; Yost et al., 1982a, b;

Parra, 1983; Trangmar et al., 1984).

Kriging is a technique of optimal, linear, unbiased minimal variance estimation of regionalized variables at unsampled locations using the structural properties of the semi-variogram and the initial set of data values (Yost et al., 1982a). The simplest forms of kriging involve estimation of point values (punctual kriging) or areas (block kriging).

The relationship between variability and spatial orientation of sample points obtained from the semi-variograms is used to make estimates of values at unsampled locations by the process of kriging. The first step in kriging is to calculate spatial variation in a soil property of interest. Spatial variability measurements provide the quantitative data necessary for interpolation, and also guide in choosing sampling techniques and strategy. Kriging is a form of weighted averaging that incorporates the spatial relationship of properties obtained from semi-variograms. An estimation variance is provided for each estimated point which gives an indication of the reliability of the kriged value. When points have been estimated, they can be plotted on maps and joined by isarithms thus creating a map.

Other estimation procedures are available if sample data depart from the above assumptions. Soil properties often exhibit lognormal or other complex probablity distributions in which case lognormal or disjunctive kriging is more appropriate. Data showing weak forms of nonstationarity can be detrended or interpolated using universal kriging (Yost et al., 1982b; Webster and Burgess, 1980).

Punctual kriging (simple point estimation) is probably the most common kriging procedure used in soil science Burgess and Webster, 1980a; Vieira et al. 1981; Vander Zaag et al., 1981; Trangmar, 1982; Trangmar et al., 1982). The main use of punctual kriging in soil studies has been to produce isoproperty maps and to optimally allocate additional sample sites to improve reliability of mapping. Burgess and Webster (1980a) mapped Na content by punctually kriging a grid of values at 7.6 m intervals using the nearest 16 data points for each interpolation. In the same study, they kriged cover loam at 6.7 m intervals to give a fine grid with nine times as many points as the original observation grid.

Vander Zaag et al. (1981) used punctual kriging to provide maps of soil chemical properties in Rwanda. Yost et al. (1982b) used lognormal punctual kriging to map P sorption and its estimation variance on the Island of Hawaii.

When samples are collected they are usually intended to represent the area surrounding the sample location. Similarly, one may wish to interpolate an average value for an area or block which is larger than the cross-sectional area of the soil volume sampled. Local discontinuities can obscure longer range trends when point estimates are used for sampling. Detection of such discontinuities also depends on the locations of the sampling points and different maps may result from punctual kriging if different sampling schemes are used over the same area (Burgess and Webster, 1980a).

Some shortcomings of punctual kriging can be avoided by
estimating average values over areas using block kriging, which results
in smaller estimation variances and smoother maps (Trangmar, 1984).

Average values of soil properties estimated over areas may be more
useful for soil management purposes than point estimates. Burgess and
Webster (1980b) found that block kriging of Na, stone content and
thickness of cover loam on several farms in Great Britain resulted in
smoothing of local discontinuities in estimated values and smaller
estimation variances compared to punctual kriging. Both effects accrue
from the use of block averages rather than point values. McBratney et
al. (1982) used block kriging in preference to punctual kriging for
mapping extractable Cu and Co in topsoils of south-east Scotland. The
local detail produced by punctual kriging obscured regional differences
while kriging for blocks of 1 km^2 resulted in smoother isoproperty
and estimation variance maps. Estimation variance was also smaller for
block kriging. Optimal sampling schemes for block kriging of pH and
peat thickness were determined by McBratney and Webster (1981a) for
varying block sizes and grid spacings.

Many regionalized variables do not vary within the estimation
neighborhood but show local trends and/or components of broader
regional trends. Simple kriging can be used satisfactorily where there
is a regional trend but local stationarity because the trend (or drift)
is more or less constant within the local estimation neighborhood
(David, 1977). In contrast, drift changes within the estimation
neighborhood where there is overall stationarity but local trends and

the assumptions of simple kriging break down. Universal kriging can be used in such circumstances.

In practice, the additional time and computation costs of solving the kriging system to obtain the weights generally exceeds the improvement in accuracy of interpolation by universal kriging over simple puntual or block kriging (David, 1977); Webster and Burgess, 1980). In this regard, Yost et al. (1982) observed that correction for apparent nonstationarity of P sorption by trend removal or universal kriging provided little improvement in estimation bias over lognormal punctual kriging. Webster and Burgess (1980) also concluded that the presence of short range variation in most soils and noisy data over short lags generally makes local trend identification difficult, suggesting that the scope for universal kriging in soil survey is limited.

In the case where regionalized variables are stationary and lognormally distributed, interpolation can be carried out using lognormal puntual, block or universal kriging.

Computation of semi-variograms and kriging is performed on lognormally (base e) transformed values of the original data using the same procedures as for simple linear kriging. The log-kriged values and estimation variances then require transformation back to the form of the original data.

Vander Zaag et al. (1981) obtained improved structure in semi-variograms for Si and NH_4 in Rwanda following log transformation. They also mapped lognormally kriged values and

estimation variances of these variables re-expressed in terms of the original data. Similarily, Yost et al. (1982a, b) used lognormal methods for simple punctual and universal kriging of soil chemical properties in Hawaii.

G. Maui Growth Failure and Zinc Deficiency in Sugarcane

Maui growth failure is a name given to a malady of sugarcane growing in central Maui. As the name suggests, growth of some varieties virtually ceases. The condition seems to be associated with Maui's saline basal ground waters used for irrigation (Clements et al., 1974). The disease may adversely affect sugarcane growth and reduce yields on as many as 8000 hectares, though obvious symptoms have been noted on only a few thousand hectares, usually in dry years (Hagihara and Bosshart, 1984). Maui growth failure has been the subject of discussion and research for over 50 years. Martin (1938) in his book on sugarcane diseases, wrote in part: "The early symptoms (of Maui growth failure) are recognized by a slowing up of the growth of the cane and by the presence in the leaves of one or more wide chlorotic stripes that often extend the length of the leaf ...." He went on to observe that some varieties withstood the malady better than others, but suggested no causal or remedial factors.

In 1951, Clements wrote, "The so-called Maui growth failure at Hawaiian Commercial and Sugar Company is another (unexplained) phenomenon . . . It seems likely that growth failure, of 1933 particularly, is due to Mg toxicity".

Clements et al. (1974) thought Zn deficiency, both in the field and in sand culture, to be one of the causes of the so-called Maui growth failure which is associated with very broad, light green paraveinal stripes, sometimes a full cm in width, alternating with the normal dark green color. However, they were not able to produce this condition in sand culture. But in certain fields in central Maui where Maui growth failure occurs, the symptoms are quite common. According to these authors, the disorder may also show minus-Mn symptoms, low N, and very high monovalent cation concentrations, both in the plant and in the soil. Applying Zn along with diammonium phosphate corrects the growth problem. But Clements et al. (1974) were surprised to note that when the soil was thoroughly leached to reduce the Na from 116 mg/kg in the soil solution down to 15 mg/kg, Zn deficiency disappeared without adding Zn, but Mn and Cu deficiencies developed.

So far the only solution to this problem has been the selection of tolerant varieties which give satisfactory yields. Even so, yields are lower than in unaffected areas (Hagihara and Bosshart, 1984; Clements, 1980).

In severe cases of Maui growth failure, growth is much retarded, with spindly , short internodes and chlorotic leaves, which in some cases may show brown stripes or lesions. On less severely afflicted cane, broad, irregularly shaped yellow bands on the leaf blade may be visible. The latter is more characteristic of Maui growth failure. However, adjacent to plants afflicted with Maui growth failure other plants with broad green leaves and apparently healthy stalks may be

growing normally (Hagihara and Bosshart, 1984).

Symptoms of Maui growth failure are not exhibited throughout the growing period except for severe cases. Age of the crop and time of year may be factors to consider. In November 1983, in Field 822 of HC&S Company, widespread Maui growth failure symptoms were noted on variety H70-0144 at a crop age of 6 to 7 months.

Hagihara and Bosshart (1984) were able to obtain symptoms of Maui growth failure in a greenhouse experiment. They used Maui growth failure-susceptible variety, H73-1451. Materials used for this study, including soil, seedpieces and irrigation water, were from a Maui growth failure site at HC&S Company. After 2 months of growth, weak Maui growth failure symptoms appeared on a few leaves of the susceptible variety H73-1541 in the form of broad light green bands alongside the midrib. At 6 months of age, Maui growth failure symptoms were still visible on young suckers of variety H73-1541 and appeared to be concentrated on leaf numbers 4, 5, and 6. These authors believed that water quality and varietal characteristics may be a more important cause of Maui growth failure than the soil properties.

III. MATERIALS AND METHODS

The internal and external Zn requirements of eight crops, corn,
sorghum, millet, wheat, rice, sugarcane, soybean, and cowpea, were
estimated in a series of pot experiments in a greenhouse. Grains of
seed-bearing crops were evaluated for possible use in the diagnosis of
Zn deficiency problems. To verify greenhouse results, relationships
between Zn contents of wheat grain and soil Zn were studied using
samples from farmers' fields of eastern Colorado.

Spatial variability studies on Zn were conducted with the soil
and wheat grain samples collected from Colorado. Similar studies were
conducted by collecting soil and sugarcane tissue samples from two
sugarcane plantations on the island of Maui. Relationships between soil
Zn and Zn contents of sugarcane tissues were also studied to investigate
the role of Zn deficiency in Maui growth failure of sugarcane.

A. Greenhouse Pot Studies

1. Comparative Zinc Requirements of Crop Species

a. Identification of zinc deficient soils

This greenhouse study involved two soils, five Zn levels and eight
crops. The major objective of these experiments was to study the
comparative response of various crops to increasing levels of Zn
application and to estimate critical levels of Zn in various plant

tissues, including grain for seed-bearing crops. Paaloa silty clay
(Ultisol) and Keahua silty clay loam (Mollisol), were used to compare
response curves for two Zn deficient soils which were otherwise very
different. Two different kind of soils were used to decrease the
chances of abnormal response curves. A wide range of Zn levels were
applied so that valid response curves could be constructed.

Kanehiro and Sherman (1967) reported that Paaloa silty clay loam
was low in HCl-extractable Zn and that corn was highly responsive to Zn
fertilization on this soil. Subsoils are generally more deficient in
Zn than surface soils. A critically Zn-deficient soil was essential to
the success of the experiment. Therefore, subsoil material of this
soil series was used for the study. The sample was collected from an
upland area adjacent to an unirrigated field of sugarcane, Waialua
sugarcane Company, Oahu.

Parra (1983) had collected soil samples from 74 sites on the
island of Maui for evaluating and mapping the fertilituy of soils of
that island. Both surface (0-15 cm) and sub-soils (30-45 cm) were
collected. One tenth N HCl-extractable Zn was determined in these
soils (Wear and Sommer, 1948; Tucker and Kurtz, 1955; and Kanehiro and
Sherman, 1967). Experience with 0.1 N HCl as an extractant for Zn goes
back many years. See for example that soils of East Maui vary greatly
in extractable Zn (Table 1). According to Kanehiro and Sherman (1967),
the critical concentration of 0.1 N HCl extractable Zn in Hawaiian
soils is 1 to 2 mg Zn/kg soil. Using this criterion, several soils
listed in Table 1 fell into the deficient range.

Table 1   HCl-extractable zinc status of Maui soils, collected by Parra (1983).

Sample no.	Soil series	Sub-group	0.1 N HCl-extractable Zn (mg Zn/kg soil)	
			Surface soil	Subsoil
1	Io	Typic Eutrandepts	8.3	3.4
2	Io	Typic Eutrandepts	26.6	21.9
3	Io	Typic Eutrandepts	12.6	8.1
4	Io	Typic Eutrandepts	5.3	6.9
5	Kula	Typic Eutrandepts	27.2	-
6	Io	Typic Eutrandepts	14.6	7.8
7	Kula	Typic Eutrandepts	14.3	5.7
8	Kaimu	Typic Tropofolists	19.7	-
9	Kaimu	Typic Tropofolists	26.0	-
10	Kaimu	Typic Tropofolists	23.3	-
11	Kula	Typic Eutrandepts	14.7	3.7
12	Kula	Typic Eutrandepts	22.4	-
13	Kula	Typic Eutrandepts	7.0	1.8
14	Kula	Typic Eutrandepts	10.7	1.9
15	Kula	Typic Eutrandepts	13.4	10.8
16	Kula	Typic Eutrandepts	11.7	7.4
17	Kula	Typic Eutrandepts	10.9	7.7
18	Kula	Typic Eutrandepts	8.7	0.1
19	Kula	Typic Eutrandepts	3.5	6.5
20	Pane	Typic Dystrandepts	12.3	10.9
21	Pane	Typic Dystrandepts	3.0	0.3
22	Pane	Typic Dystrandepts	5.4	3.0
23	Pane	Typic Dystrandepts	17.9	10.8
24	Haliimaile	Ustoxic Humitropepts	10.0	6.9
25	Haliimaile	Ustoxic Humitropepts	11.9	13.2
26	Kula	Typic Eutrandepts	2.5	0.6
27	Kula	Typic Eutrandepts	0.2	-
28	Keahua	Torroxic Haplustolls	5.0	4.7
29	Kumuola	Aridic Haplustolls	14.5	4.7
30	Haliimaile	Ustoxic Humitropepts	6.6	0.8
31	Haliimaile	Ustoxic Humitropepts	19.2	17.0
32	Haliimaile	Ustoxic Humitropepts	9.4	19.7
33	Haliimaile	Ustoxic Humitropepts	11.4	2.7
34	Makawao	Humoxic Tropohumults	12.8	6.2
35	Makawao	Humoxic Tropohumults	8.7	2.4

Table 1 (cont.)   HCl-extractable zinc status of Maui soils,
                  collected by Parra (1983).

Sample no.	Soil series	Sub-group	0.1 N HCl-extractable Zn (mg Zn/kg soil)	
			Surface soil	Subsoil
36	Haiku	Humoxic Tropohumults	20.3	3.6
37	Haiku	Humoxic Tropohumults	3.0	2.0
38	Haiku	Humoxic Tropohumults	3.4	1.3
39	Haiku	Humoxic Tropohumults	1.6	2.2
40	Haiku	Humoxic Tropohumults	26.3	22.3
41	Haiku	Humoxic Tropohumults	3.5	3.9
42	Haiku	Humoxic Tropohumults	3.0	3.1
43	Haiku	Humoxic Tropohumults	16.1	12.3
44	Ewa	Aridic Haplustolls	4.2	5.2
45	Ewa	Aridic Haplustolls	15.2	15.8
46	Mololkai	Typic Torrox	5.9	3.5
47	Mololkai	Typic Torrox	4.3	0.5
48	Keahua	Torroxic Haplustolls	6.8	5.6
49	Haliimaile	Ustoxic Humitropepts	4.9	3.3
50	Paia	Typic Haplustolls	30.0	84.5
51	Haliimaile	Ustoxic Humitropepts	18.6	14.2
52	Haliimaile	Ustoxic Humitropepts	293.0	326.0
53	Haliimaile	Ustoxic Humitropepts	12.6	7.3
54	Very stony land		24.2	–
55	Very stony land		5.5	–
56	Very stony land		3.7	–
57	Very stony land		14.9	–
58	Very stony land		8.7	–
59	Very stony land		–	4.6
60	Very stony land		–	0.0
61	Laumaia	Typic Dystrandepts	43.0	20.1
62	Uma	Typic Vitrandepts	58.5	78.9
63	Laumaia	Typic Dystrandepts	36.9	0.4
64	Kaipoioi	Typic Dystrandepts	3.6	0.0
65	Makawao	Typic Dystrandepts	11.9	0.1
66	Pauwela	Humoxic Tropohumults	10.3	0.0
67	Pulehu	Cumullic Haplustolls	6.1	8.0
68	Haiku	Humoxic Tropohumults	8.1	4.3
69	Waikoa	Aridic Haplustolls	4.8	1.6
70	Keahua	Torroxic Haplustolls	20.5	6.1
71	Paia	Typic Haplustolls	13.2	7.3
72	Io	Typic Eutrandepts	9.4	1.7
73	Waikoa	Aridic Haplustolls	1.9	4.6
74	Keahua	Torroxic Haplustolls	5.2	0.1

Table 2 Zinc status of soil samples collected on a grid from two
fileds of HC&S, Maui.

Sample location	Soil series & classification	Sample no.	HCl-extractable Zn (mg Zn/kg)	
			Surface soil	Subsoil
Sample no. 4	Molokai series	1	3.6	2.7
Transect no. 2	(Typic Torrox)	2	3.3	0.8
		3	5.0	3.7
		4	3.2	2.0
		5	5.1	1.7
		6	2.9	1.0
		7	5.1	0.4
		8	3.7	1.8
		9	2.6	1.0
Sample no. 3	Keahua series	1	1.5	0.7
Transect no. 6	(Torroxic	2	1.0	0.8
	Haplustolls)	3	1.9	0.6
(HC&S filed 405)		4	0.9	0.8
		5	1.2	0.6
		6	2.3	1.3
		7	1.2	0.6
		8	1.8	0.5
		9	1.3	0.7

Because approximately one tonne of soil needed to be transported from Maui to Oahu, further testing of two selected low-Zn soils was done before bringing the bulk soil sample to Honolulu. This selection was based on the preliminary screening of soils listed in Table 1. Keahua (Transect no. 6, soil no. 3; a Mollisol) and Molokai (Transect no. 2, soil no. 4; an Oxisol) soils (Parra, 1983) were selected to further evaluate the feasability of using using one of them for these studies. Both of these sites were within the Hawaiian Commercial and Sugar Company (HC&S) plantation. Nine soil samples (about 5 m apart) were collected on a grid from both of these sites. Both 0-15 and 30-45 cm depth increments were sampled seperately. Samples were air-dried, crushed and screened through a 2-mm sieve. Their 0.1 N HCl extractable Zn contents were determined and presented in Table 2. Subsoils were lower in extractable Zn than the surface plow layer in most cases. Keahua soil was lower in HCl-extractable Zn and was more uniformally deficient in Zn supplies than the Molokai soil. This subsoil therefore was used to represent the Maui condition in pot studies.

b. Herbicide test

Since sugarcane plantations use herbicides for weed control, both soils were tested for residual effects of herbicide. This was believed necessary because herbicide-sensitive crops, like soybean and cowpea, were among the proposed test crops. Surface soil and subsoil from both sites, 0.5 kg portions in plastic cups, were suppied with 100 mg N/kg soil as urea, 200 mg P/kg soil as $Ca(H_2PO_4)_2 \cdot H_2O$, 100 mg K/kg

soil as K_2SO_4 and 10 mg Zn/kg soil as $ZnSO_4 \cdot 7H_2O$. Four

plants of corn, millet, soybean and cowpea were grown in both surface

and sub-soils (4 soils X 4 crops= 16 cups). The soil moisture in each

cup was brought to field capacity by daily adding deionized water. All

crops were grown for 4 weeks.

Whereas corn and millet grew normally in both surface and

sub-soils, cowpea and soybean grew normally in Keahua soil (both in

surface and in sub-soil) but only in sub soil of Molokai series.

Surface soil of Molokai series produced herbicidal effects on both of

these legume crops. Growth of seedlings was poor during the first few

days, after which leaves wilted, necrosis and other adverse symptoms

followed and ultimately legume seedlings died.

Because no herbicide effects were observed on the Keahua soil and

its sub-soil was uniformally low in HCl-extractable Zn, this soil was

selected for further Zn nutrition studies. The particular location

selected was HC&S field no. 405 growing one year-old sugarcane.

c. <u>Bulk soil collection and preparation</u>

Surface soil to a depth of 30 cm was removed from the sites before

collecting subsoils. Approximately one tonne of each soil was

collected in plastic bags and transferred to the greenhouse where it

was air dried, crushed, screened through a 6.4 mm sieve, and used to

fill appropriate-sized polyethylene-lined plastic pots as follows:

Crop	Soil/pot (kg, oven dry basis)
Corn	12.00
Sorghum	5.00
Millet	5.00
Rice	6.25
Wheat	4.50
Sugarcane	7.00
Soybean	5.00
Cowpea	5.00

The quantity of soil used was such that plants could be grown to maturity so that seed samples could be analyzed for Zn.

d. **Properties of soils**

Both soils were analyzed for pH (1:1 soil-water ratio, by weight), Organic matter, 0.1 N HCl-extractable Zn, 1 N NH_4OAc-extractable bases (Ca, Mg, K, and Na), and effective CEC. Field moisture capacity was determined by the mud ball method. P sorption isotherms for these soils were prepared according to the method of Fox and Kamprath (1970). These and some other pertinent soil properties are presented in Table 3. Phosphorus sorption capacity of Paaloa soil increased after liming the soil. Whereas the acid soil (pH 4.5) needed 770 mg P/kg soil for establishing standard soil solution P concentration of 0.2 mg P/L, the limed soil (pH 6.3) required 920 mg P/kg soil to attain this P concentration.

e. **Liming of Paaloa soil**

Whereas the pH of Keahua subsoil (6.6) seemed appropriate for the crops to be grown, the Paaloa sub-soil pH was so low (4.5) that Al

Table 3   Properties of soils used for greenhouse experiments.

Property	Paaloa soil	Keahua soil
Soil subgroup	Humoxic Tropohumult	Torroxic Haplustoll
Family	Clayey, oxidic, isothermic	Fine, kaolinitic, isohyperthermic
Soil pH (1:1)	4.5 (initial) 6.3 (limed)	6.6 (initial)
Olsen's P (mg/kg)	0.9 (subsoil)	4.8 (subsoil) 10.4 (surface soil)
P fertilizer req. for 0.2 mg P/L (mg P/kg soil)	770 (pH 4.5 soil) 920 (pH 6.3 soil)	460 (subsoil) 270 (surface soil)
0.1 N HCl-extractable Zn (mg Zn/kg soil)	0.7 (pH 4.5 soil) 0.6 (pH 6.3 soil)	0.5 (subsoil) 1.4 (surface soil)
Organic matter (%)	2.8 (subsoil)	1.2 (subsoil) 1.7 (surface soil)
NH_4OAc-extr. bases (cmol(+)/kg) Ca	(limed soil) 9.48 (95.8 % of B.S.)	3.76 (58.8 % of B.S.)
Mg	0.08 (0.81 % of B.S.)	1.89 (29.5 % of B.S.)
K	0.08 (0.81 % og B.S.)	0.14 (2.19 % of B.S.)
Na	0.26 (2.63 % of B.S.)	0.61 (9.53 % of B.S.)
Effective CEC (cmol(+)/kg)	9.90	6.40
Field capacity	38 % (subsoil)	30 % (subsoil)

B.S. -- Base saturation.
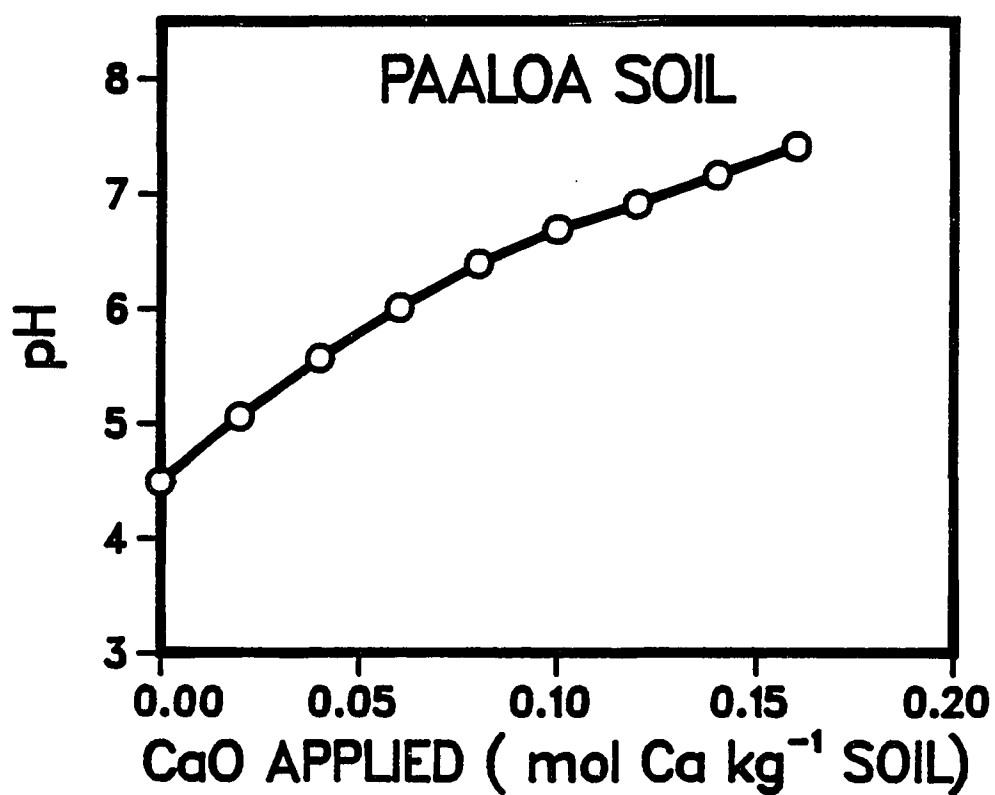
Fig. 2 Titration curve for the estimation of lime requirement
of Paaloa silty cla soil.

toxicity was assured. A lime curve was prepared (Fig. 2) from which a

lime recommendation of 0.07 mol $CaCO_3$/kg soil was derived. Lime

was thoroughly mixed into the Paaloa soil. The soil was equilibrated

at field water capacity for five weeks in the greenhouse during which

time its moisture content was maintained by daily additions of

deionized water. After every week, the soil of each pot was

transferred on a plastic sheet, mixed thoroughly and repoted. At the

end of a 5-week equilibration period, the soil pH was 6.3.

f. Basal fertilizers

Fertilizers were applied to adequately supply plants with macro-

and micro-nutrients, except Zn. All fertilizers were applied in

solution except for phosphate. The philosophy and details of basal

fertilizer application for growing plants to maturity in pots is given

below:

Nitrogen and K fertilizer requirements of various crop and soil

combinations were predicted on the basis of:

i) optimum internal element requirement of crops,

ii) optimum yield of crops,

iii) contribution from the soil, if any, and

iv) efficiency of fertilization.

Estimates of fertilizer requirements emphasized optimum

nutritional requirements of plants rather than fertilizer requirement

of soils. Soil requirements of fertilizer for pot-grown plants are

higher than field-grown plants. In this study all the grain crops were

grown to maturity to obtain seeds for Zn analysis. Therefore, enough

Table 4 Summary of blanket fertilizers applied in greenhouse experiments.

Element/ Source	Crops	Rate of application Paaloa soil	Keahua soil	Time of application
N as NH_4NO_3	Legumes	10 mg/kg	10 mg/kg	All before planting
	Non-legumes	900 mg/kg	900 mg/kg	1/4 before planting, 1/2 after 30 days, and 1/4 after 60 days
P as $Ca(H_2PO_4) \cdot H_2O$	Legumes	1250 mg/kg (0.5 mg P/L)	625 mg/kg (0.5 mg P/L)	All before planting
	Non-legumes	1050 mg/kg (0.3 mg P/L)	500 mg/kg (0.3 mg P/L)	All before planting
K as K_2SO_4	All crops	3.5 me/100 g	3.5 me/100 g	1/4 before planting, 1/2 after 25 days, and 1/4 after 50 days
Mg as $MgSO_4 \cdot 7H_2O$	All crops	1.90 me/100 g	–	All before planting
B as H_3BO_3	All crops	1.00 mg/kg	1.00 mg/kg	All before planting
Mo as Ammonium molybdate	All crops	1.00 mg/kg	1.00 mg/kg	All before planting

nutrients were added to produce mature plants. Fertilizer estimates were based on soil nutrient status , internal nutrient requirements of plants, and expected yields. Because the N and K fertilizer levels needed for pot grown plants were much higher than their optimum fertilizer levels in the field, both of these nutrients were applied in 3 to 4 installments to avoid adverse effects of high ionic concentration in the soil solution.

Phosphorus fertilizer requirements were determined by preparing P-sorption curves for both soils (Fox and Kamprath, 1970). Higher than normal external P requirements were assumed because of barrier effects in pots (Fox and Kamprath, 1970). Soil solution concentration of 0.3 mg P/L was selected for grasses (cereals and sugarcane) and 0.5 mg P/L for legumes.

Only the Paaloa soil needed a Mg application because its native extractable Mg was low (0.0004 mol Mg/kg soil, which was only 0.8 % of effective CEC). To raise the Mg status of this soil to 20 % of effective CEC, 0.01 mol Mg/kg soil was applied as $MgSO_4 \cdot 7H_2O$ in solution form.

As a precautionary measure, B and Mo were applied at the rate of 1 mg/kg soil to avoid possible deficiency problems. Boron was applied as boric acid and Mo as ammonium molybdate in solution by mixing with soil before seeding. A summary of blanket fertilizer applications for various soil and crop combinations is presented in Table 4.

g. Inoculation of legumes

Ample N fertilizer was applied to non-leguminous crops, but only

starter N was applied for legumes. Before sowing, seeds of soybean and cowpea were inoculated with rhizobium strains, USDA-110 for soybean and CB-756 for cowpea, obtained from the NifTAL Project of the University of Hawaii.

h. Zinc treatments

Because the subsoils were exceedingly low in HCl-extractable Zn, substantial yield responses of various crops were expected with Zn fertilization. Five levels of Zn: 0, 1, 3, 9, and 27 mg Zn/kg soil, were applied in the form of $ZnSO_4 \cdot 7H_2O$. This wide range of Zn rates was used in expectation of a Mitscherlich type response curve, at least for the most responsive crops.

Zinc was applied in solution and was mixed thoroughly with the soil at the time of blanket fertilizer application before seeding.

i. Crop species, varieties and plant population

The eight crops included in this study are listed below:

Crop	Botanical Name	Cultivar
Corn	Zea mays L.	H-652
Sorghum	Sorghum bicolor (L.) Moerch.	T-E Y-101-R
Millet	Pennisetum americanum (L.) K. Schum.	RMP-1
Rice	Oryza sativa L.	M101
Wheat	Triticum aestivum L.	Anza
Sugarcane	Saccharum officinarum L.	73-1541
Soybean	Glycine max (L.) Merr.	Davis
Cowpea	Vigna unguiculata (L.) Walp.	California Black Eye no. 5 (Burpee)

The number of plants grown per pot was based on population densities in field situations and the amount of soil used in the pots. Corn was taken as a standard to calculate the planting density of other crops. A few extra seeds of each crop were planted; plants were thinned to the desired number per pot a few days after germination.

One-eye seed pieces of sugarcane, 2 to 3 inches long, were treated with a fungicide before planting. The seed pieces were submerged for 20 minutes in 3.42 g Benlate/3 gallons water heated to 52° C, a procedure used by sugarcane plantations. Seed pieces were placed in a single layer, eyes facing upward, in plastic trays on thoroughly wet paper towels and covered with wet paper towels. The trays were covered with white butcher paper to minimize evaporation and placed in the greenhouse. Paper towels were re-moistened daily. Shoots began to grow after 4 to 5 days. Germinated seed pieces were transferred to pots containing soil which had been fertilized and irrigated the previous day. The details of planting density and stage of plant sampling is presented in Table 5.

j. Water control/irrigation

Field capacity moisture level of both soils was determined by a mud-ball method. The pots were irrigated to field capacity and seeds or sugarcane sets were planted after a few days. Moisture was brought to field capacity once each day(when plants were small) or twice each day (water requirement increased with plant growth) bringing pots to a calculated weight with deionized water to replace water lost by

Table 5   Planting density and stage of plant tissue sampling in
          greenhouse experiments.

Crop	Total plants (per pot)	Seedlings harvested (per pot)	Diagnostic tissue	Plants harvested at maturity (per pot)
Corn	2	1	Ear leaf	1
Sorghum	4	2	Flag leaf	2
Millet	5	2	Flag leaf	3
Rice	10	4	Ear leaf	6
Wheat	10	4	Ear leaf	6
Sugarcane	1	–	Primary shoot* (75 day age)	1* (90 day age)
Soybean	6	–	Most recent fully expanded leaf	6
Cowpea	2	–	Most recent fully expanded leaf	2

* Leaf sheath nos. 3, 4, 5, and 6 from primary shoot (after 75
   days growth) and two leading tillers (after 90 days growth) were
   sampled according to Clements' (1980) crop logging procedures.
   In addition, the middle one-third of first-visible dew-lap leaf,
   excluding midrib, was also sampled.

73
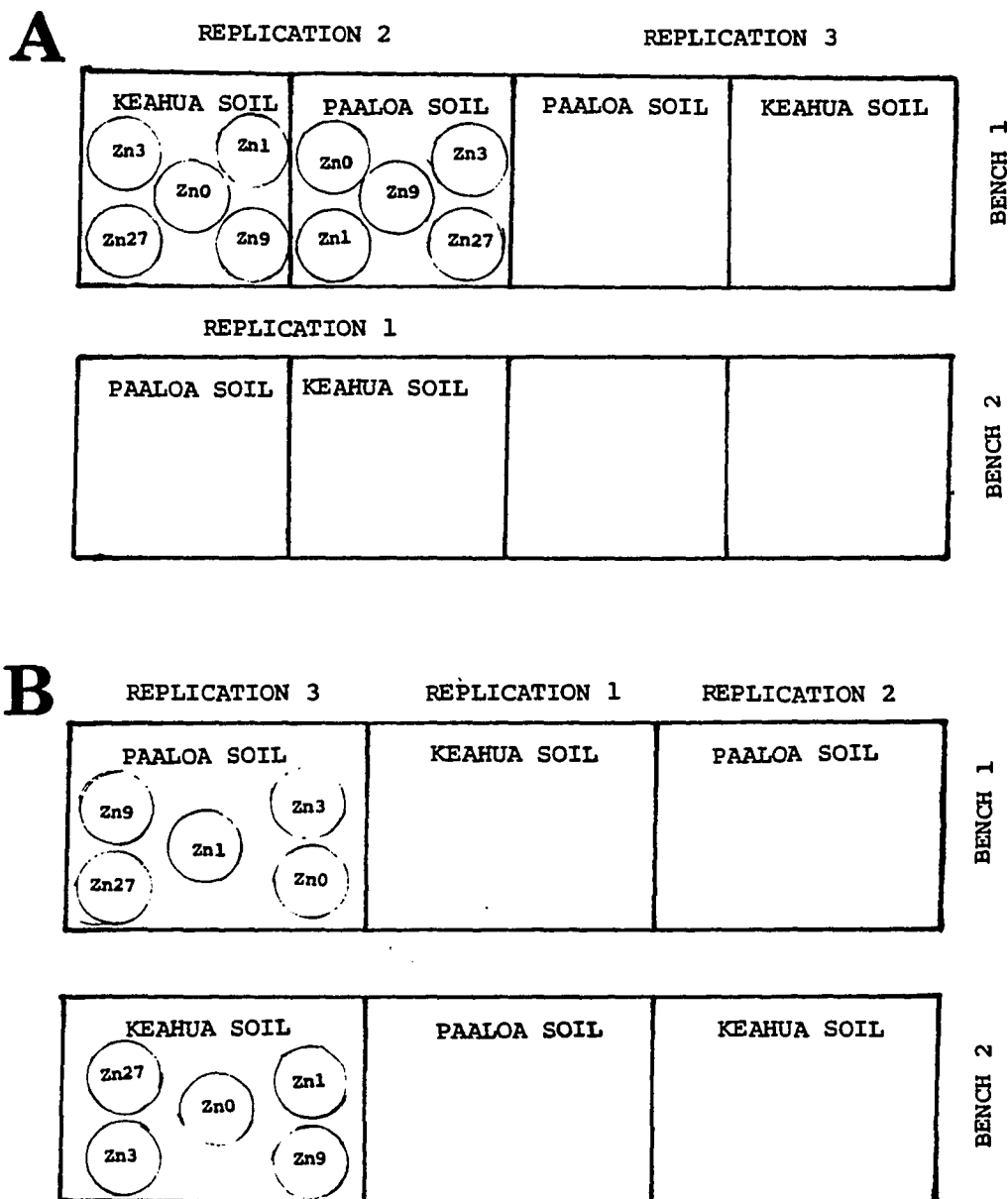
Fig. 3 Arrangement of pots in the greenhouse according to split plot design: (a) sorghum, millet, rice, wheat, sugarcane, soybean, and cowpea, 4.5 to 7.0 kg soil per pot; (b) corn, 12.0 kg soil per pot.

^{e}vapo-transpiration. Because of high water consumption by corn, water was added three times a day from silk initiation to maturity.

k. Arrangement of pots

The effects of Zn application was considered more important than differences between soils; therefore, the pot arrangement was a split plot design, treating the two soils as main plots and the five Zn levels as sub-plots. Treatments were replicated three times, except that rice, wheat and sugarcane were in two replications.

The experimental layout in the greenhouse is presented in Fig. 3. Replications were arranged across the length of the tables. This was done to partition the gradients of temperature, light, and wind in the greenhouse. Thus an effort was made to keep different replications under more or less similar temperature and light conditions.

Frequently the magnitude of microclimate variation in the greenhouse is much greater than in the field. Regardless of all precautions, the pots of the same replication were suspected of recieving different intensities of light, temperature, and wind, etc. To minimize this hazard, the pots within a replication were rerandomized frequently following the procedure of Radjagukjuk et al. (1980). Space allocation to different replications was exchanged frequently.

2. Potassium and/or Sodium Induced Zinc Deficiency
in Sugarcane

A pot experiment was conducted to study the effect of K and Na

salt on Zn uptake by sugarcane. Only one soil, Keahua sub-soil, was

used for this experiment. The sugarcane variety used, 73-1541, was

known to be affected by Maui growth failure at Hawaiian Commercial &

Sugar Company (HC&S) plantation on Maui. Management practices and

harvesting procedures were the same as in previous greenhouse studies.

Basal fertilizers, however, did not include K. Three levels of Zn; 0,

3 and 27 mg/kg, were superimposed on three increasing levels of K;

0.012, 0.035 and 0.105 mol K/kg. The same three levels of Zn were also

superimposed on a combination treatment, Na 0.07 mol and K 0.035

mol/kg, respectively. This experiment, in two replications, was

arranged in the greenhouse in a randomized complete block design.

B. Field Investigations

1. Soil and Wheat Grain Sampling in Colorado

Colorado State University Agricultural Extension Service and

Agricultural Experiment Station conduct wheat demonstration-research

trials at experiment stations and in farmers' fields throughout wheat

producing areas of eastern Colorado. Thirty-two of the 1983-84 winter

wheat locations, in eastern Colorado were sampled in 1984. Figure 4

presents the sample locations.

A single fertilizer treatment (30-0-0, 40-0-0, or 60-0-0) in four

replications was sampled at each location. Soil samples were collected

from two depths, 0-15 cm and 30-45 cm. Surface samples were intended

to reflect the prevailing nutrient status including management effects,

while deeper samples were less likely to be affected by soil
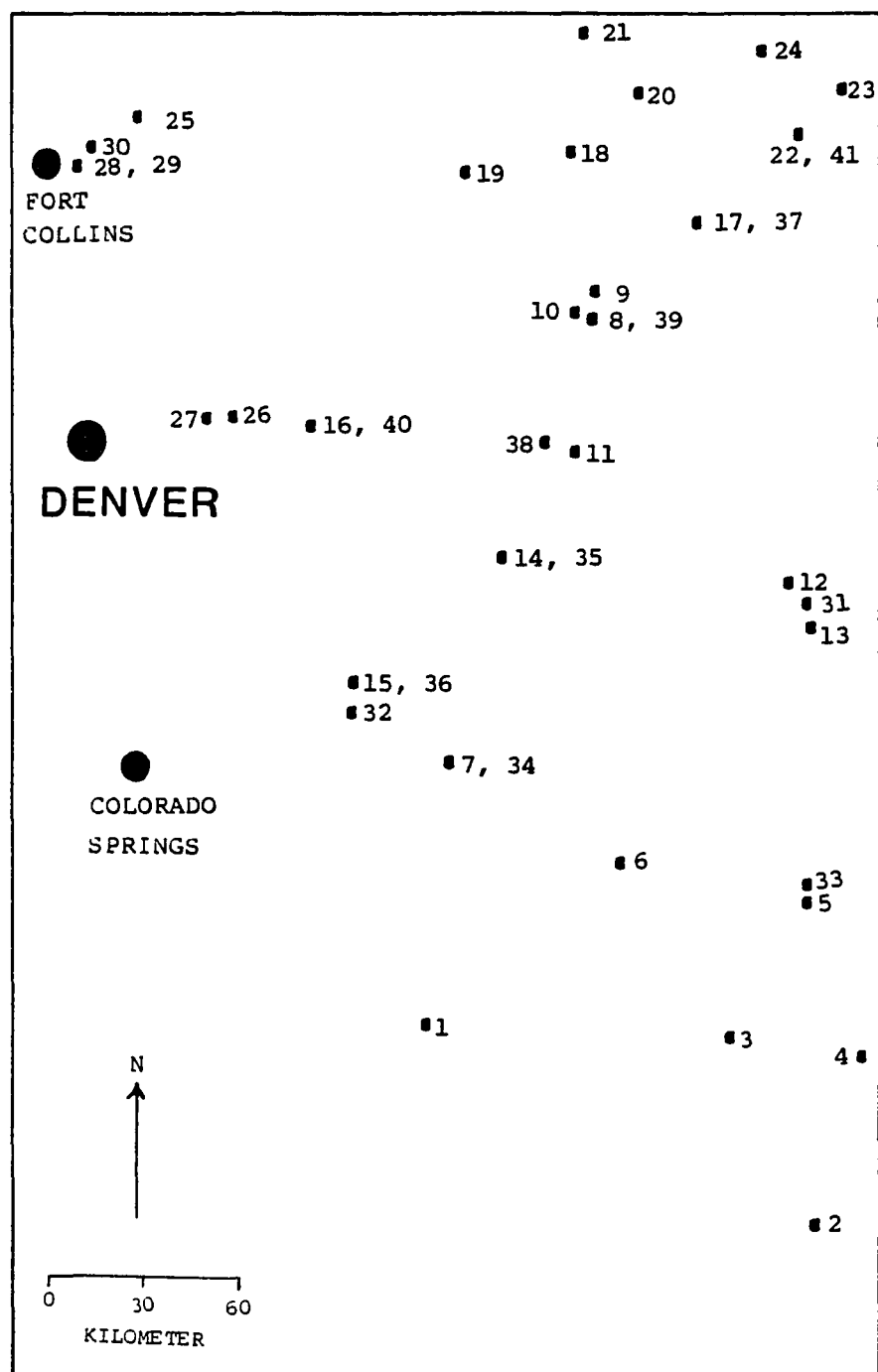
Fig. 4 Locations and site numbers of 41 soil and wheat seed
        smapling sites, eastern Colorado.

management. The deeper soil sample should also indicate the soil condition that will develop as erosion or earth moving exposes subsoil material at the surface. Four soil cores about 1 m apart were taken from each replication using a stainless steel auger. Soil from a common depth was composited and soil samples were placed in plastic-lined paper bags. Site locations were marked on a Colorado state map and on individual experiment layout maps. Soil samples were brought to the Colorado State University Soil Testing Laboratory where they were air dried, crushed with an automatic grinder equipped with a porcelain mortar and screened through a 2-mm stainless steel sieve. Soil moisture was determined on each soil sample.

At maturity, wheat seeds were sampled from all locations where soil samples had been taken. About 10 to 15 heads of wheat were collected from plants growing next to soil sample points. Wheat heads were brought to Colorado State University where they were threshed and whole grains used for chemical analysis.

In addition to the 32 sample sets from 1983-84 experiments, another nine soil and grain samples, from 1982-83 field experiments, were obtained from the Colorado State University Soil Testing Laboratory. The 1982-83 experiments were similar to those in 1984 as described above except that 1983 samples were composites of four replications rather than samples of individual replications.

Soil classification information (Soil Survey Staff, 1975) is presented in Appendix 1.

2. Soil and sugarcane tissue sampling on the Island of Maui

Soil and plant tissue samples from 100 locations were sampled on
the Island of Maui. Two areas were sampled for this study; Central
Maui and West Maui (Fig. 5). Central Maui is mostly comprised of the
isthmus that connects West and East Maui. Elevations range from 5 to
303 m and the topography is gently sloping to nearly level. The area
is used mainly for sugarcane. Much of the isthmus is covered with
alluvium and aeolian materials from the windward coast. The margin of
West Maui is a moderately sloping, smooth, narrow belt with a few
gulches decending from an ancient mountain. Basal ground water occurs
across the isthmus and along the coast of West Maui (Foote, et al.,
1972).

The Central Maui areas sampled extend from Maalaea Bay in the
west, near Kihei, to Maliko Gulch, east of Hamakupoko, in a west to
east direction, and from Hamakua to north of Puunene in the south to
north direction. A total of 70 sites were sampled in this area (Fig.
6, 7). Elevations in the area sampled range from 5 m near the ocean to
304 m on the north-west slope of Haleakala. Average rainfall ranges
from 348 to 1212 mm, with a mean of 613 mm. Rainfall is greatest in
the north-east (wind-ward) side of the plantation. Fields in the
south-west (toward Maalaea Bay) receive less rainfall. There is a
trend of increasing rainfall from west to east and weaker gradient from
south to north. Mean annual temperature varies only from 21 to
25°. The area sampled, 1500 hectares, was entirely planted to
sugarcane by Hawaiian Commercial and Sugar Company (HC&S). This study

ISLAND OF MAUI, HAWAII

Pioneer Mill

WEST MAUI

MOUNTAINS

Kaanapali

Lahaina

Wailuku

Paia

Kahului

HC & S

Hana

Makena

HALEAKALA
NATIONAL PARK
Summit Elevation 10,025

N
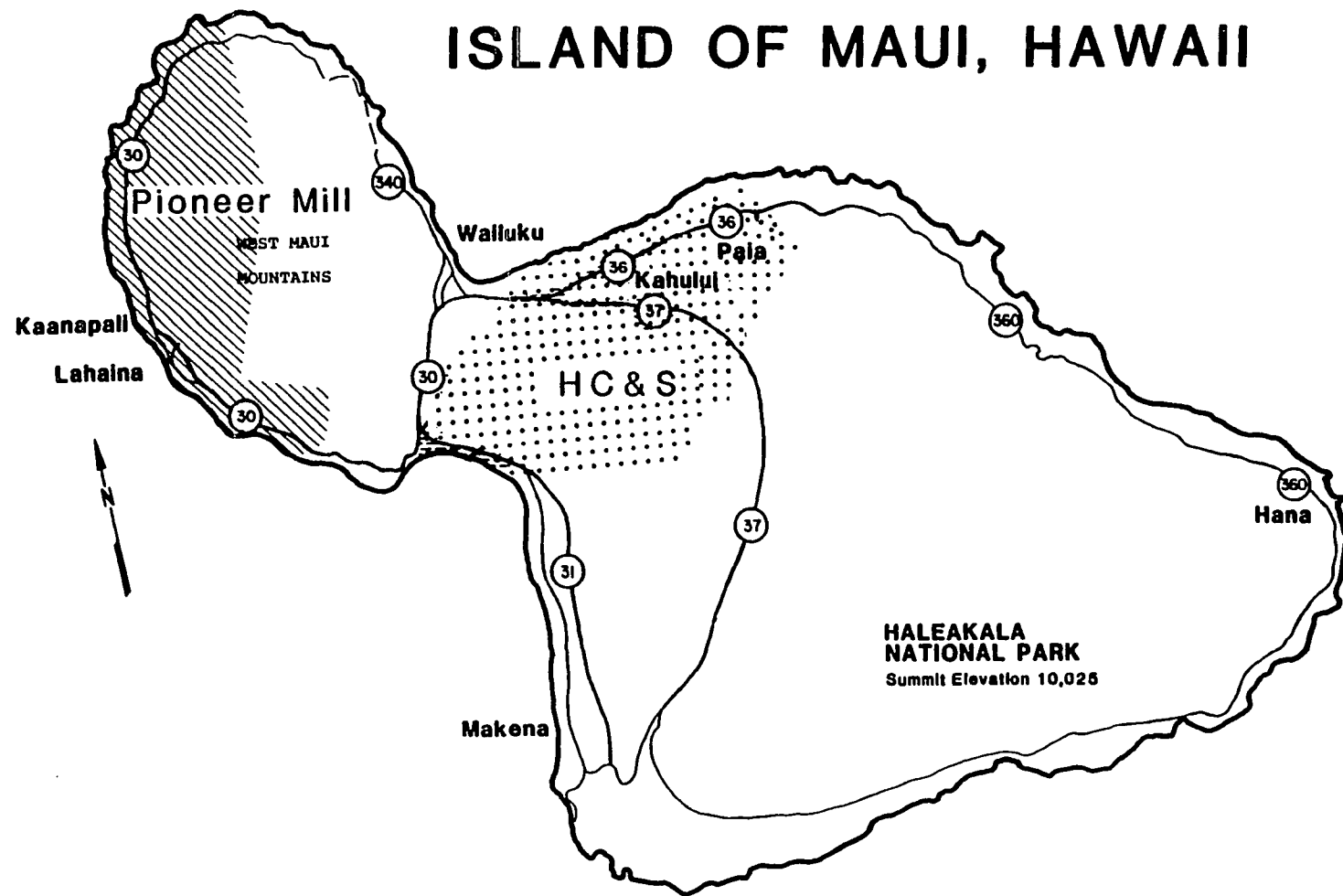
Fig. 5 Location of two sugarcane plantations on the Island of Maui.
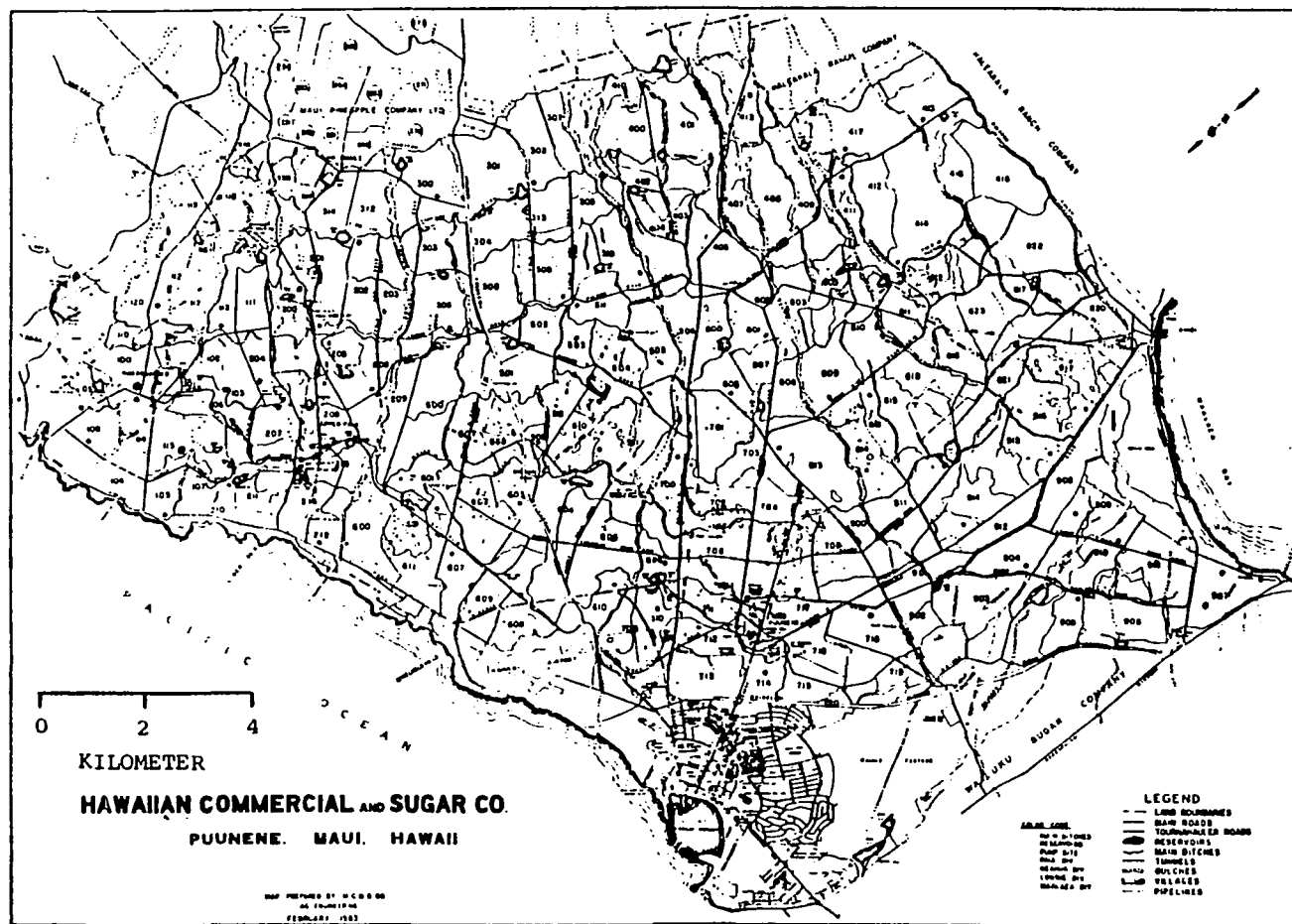
Fig. 6 Plantation map of Hawaiian Commercial & Company, Maui, Hawaii.
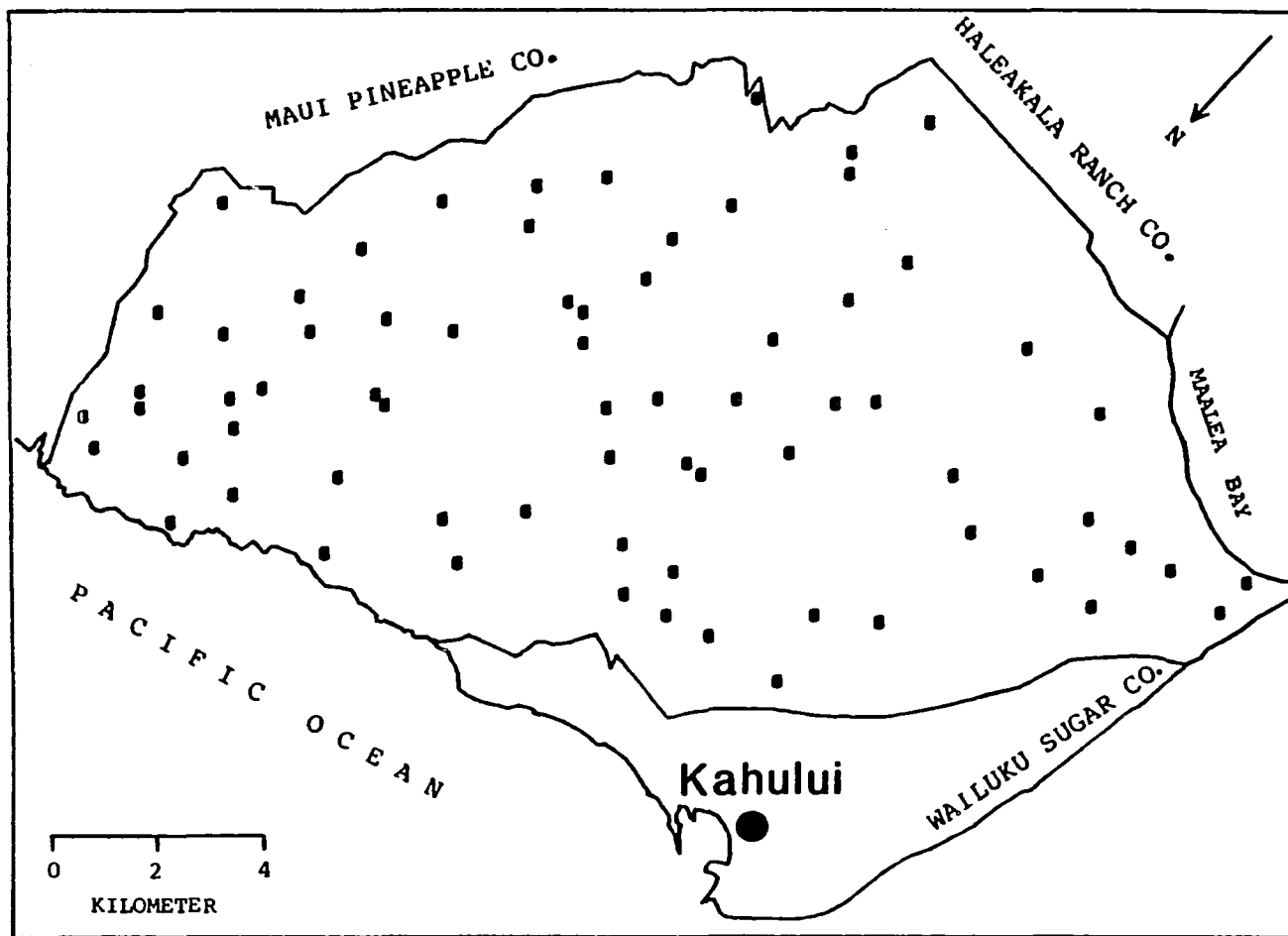
Fig. 7 Locations of 70 soil and sugarcane tissue sampling sites, HC&S, Maui, Hawaii.

included 19 soil series belonging to 5 different soil orders: Inceptisols, Entisols, Mollisols, Oxisols, and Ultisols. Most soils in the west of the plantation are Mollisols. In the east, soils are orders Ultisols and Inceptisols. Some Oxisols lie in the middle of the plantation. Soil descriptions for Maui Island are given in the Soil Survey of Islands of Kauai, Oahu, Maui, and Lanai, State of Hawaii (Foote, et al., 1972) and their classification (Soil Survey Staff, 1975) is given in Appendix 2 and 3.

The West Maui area sampled was entirely planted to sugarcane by Pioneer Mill Company. It extended from Honoakiilani highway, near Kaanapali, in the west to Kealii gulch in the east in a west to east direction, and from north of Papalaua to Kahana in the south to north direction. Thirty sites were sampled in this area (Fig. 8a, 8b). Elevation in the area sampled ranges from 5 to 385 m, and the average rainfall ranges from 152 to 1194 mm, with a mean of 520 mm. The area included 13 soil series belonging to three soil orders: Mollisol, Oxisol, and Ultisol (Appendix 3). One sample location did not have well developed soil; it is listed as 'stony alluvial land' (Foote et al., 1972). Soils along the Pacific Ocean coast are mostly Mollisols alongwith some Entisols. At high elevations, near Lahaina and Kaanapali, soils are Ultisols. Some Oxisols are located at moderate slopes.

Sampling was done in September-October 1984. Soil and sugarcane plant tissues were sampled from each site at the same time. The criteria and procedure used for sampling are detailed below:

Fig. 8a Plantation map of Pioneer Mill Company, Maui, Hawaii.
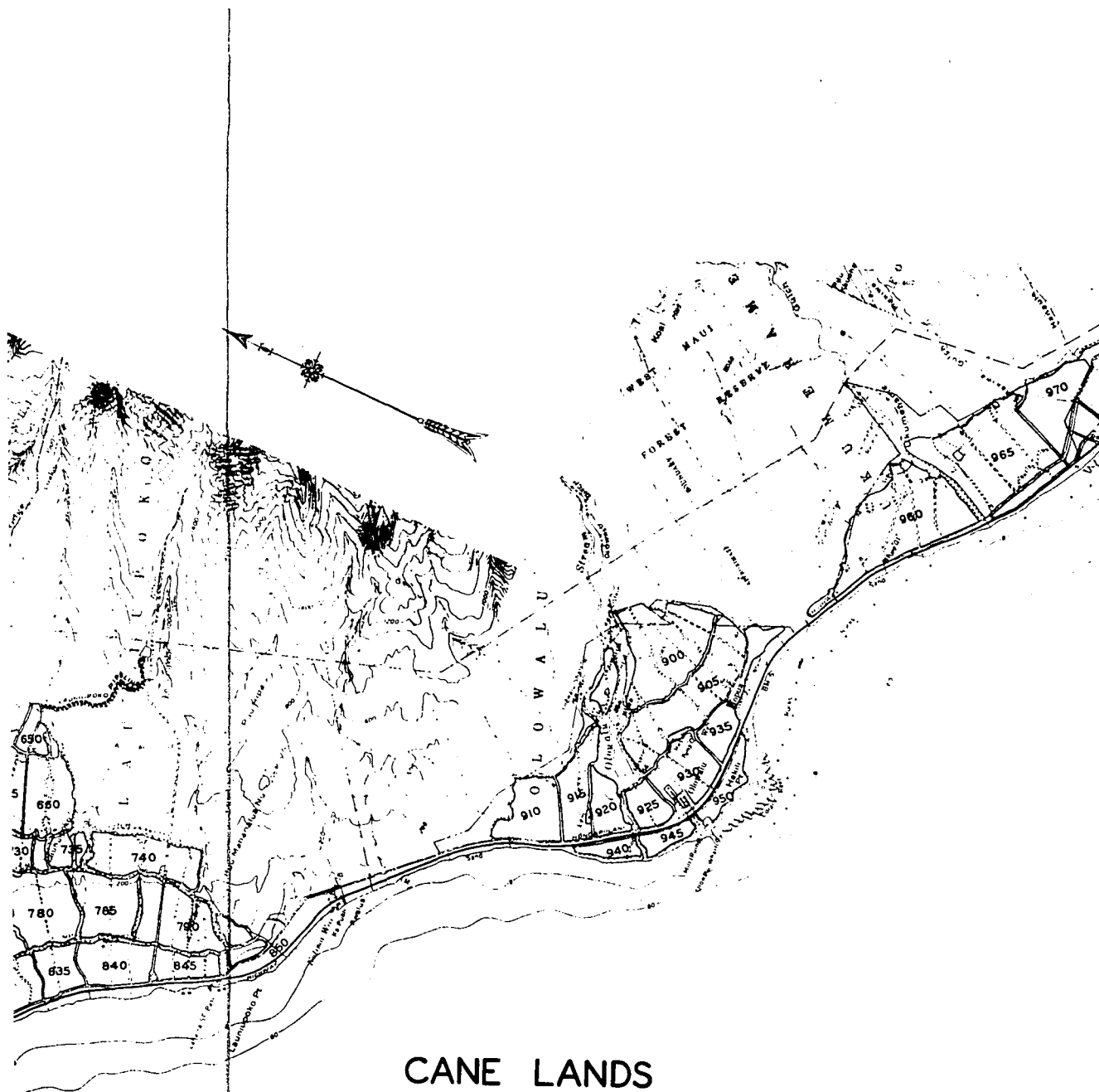
CANE LANDS
PIONEER MILL CO., LTD.
LAHAINA, MAUI, HAWAII

COMPILED FROM U.S.G.S QUADRANGLES

Scale: 1"=4000'
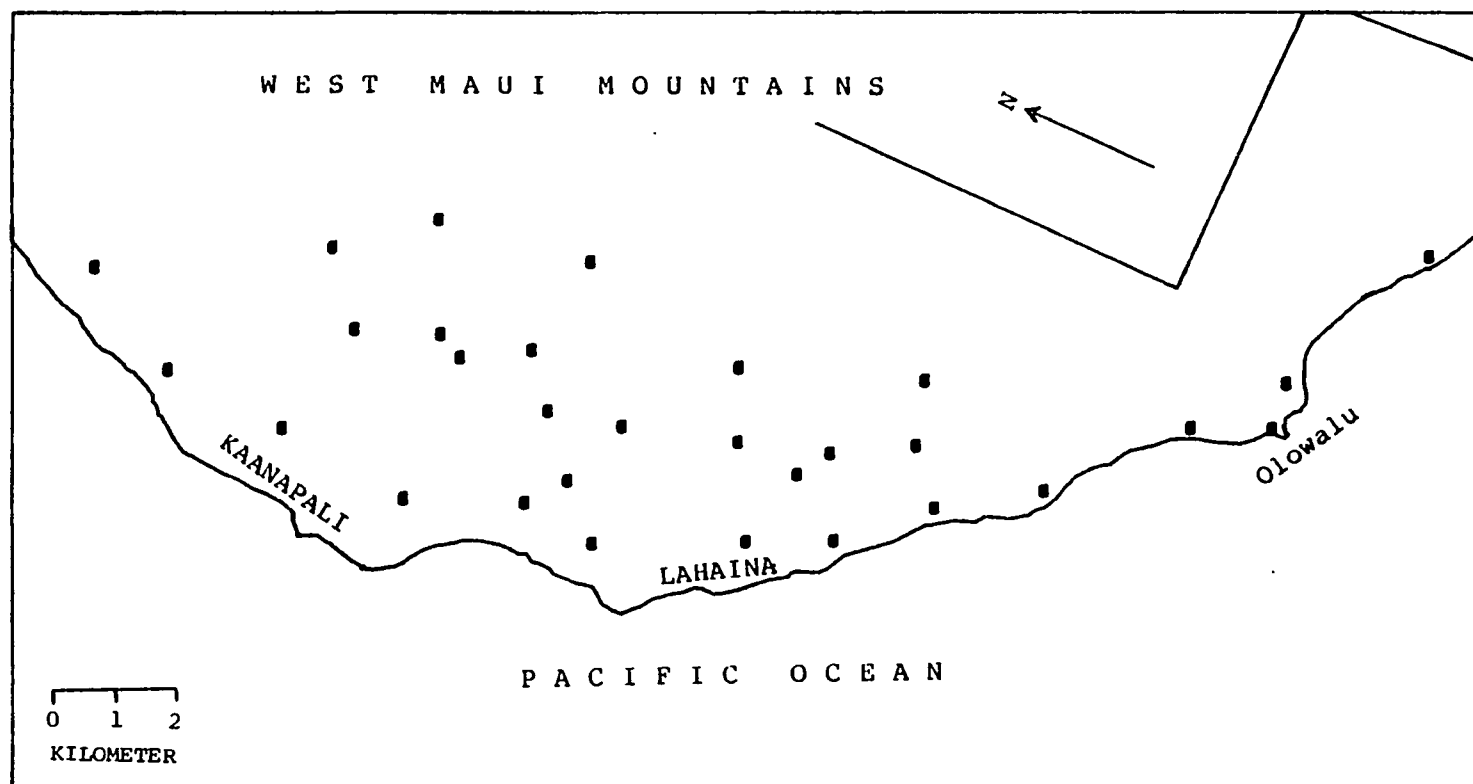
Fig. 8b   Locations of 30 soil and sugarcane tissue sampling
sites, Pioneer Mill Company, Maui, Hawaii.

a. Soil sampling

Soil sampling was based on the following considerations:

1) Sample on a grid (or along transects) which traverse a range of one or more soil forming factors such as temperature, rainfall, parent material, rainfall or elevation.

2) Prefered sample sites were fields where crop age was in the range of 4 to 16 months.

3) Samples included soils on which sugarcane was known to be affected by Maui growth failure.

4) Sampling was done according to soil classification information – that is, attempts were made to sample within major soil mapping units.

Soil from two depth increments, 0 to 15 cm and 30 to 45 cm, were collected at each site. Three holes, about 3 to 5 m apart in a trianglar orientation, were dug with a soil auger at each site. Soil of each depth from all the three holes was mixed and composite sub-samples were placed in plastic bags. Location and other important features of the sampled location were recorded on individual field maps provided by the sugarcane plantations. Soil samples were brought to the University of Hawaii at Manoa, air dried, and screened through a 2-mm stainless steel screen. Moisture contents of soil sample were determined.

b. Plant tissue sampling

Sugarcane plant tissues were sampled from all of the locations from which soil samples were collected. The desired considerations for

collecting plant tissue were:

1) Crop age to range from 4 to 16 months at the time of sampling (actual crop age ranged from 3.6 to 19.2 months).

2) Variety to be one of those predominantly grown by the plantation or a cane variety, such as 70-0144, known to be affected by Maui growth failure.

3) Samples to be from a representative part of the field.

Tissue samples were collected on the day of soil sampling - or at the most, two to three days thereafter. Tissue sampling was done by following Clements' (1980) recommendations for crop logging. Five representative cane stalks were selected, each from a differnt hill growing close to the three holes from which soil was sampled. These stalks were cut below leaf sheath number 8. Field number, sample location in the field, crop age, and cane variety were recorded. All plant samples were taken before 9:00 AM and brought to a laboratory for immediate processing. The middle one-third of the first visible dew-lap leaf, which was leaf no. 4 in most cases, was sampled from each of the five cane stalks. Leaf numbering was such that leaf sheath no. 1 was nearly as long as leaf sheath no. 2 and both of these were drastically smaller in length as compared with leaf sheath nos. 3, 4, 5, and 6. Leaf blades were stripped from the midrib, washed with distilled water and then oven dried at 70° C for 24 hours. Four leaf sheaths (no. 3, 4, 5, and 6) were severed from the five stalks. After recording their fresh weight, the sheaths were chopped into small pieces and dried in an oven at 70° C for 24 hours to calculate

their moisture contents. Green weights of the 20 leaf sheaths, 4 from each stalk, (the Growth Index) was recorded (Clements, 1980).

Dry leaf blades and leaf sheath samples were brought to the Univeristy of Hawaii at Manoa and ground for analysis in a Wiley mill fitted with stainless steel cutting parts.

C. Laboratory Methods

1. Soil Analysis

a. Electrical conductivity and pH

Soil pH and electrical conductivity (EC) were measured in a 1:1 (w/v) soil:water suspension (Soltanpour and Workman, 1981). Twenty g of soil (oven dry basis) was placed in 50 ml plastic beakers and 20 ml of distilled water was added. The mixtures were stirred vigorously and equilibrated with occasional stirring for two hours. Conductivity of suspensions was recorded with a conductivity meter.

Soil pH was measured on the same suspensions using a glass electrode. Suspensions were stirred just prior to immersing of the electrodes.

b. Free lime

Two g soil (oven dry basis) was placed into 125 ml Erenmyer flasks. Standard H_2SO_4 (about 0.4 N) was added from a burette until bubbling stopped. At least 2 ml acid was added in excess and the total volume of acid used was recorded. About 50 ml of distilled water was added to each flask. The mixture was boiled for 3 to 5 minutes, and then cooled to room temperature. Two drops of phenolphthalein

indicator were added and back titrated with standard NaOH (about 0.4 N) added until the first faint pink color appeared. The volume of NaOH used was recorded.

Calculation: % Lime= {[(ml acid x N) - (ml base x N)]

x 0.05 x 100} / wt. of soil.

c. Lime requirement

Eight 50 g portions of the Paaloa soil were placed in glass beakers and increasing levels of CaO, ranging from zero to 32 cmol(i)/kg, were applied. Enough deionized water was added to attain a soil:water ratio of 1:1 (w/v) and soil suspensions were mixed vigorously twice a day. Suspension pH remained constant after 7 days. A plot of soil pH versus me CaO added/100 g soil was constructed. (Fig. 2) and the lime requirement of the Paaloa soil was read from this curve.

d. Soil texture

Particle size analysis was done by the hydrometer method (Day, 1965). 50 g soil (oven dry basis) was placed in 250 ml glass bottles. 100 ml of 5 % calgon solution was added and bottles were shaken on a reciprocating shaker overnight. Soil suspensions were transferred into glass cylinders and distilled water was added to the mark. Soil suspensions were stirred with a plunger and the temperature was noted. Suspensions were again stirred thoroughly with a plunger for about 40 seconds, finishing with 2 or 3 slow and deliberate strokes. Time was recorded immediately. A hydrometer was lowered carefully into the suspension, and read at exactly 40 seconds. After removing the

hydrometer carefully, the suspensions were left undisturbed until a second hydrometer reading was taken at 120 minutes. A temperature reading was also taken at that time. The USDA textural triangle was used to determine the textural class.

e. Organic matter

Soil organic matter was determined colorimetrically (Graham, 1959). 1.00 g soil (oven dry basis) was placed in 250 ml wide mouth flask. 10 ml of potassium dichromate solution (49.03 g potassium dichromate dissolved in 1 liter of distilled water) was added to each flask and flasks were swirled gently after which 20 ml concentrated sulfuric acid was added rapidly and the flasks were swirled immediately for 5 to 10 seconds. The mixture was allowed to stand for 10 minutes and then 100 ml distilled water was added to each flask. After a little swirling, flasks were allowed to stand undisturbed overnight (>16 hours, <24 hours). Then supernant was carefully poured into a colorimeter funnel tube so as not to disturb the sediment and color intensity was read on a spectronic 20 at 610 nm adjusted to 100 percent transmittance with distilled water. A standard curve was prepared by using different known concentrations of organic matter (obtained from Soils Department, University of Missouri, Columbia, Mo). For the zero point of the standard curve, 20 ml of concentrated sulfuric acid was added to 10 ml of potassium dichromate and mixed well. Then 100 ml of distilled water was added to this before reading on the colorimeter.

f. Exchangeable bases

Calcium, Mg, Na, and K were extracted with 1 N ammonium acetate

adjusted to pH 7.0. Five g soil portions were placed in 250-ml
Erlenmeyer flasks. One hundred ml of 1 N ammonium acetate were added
and samples were shaken for half an hour on a reciprocating shaker.
Samples were then filtered through Whatmatman no. 42 filter paper.

Calcium and Mg in the filterate were determined by atomic
absorption spectroscopy and Na and K were determined by flame emmission
spectroscopy.

g. Phosphorus sorption curves

The procedure for determining P sorption curves was that of
Fox and Kamprath (1970). Three-gram samples of soil, in 30 ml of
0.01 M $CaCl_2$ containing graded ammounts of $Ca(H_2PO_4)_2$, were
equilibreted in 50 ml plastic centrifuge tubes shaken longitudinally in
a reciprocating shaker for two 30-minute periods daily for 6 days. Two
drops of toluene per sample were added to retard microbial growth. The
equilibrated samples were centrifuged in a super-speed centrifuge at
15000 rpm for 15 minutes. An aliquot, usually 10 ml, was used to
determine P in the supernatent solution (P in solution) (Murphey and
Riley, 1962). Phosphorus which disappeared from solution was
considered to have been sorbed (P-sorbed). Phosphorus sorbed was
plotted against P concentration in the supernatent solution (Fig. 9).

h. NaHCO_3-extractable phosphorus

Sodium bicarbonate-extractable P was determined by the procedure
of Banderis et al. (1976). Five g soil portions (oven dry basis) were
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.
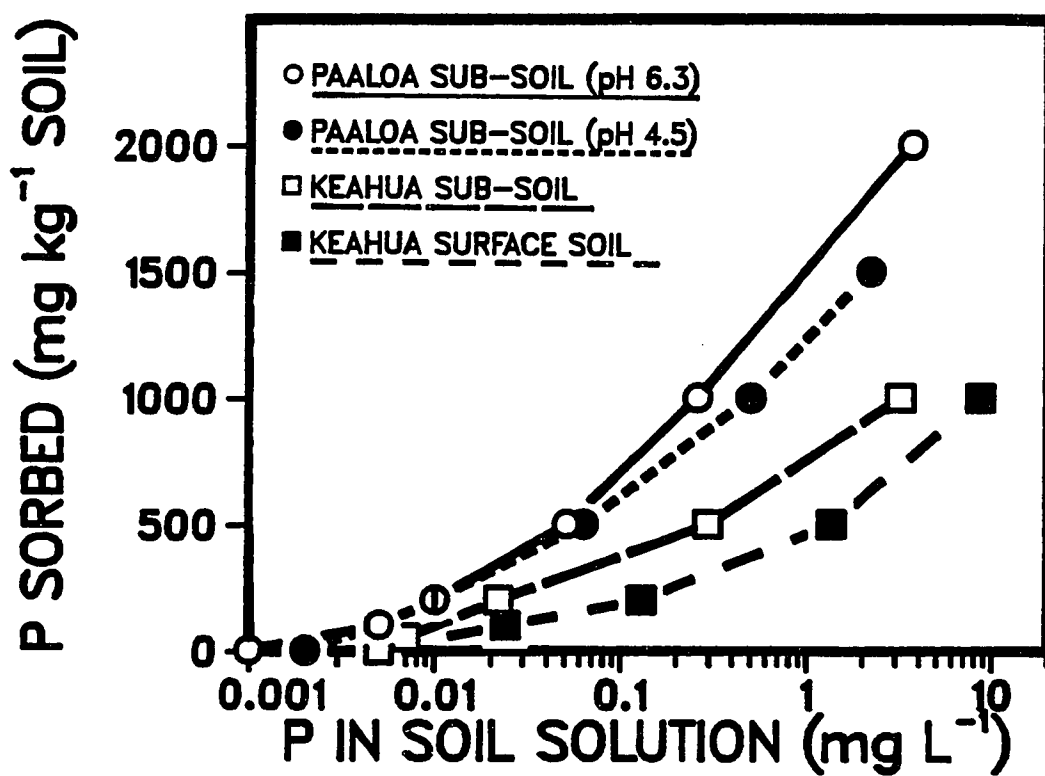
Fig. 9   Phosphate sorption curves for Paaloa and Keahua soils.

The solutions were filtered through Whatman no. 42 filter papers and the optical density of the aliquots was read at 840 nm to correct for color in the extracts. One to two ml aliquots were used for actual color development (Murphy and Riley, 1962) and optical density read again at 840 nm. For each ml of aliquot, one ml of 0.5 N sulfuric acid was added so that the pH of the system sould be correct for color development.

i. **KCl-extractable manganese**

Method for soil extractable Mn was that of Fox et al. (1985). It employed 1 M KCl at a ratio of 1 g soi per 25 ml of extractant. Shaking was for 30 minutes followed by centrifugation and filtration. There was no washing with KCl. Manganese in the filtrates was determined by atomic absorption spectrophotometry.

j. **HCl-extractable zinc and copper**

The method of extraction was similar to those of Wear and Sommer (1948), Tucker and Kurtz (1955), Kanehiro and Sherman (1967), and Baker and Amacher (1982). To 3.00 g soil (oven dry basis) in a 50 ml centrifuge tubes, 30 ml of 0.1 N HCl was added. The tubes were stoppered with plastic stoppers (or with parafilm covered rubber stoppers) and samples were shaken longitudinally for 45 minutes on an end to end shaker at 180 cycles per minute. After removing the stoppers, the tubes were centrifuged for 5 minutes at 10,000 rpm. The supernatant was filtered through Whatman no. 42 filter paper. Zinc and Cu in the extracts were analyzed by atomic absorption spectrophotometry.

If soils contained free carbonates or if pH of extracts by the above method was $\geq$ 2.0, two modified extraction procedures were tried. In the first modification, referred to as the sequential extraction procedure by Baker and Amacher (1982), a 2.00 g sample of soil in 50-ml centrifuge tubes containing 20 ml of 0.1 N HCl were shaken for 5 minutes. The suspensions were centrifuged and filtered into 100-ml volumetric flasks. The extracion was repeated two or more times until the equilibrium pH was < 2.0. The combined extract was made to volume, and analyzed for Zn and Cu by atomic absorption spectrophotometry. The second modification consisted of placing 3.00 g soil (oven dry basis) in 50-ml centrifuge tubes wet with about 10 ml of distilled water and neutralizing free carbonates by adding an equivalent amount of approximately 2 N HCl from a burette with occasional shaking. Some soils contained $CaCO_3$ particles that reacted slowly. Therefore, soils with added HCl were left overnight for completion of the reaction. Then standard 2.00 N HCl, equivalent to 30 ml of 0.1 N HCl, was added to each tube. Additional water, if needed, was added to these tubes to bring the final water volume to 30 ml (1:10 soil:water ratio). Tubes were stoppered and shaken for a single extraction of 45 minutes. Suspensions were centrifuged, filtered and extracts analysed for Zn and Cu by atomic absorption spectrophotometry.

k. DTPA-extractable soil zinc

None of the HCl extraction procedures proved satisfactory for soils containing free carbonates. These soils were, therefore, also

extracted by the DTPA (Diethylenetriaminepentaacetic acid) method

(Lindsay and Norvell, 1978). The extractant contained 0.005 M DTPA,

0.01 M calcium chloride, and 0.1 M triethanolamine adjusted to pH 7.3

with HCl. To 10 g of soil (oven-dried basis) placed in 125-ml conical

flasks, 20 ml of DTPA extraction solution was added. Flasks were

covered with stretchable parafilm and shaken for 2 hours on a

horizontal shaker at 180 cycles per minute. The suspensions were

filtered through Whatman no. 42 filter paper and analyzed for Zn by

atomic absorption spectrophotometry.

1. Macro- and micro-nutrients by ammonium bicarbonate-

   DTPA extraction procedure

The ammonium bicarbonate-DTPA (AB-DTPA) soil test was developed to

simultaneously extract P, K, Zn, Fe, Cu and Mn (Soltanpour and Schawab,

1977; Solatanpour and Workman, 1979). The extractant was prepared by

dissolving 1.97 g of DTPA in 800 ml of distilled water. Approximately

2 ml of 1:1 NH_4OH was added to facilitate dissolution. After the

DTPA was dissolved by using a magnetic stirrer, 79.06 g NH_4HCO_3

was added and stirred gently with a glass rod until the salt was

dissolved. The pH was adjusted to 7.6 using either NH_4OH or HCl

and final solution volume solution was brought to 1 liter with

distilled water.

10.00 g soil portions (oven dry basis) were placed in 125-ml

polyethylene Erlenmeyer flasks. 20 ml of extraction solution was added

to each flask and shaken for 15 minutes on a reciprocating shaker at

180 cycles per mintuute. The flasks were kept open. Suspensions were

filtered through Whatman no. 42 filter paper. Concentrated HNO_3 (0.25 ml) was placed in 10 ml beakers. Then 2.5 ml of extracts were added carefully to these beakers and mixed on a rotary shaker for 15 minutes to drive off CO_2. Extracts were then analysed for Zn, Cu, Fe, Mn, P, and K by inductively coupled plasma atomic emission spectrometry (ICP-AES).

m. <u>Inorganic phosphorus in ammonium bicarbonate-DTPA extracts</u>

The method is based on the reduction of the ammonium phosphmolybdate complex by ascorbic acid in the presence of antimony (Murphy and Riley, 1962). Color-developing reagent A was prepared by dissolving 12.7 g of ammonium molybdate in 250 ml of distilled water. 0.291 g of antimony potassium tartarte was dissolved seperately in 100 ml distilled water. Both of the dissolved reagents were added to 1,000 ml of 5 N sulfuric acid and mixed thoroughly. The volume was made to 2,000 ml with distilled water.

Ascorbic acid (0.74 g) was added to 140 ml of mixed reagent (reagent A) and dissolved to get color-developing Reagent B. The reagent was prepared fresh each day because it is not stable for more than 24 hours.

Aliquots of AB-DTPA soil extract (0.25 ml) or standard were placed in a 2.5 cm path-length matching spectrometric tubes. After making to 10 ml with distilled water, 2.25 ml of color developing reagent was added and mixed well. Color intensity was read at 880 nm after 10 minutes.

n. Zinc sorption curves

The procedure adopted was that of Saeed and Fox (1979). 10.0 g soil (oven dry basis) and 20 ml 0.01 M $CaCl_2$ containing varying amounts of Zn (0 to 500 mg/kg soil) in the form of $ZnSO_4 \cdot 7H_2O$ were introduced into 50-ml centrifuge tubes having plastic stoppers. Two drops of toluene were added to retard microbial activity. Tubes were shaken longitudinally at 180 cycles per minute for 30 minutes twice each day for six days at 25° C. The suspensions were centrifuged and filtered to remove floating debris. Zinc remaining in solution was determined with an atomic absorption spectrophotometer. Zinc which disappeared from solution was considered to have been adsorbed. The amount of adsorbed Zn was plotted against Zn remaining in solution.

2. Tissue Analysis

a. Wet-digestion

Zinc determinations were made from nitric-perchloric acid digest of tissue. The digestion procedure was similar to that of Fox et al. (1977). The essential features of the method were as follows:

Plant material (1.00 g, oven dry basis) was predigested in Taylor digestion tubes at room temperature in 10 ml of a 2:1 mixture of nitric-perchloric acid overnight or until the vigorous reaction phase was past. Small, short stemmed funnels were placed in the mouth of the tubes to reflux acid. After the preliminary digestion, tubes were placed in a cold aluminium block digestor and the temperature raised to 150° C for 1 hour after which U-shaped glass rods were placed under

each funnel to permit exit of volatile vapors. Temperature was slowly
increased until all traces of nitric acid had disappeared, after which
the U-shaped glass rods were removed and the temperature raised to
235° C. Time was noted when dense white fumes of $HClO_4$
appeared in the tubes and digestion was continued for 30 minutes more.
Samples were removed from the digestor, allowed to cool a few minutes,
and a few drops of distilled water was added carefully through the
funnel. After vapors had condensed, water was added in small
increments washing down walls of tubes and funnels. Appropriate
dilutions were made with distilled water. The solution of each tube
was mixed and then left undisturbed for a few hours. Supernatent
liquid was then decanted and Zn, Fe, Mn, Cu, Ca, and Mg in the aliquots
were analysed by atomic absorption spectrophotometry. Potasium and Na
were determined by flame photophotometry.

Phosphorus was determined colorimetrically (Murphy and Riley
1962). Small amounts of digests (usually 0.5 to 2.0 ml) were diluted
30 times and sub-samples of diluted digests were used for color
development. Optical density was read on a spectrophotometer at 840 nm.

b. Dry-ashing

The procedure was that of Chapman and Pratt (1961) with slight
modifications. Plant material (usually 1.00 g oven dry basis) was
weighed into 30 or 50 ml Pyrex glass beakers. Beakers were placed in a
cool muffle furnace, then temperature was increased gradually to
550° C and samples were ashed for about 5 hours. The cooled ash
was dissolved in 5 ml of 2 N HCl and mixed. After about 15-20 minutes,

0.1 N HCl was added to make up to a suitable volume (usually 30 ml).

Solutions were mixed with a plastic policeman, allowed to stand for

about 30 minutes and filtered through Whatman no. 42 filter paper

discarding the first portion of the filtrates.

Filterates were analysed for Zn by atomic absorption spectrometry.

Zinc concentrations determined by wet-digestion were consistently

higher than those by dry-ashing. Therefore, discussion of experimental

data is based on wet digestion. Dry ash data and their ratio to wet

digest Zn values is presented in Appendices 4 to 11.

c. Silicon

The method for fusion of plant samples with lithium tetraborate

was adopted from Suhr and Ingomells (1966). Plant material (0.5 g) was

placed in platinum crucibles and samples were ashed in a muffle furnace

at 525° C overnight (for 12 hours). After cooling, 0.5 g lithium

tetraborate ($Li_2B_4O_7$) was added to each crucible and mixed

well with the ash using a plastic rod. The crucibles were placed back

in the muffle furnace and samples were heated for 10 to 15 minutes at

950° C. Power was turned off when setting the crucibles in and out

of the furnace. After removing the platinum crucibles from the

furnace, these were immediately immersed into plastic beakers

containing 100 ml 0.5 N HNO_3. The contents of each beaker were

stirred with a plastic rod until complete solution was obtained. The

solution was stored in plastic vials for Si analysis.

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 volumetric flask and glass distilled water was added until the flask was about two-thirds full. Where the aliquot was more than 3 ml, acidity was neutralized by adding equivalent quantity of NaOH. One ml of ammonium molybdate solution was added and mixed; this solution 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 dilluting to a volume of 100 ml with water. Thirty minutes were allowed for color development. Three ml of 10 % oxalic acid solution were added, care being taken to allow it to run down the neck of the flask to destroy any phospho-molybdate compound that had formed. After one to two minutes, 1 ml of reducing solution was added and mixed well. 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 nopthal-4-sulfonic acid was added and stirred. This solution was then added to 9 g of sodium bisulfite dissolved in 90 ml of water. Thirty minutes were allowed for color development and the optical density was read on a spectrophotometer at 650 nm. The Si concentration was obtained by referring to a standard curve.

d. Silica, macro-, semimacro-,and micro-nutrients in sugarcane tissue

Sugarcane tissue samples were analysed by " standard tissue analysis procedures" of the Hawaiian Sugar Planters' Association (HSPA, unpublished). 5.00 g of finely ground and oven dried samples were ashed in porcelain crucibles at 500-550° C in a muffle furnace overnight. Cooled ash was moistened with distilled water and 5 ml of concentrated HCl was added. After boiling for a few minutes, the

mixture was evaporated to dryness and heated on a steam bath for 3

hours to render silica insoluble. 20 ml of 1.2 N HCl was added,

covered with watch glass and heated on a hot plate for 15 minutes at

low-medium heat. Samples were then filtered immediately through filter

paper (S & S no. 589, white ribbon, 11 cm) and silica was washed with

hot water until pracitcally free from chlorides. The filtrate was

collected in 100 ml volumetric flasks, made to volume, mixed, and

allowed to settle. The necks of the flasks were then rinsed carefully

with the clear solution by rotating the flask at an angle. The

contents were allowed to stand overnight and samples of the clear

aliquot were analysed for K, Ca, Mg, Mn, Fe, Zn, Cu, and Na by ICP-AES

and for P on an autoanalyzer. Concentration of these elements in leaf

sheaths is reported on sugar-free basis.

$$\text{% or mg/kg of element on sugar-free basis} = \frac{\text{value of element}}{1 - (T.S.)/100}$$

Where T.S. is total sugars in leaf sheaths in %age. Filter paper

and contents were placed in the original tared crucibles, ignited

slowly at first and then at about 550° C in the muffle furnace

until constant weight was obtained. Weight of the silica was

determined by subtracting the tare weight of the crucibles from the

gross weight.

e. Nitrogen in sugarcane leaf blades

The method was adopted from Clements (1980) with slight

modifications. 0.5 g portions of oven dried leaf blade samples were

placed in digestion tubes of Technicon Block Digestor. Three glass
beads and 14 ml of Reagent 15 TN (Sulfuric-Selenious acid mixture: 6.5
g H_2SeO_3 in approximately 2225 ml of concentrated
H_2SO_4) were added to each tube and samples were digested in a
block digestor at 375° C for 2.5 hours. After cooling, the digests
were diluted to 100 ml volume. The solutioNs were mixed, allowed to
settle and clear solutions were analyzed for N using an autoanalyzer.

f. Macro- and micro-nutrients in nitric acid digests of wheat grains

The method was essentialy that of Havlin and Soltanpour (1980).
One g (oven dry basis) of unground wheat grains were placed in 50 ml
Taylor digestion tubes (graduated 25 mm x 200 mm, Corning no. 7952).
Ten ml of concentrated nitric acid was added to each tube and allowed
to predigest overnight. The tubes were then placed in an aluminum
heating blocks which are 36 cm x 36 cm capable of holding 45 tubes per
block. The tubes were heated at 125° C for about 4 hours to reduce
the volume to 2-3 ml. The solutions were clear but not colorless due
to the presence of nitrogen oxides. Amorphous silica was visible. The
digests were brought to 12.5 ml with conc. nitric acid and then
diluted to 50 ml with distilled water. After vigorous mixing, the
tubes were left undisturbed to let amorphous silica settle. The clear
portion of the digest was aspirated directly in plasma for ICP-AES
analysis of P, K, Zn, Fe, Mn, Cu, Mg, Ca, and Na. Standards were
prepared with the same acid:water ratio as the samples.

3. Measurement of Leaf Area

Area of diagnostic leaves was measured by a leaf area meter

(planeimeter). Total leaf area of corn was measured by the following

formula suggested by Mckee (1964).

Leaf area = $^{\complement}$[leaf length x maximum leaf width x 0.73)

D. Statistical and Geostatistical Analysis

Statistical calculations were made using the Statistical Analysis

System (SAS) (Ray et al., 1982). Analysis of variance was performed

for yield data of greenhouse experiments. Waller—Duncan K—ratio t—test

was used to compare the means of different treatments. Correlation and

regression analysis was used to examine soil and plant parameters

related to plant yield and Zn uptake (in greenhouse experiments) and

variables related to soil and plant tissue Zn (in field studies).

Semi-variances were calculated and semi-variograms plotted using

the method described by Matheron (1963). Some of the data were

log-normally distributed and were log transformed prior to analysis.

If the data were neither normal nor log normal, original data values

were used to construct the semi-variogram. The parameters included in

the Colorado study were soil pH, electrical conductivity, $CaCO_3$,

organic matter, sand, silt, clay, AB—DTPA—extractable Zn, Fe, Mn, Cu,

P, and K and concentrations of Zn, Mn, Fe, Cu, P, K, Na, Ca, and Mg in

wheat grain. For the two sugarcane plantations of Maui Island,

semi-variograms of soil pH, HCl-extractable soil Zn, Olsen P,

exchangeable K, and plant tissue Zn, P, K, and other parameters were

constructed. Range of spatial dependence, nugget variance and sill

were determined.

In order to estimate the properties at unsampled locations, appropriate semi-variogram models were fitted to the isotropic semi-variances. Interpolation of data points was done by block kriging (Trangmar, 1984). For most parameters, the radius of the neighborhood varied from 1/3 to 1/2 of the range . If number of pairs were less than adequate, full range was used for interpolation. A map showing the locations of 404 block kriged points in eastern Colorado is presented in Fig. 10. The number of blocks estimated at HC&S was 122 (Fig. 11) and 156 at Pioneer Mill Company (Fig. 12). The block size approximated the size of management units at sugarcane plantations (approximately 160 hectares for HC&S and 16 hectares for Pioneer Mill Company). Because the area of eastern Colorado was so large, the size of blocks was approximately 26,000 hectares. For parameters having no spatial dependence, original data values were used to prepare isarithmic maps. All maps of original and kriged data and estimation variance were computed using the SPLOT algorithm (Bridges and Becker, 1976). Relationships between soil Zn, plant Zn, and other properties in the areas were observed by superimposing Zn maps on the maps of soil and plant properties.
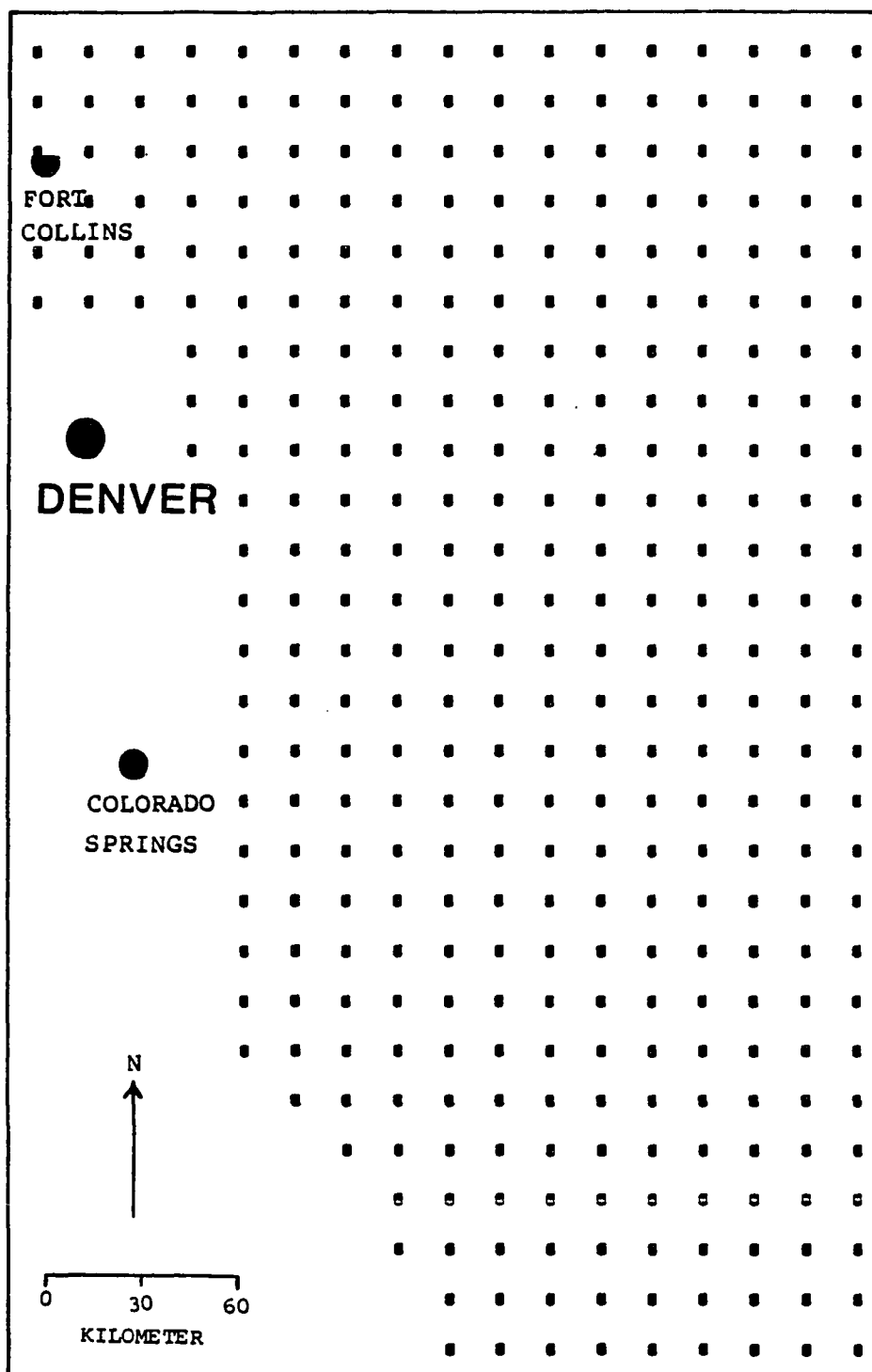
Fig. 10 Locations of 460 block kriged points, eastern Colorado.
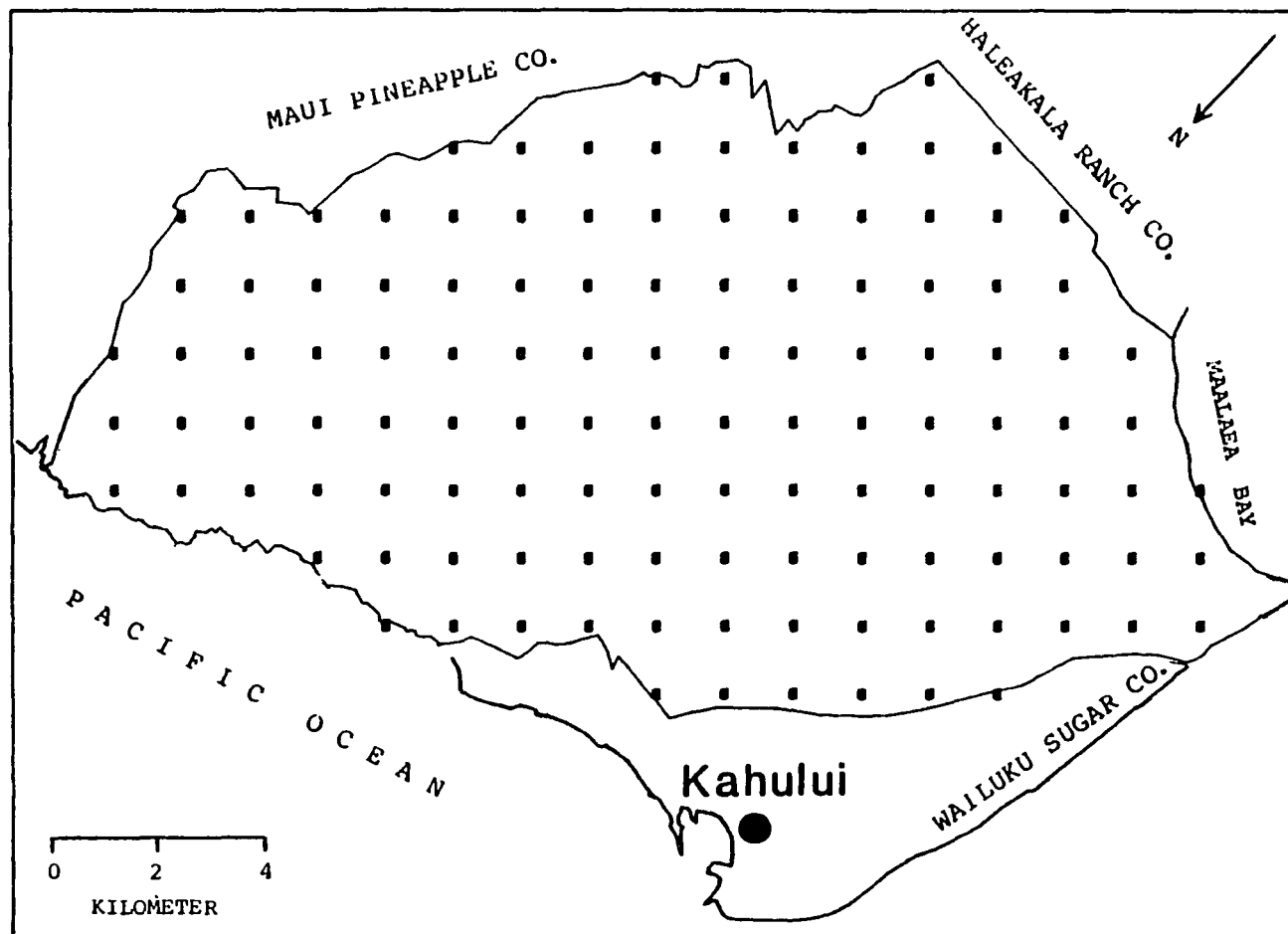
Fig. 11 Locations of 122 block kriged points, HC&S, Maui, Hawaii.
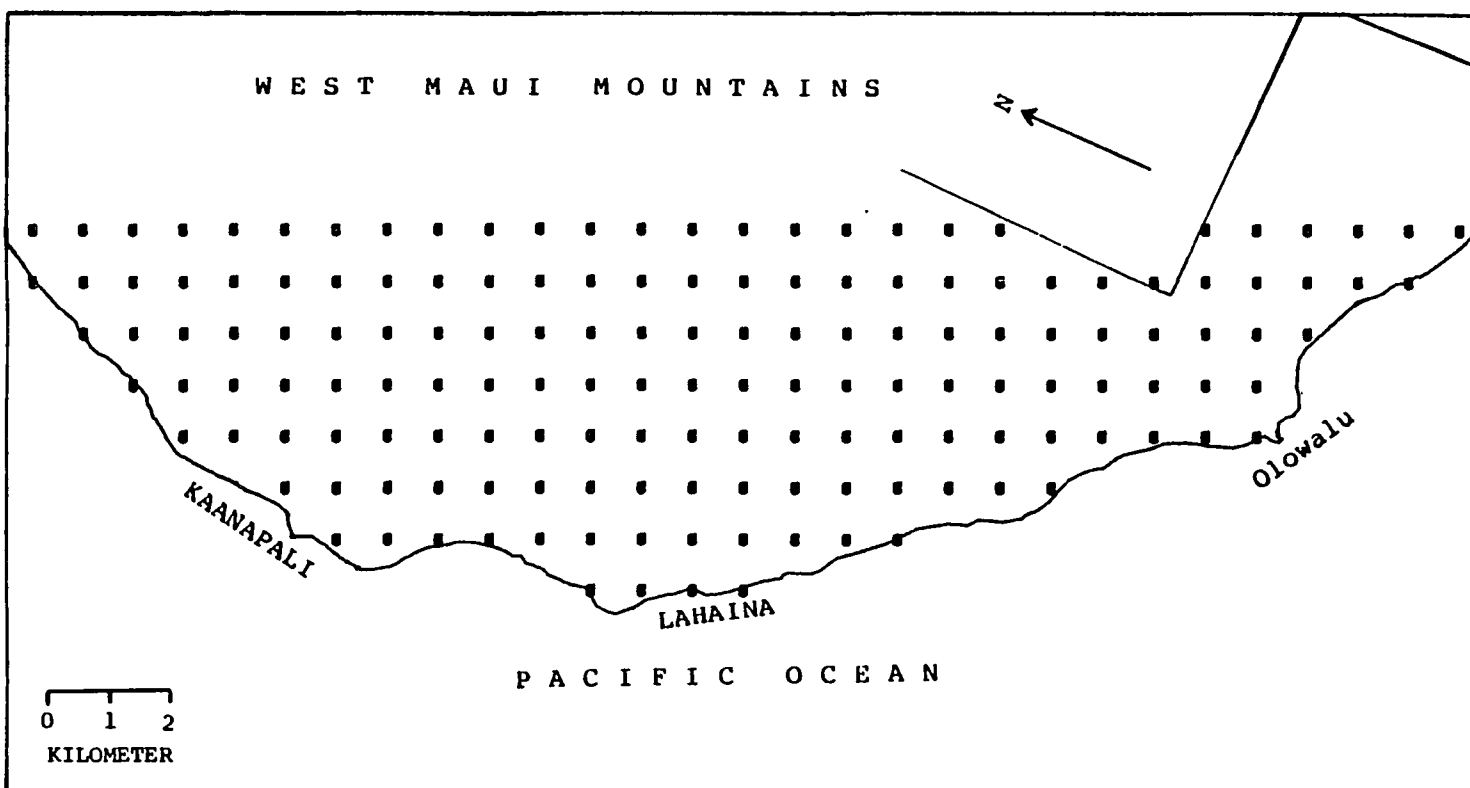
Fig. 12 Location of 156 block kriged points, Pioneer Mill Company, Maui, Hawaii.

IV. RESULTS AND DISCUSSION

A. Comparative Zinc Requirements of Crops

1. Sensitivity of Crop Species to Zinc Deficiency

Both soils used were exceedingly low in 0.1 N HCl-extractable Zn -- 0.6 mg/kg in Paaloa soil and 0.5 mg/kg in Keahua soil. When grown on Zn deficient soils, crop species differed widely in sensitivity to Zn deficiency.

The shape of response curves was largely determined by the sensitivity of the crops to Zn deficiency (Fig. 13 to 27). Corn was the most sensitive species. In the absence of Zn fertilizer only one plant survived more than two weeks and it did not produce an ear. Zinc fertilization, even at a low rate, was effective in enhancing plant growth. Application of 1 mg Zn/kg soil, for example, increased corn grain yield from 0 to 74% of maximum on Paaloa soil and from 0 to 57% of maximum on Keahua soil (Fig. 13).

The big increases in yield of some cereal crops produced by small inputs of Zn have important practical implications. No doubt there are many complete crop failures that could be avoided by nominal applications of Zn.

Crop species are ranked in decreasing order of their sensitivity to Zn deficiency in Fig. 28 and 29. Without Zn fertilizer, the corn plants survived only about two weeks past germination. Corn, cowpeas, and soybeans were very sensitive to Zn deficiency. The following text
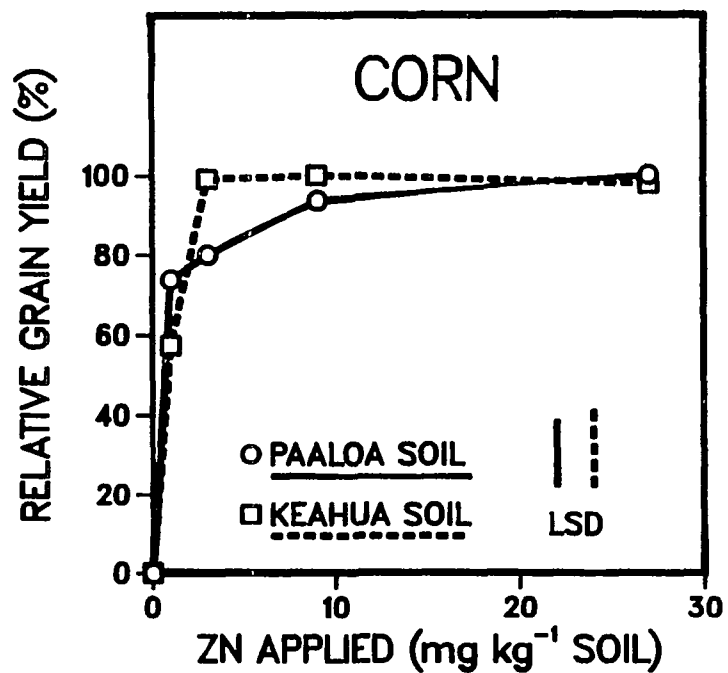
Fig. 13 Relationship between Zn fertilizer rate
and grain yield of corn. Maximum yield:
Paaloa soil, 206 g/plant; Keahua soil,
171 g/plant.
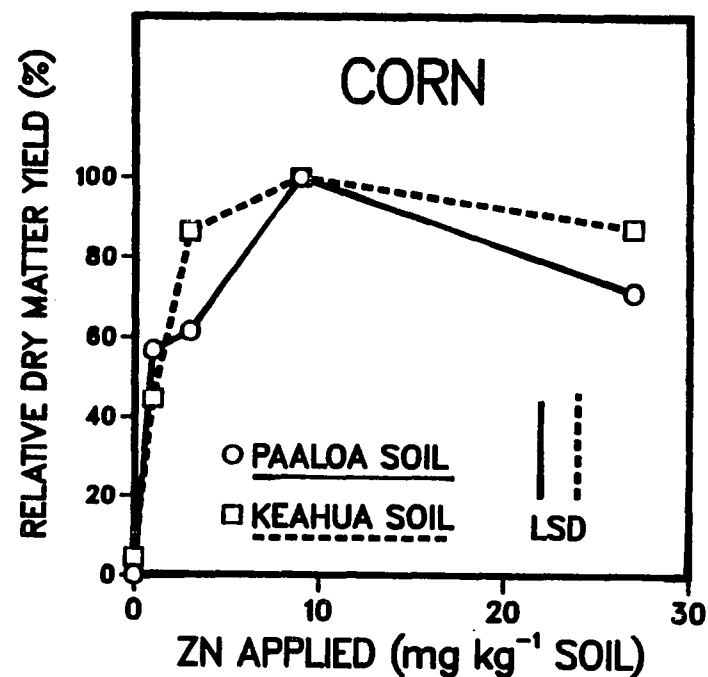
Fig. 14 Relationship between Zn fertilizer rate
and dry matter yield of corn. Maximum
yield: Paaloa soil, 403 g/plant; Keahua
soil, 311 g/plant.
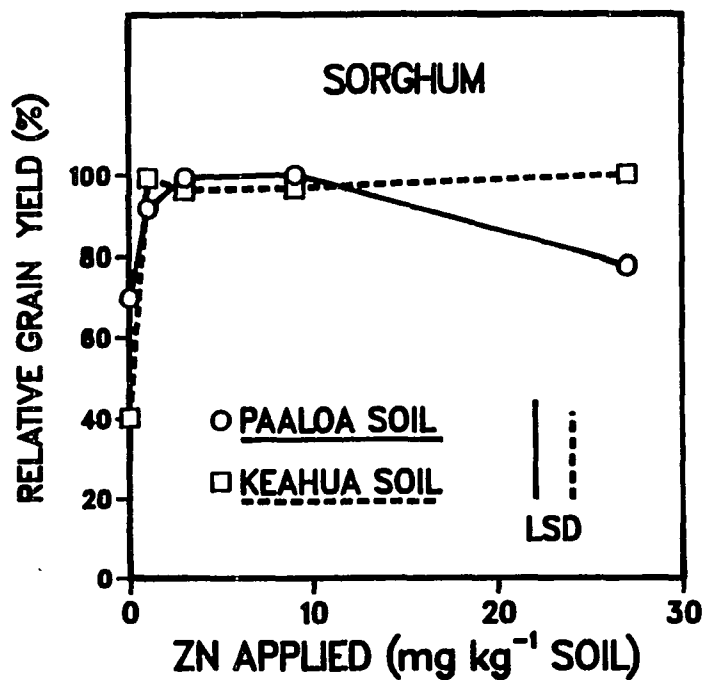
Fig. 15 Relationship between Zn fertilizer rate and grain yield of sorghum. Maximum yield: Paaloa soil, 74.3 g/plant; Keahua soil, 67.1 g/plant.
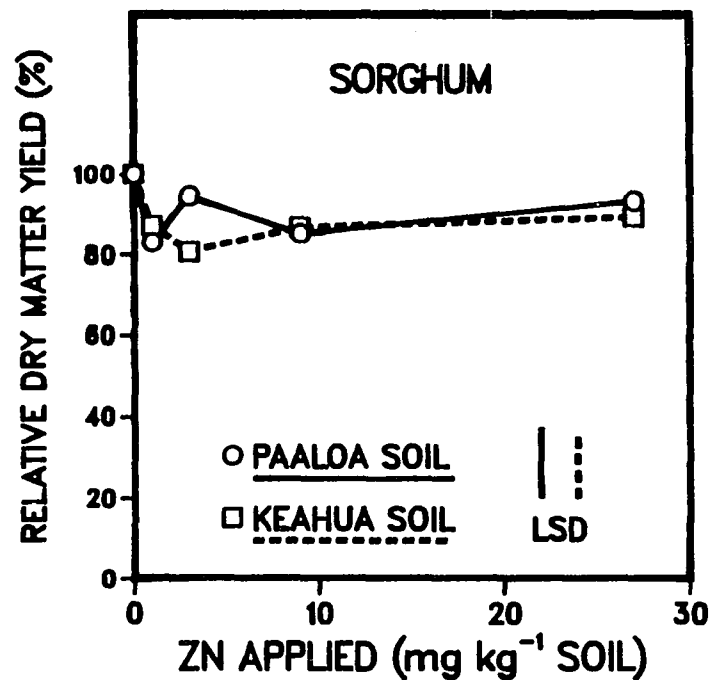
Fig. 16 Relationship between Zn fertilizer rate and dry matter yield of sorghum. Maximum yield: Paaloa soil, 68.0 g/plant; Keahua soil, 63.5 g/plant.
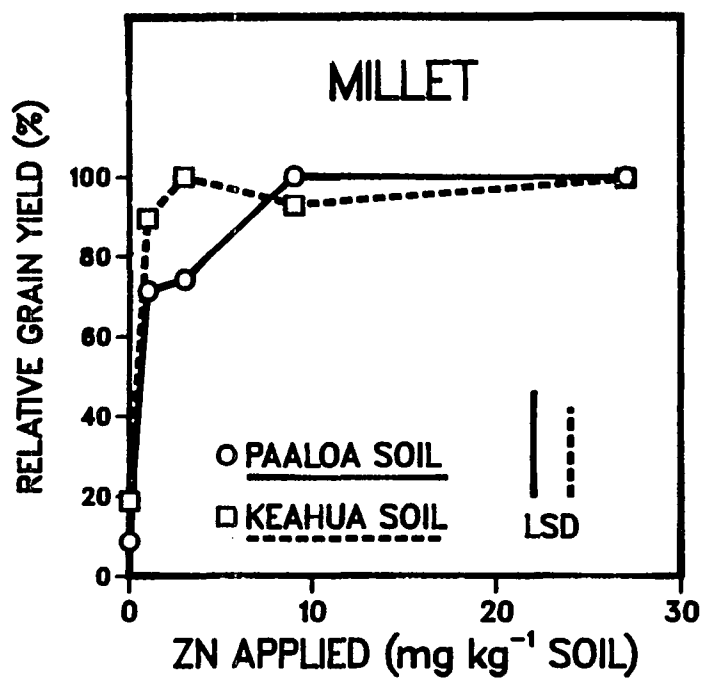
Fig. 17 Relationship between Zn fertilizer rate
and grain yield of millet. Maximum
yield: Paaloa soil, 37.5 g/plant; Keahua
soil, 32.2 g/plant.
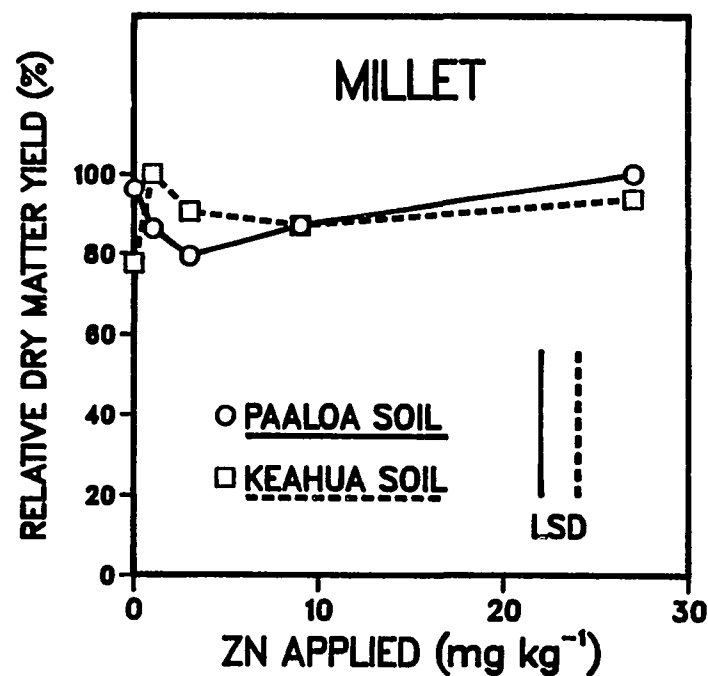
Fig. 18 Relationship between Zn fertilizer rate
and dry matter yield of millet. Maximum
yield: Paaloa soil, 41.7 g/plant;
Keahua soil, 37.0 g/plant.
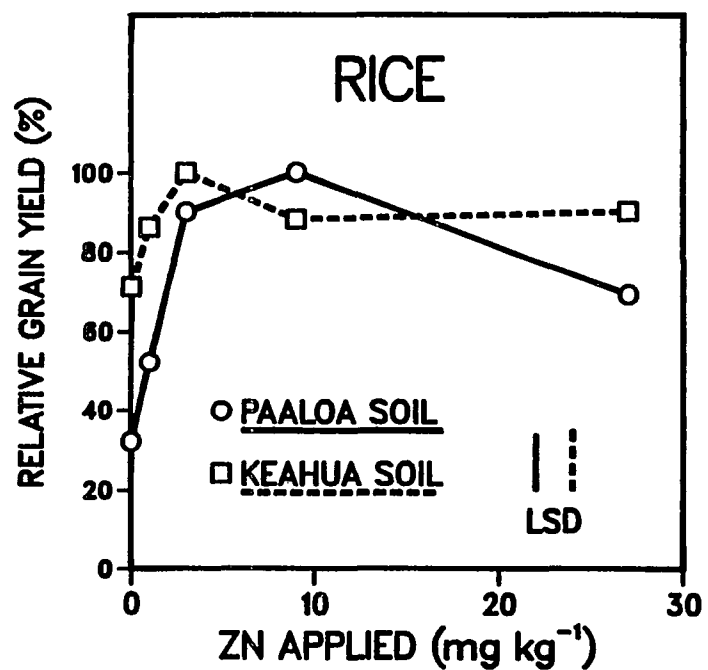
Fig. 19 Relationship between Zn fertilizer rate
and grain yield of rice. Maximum yield:
Paaloa soil, 17.9 g/plant; Keahua soil,
29.5 g/plant.
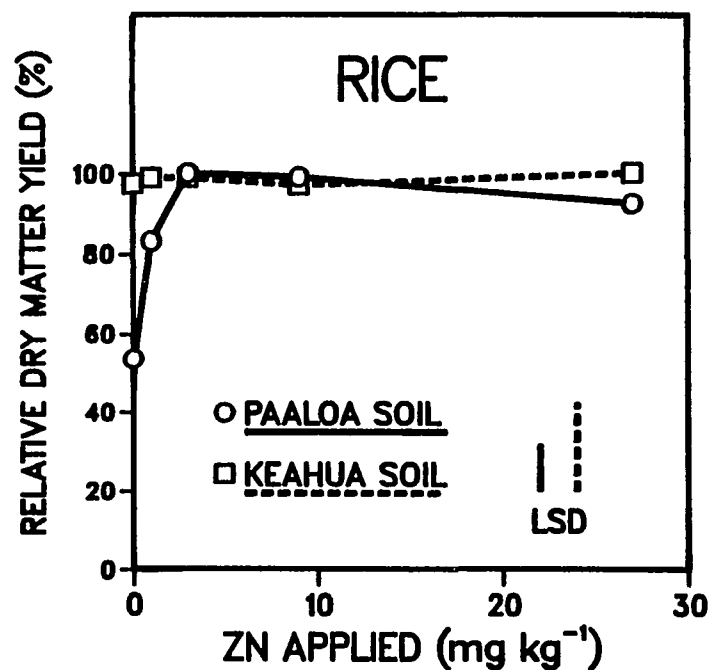
Fig. 20 Relationship between Zn fertilizer rate
and dry matter yield of rice. Maximum
yield: Paaloa soil, 20.4 g/plant; Keahua
soil, 23.3 g/plant.
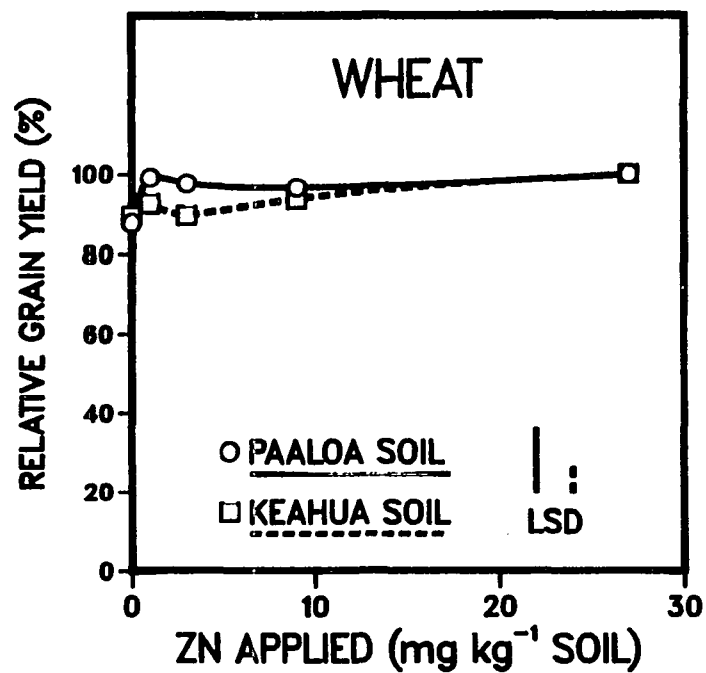
Fig. 21   Relationship between Zn fertilizer rate
and grain yield of wheat. Maximum yield:
Paaloa soil, 8.0 g/plan; Keahua soil,
5.9 g/plant.
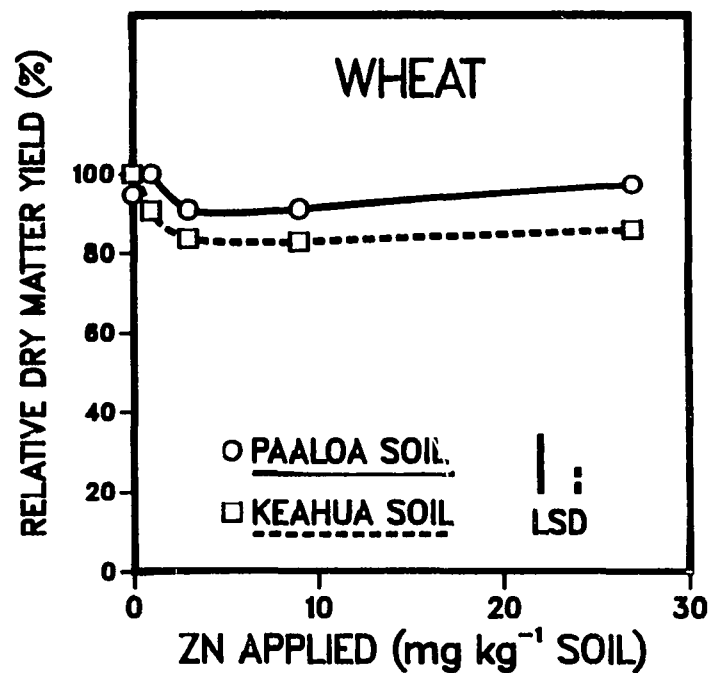
Fig. 22   Relationship between Zn fertilizer rate
and dry matter yield of wheat. Maximum
yield: Paaloa soil, 8.2 g/plant; Keahua
soil, 6.7 g/plant.
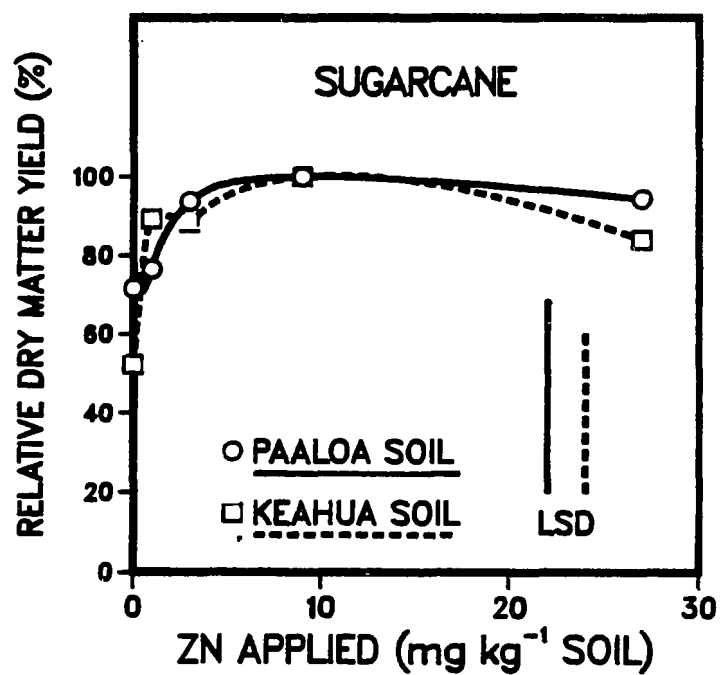
Fig. 23 Relationship between Zn fertilizer rate
and dry matter yield of sugarcane after
90 days growth. Maximum yield: Paaloa
soil, 266 g/plant; Keahua soil,
174 g/plant.
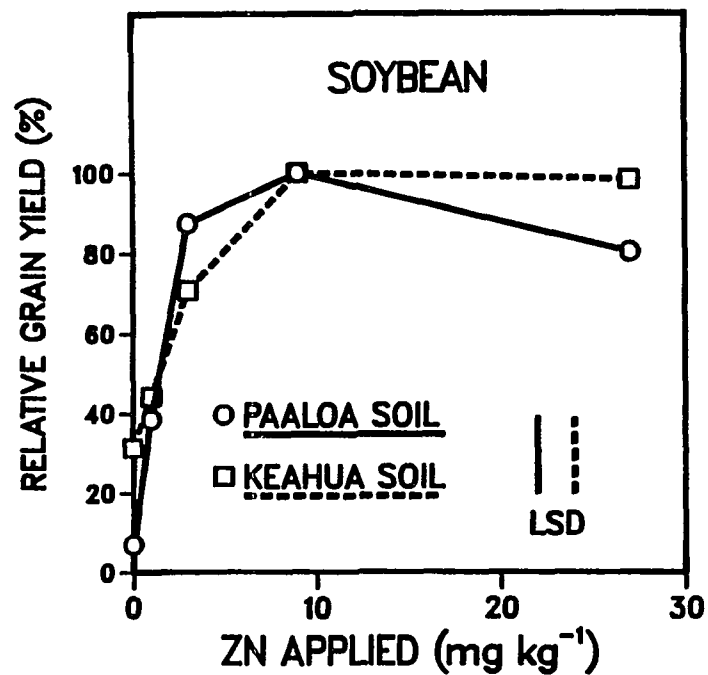
Fig. 24 Relationship between Zn fertilizer rate and grain yield of soybean. Maximum yield: Paaloa soil, 17.7 g/plant; Keahua soil, 15.1 g/plant.
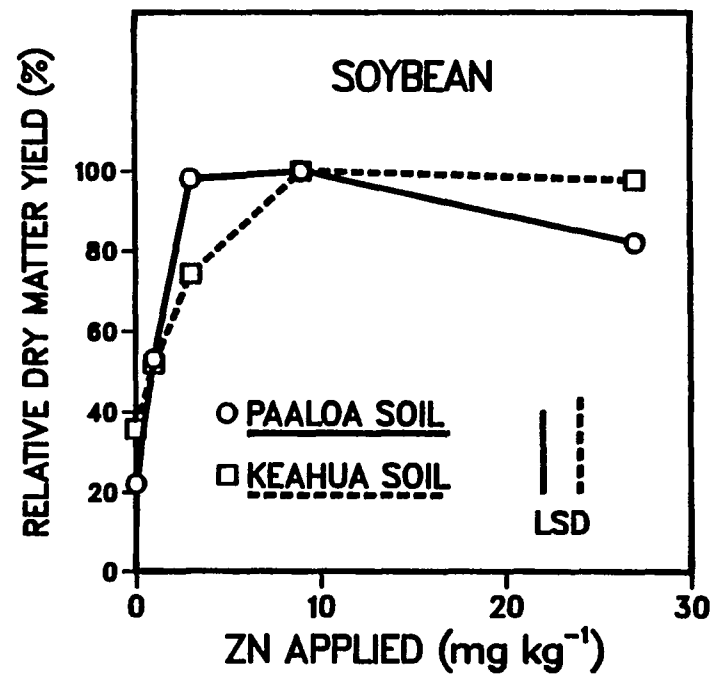
Fig. 25 Relationship between Zn fertilizer rate and dry matter yield of soybean. Maximum yield: Paaloa soil, 20.5 g/plant; Keahua soil, 19.9 g/plant.
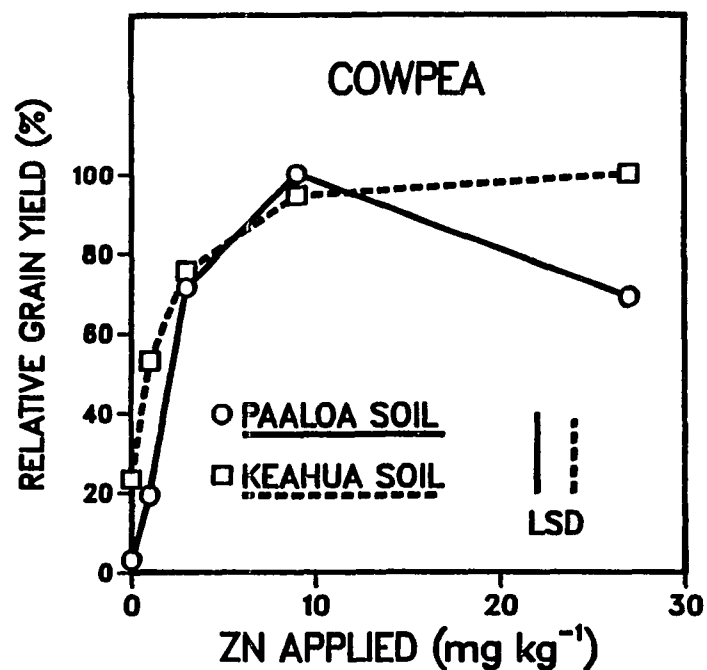
Fig. 26 Relationship between Zn fertilizer rate and grain yield of cowpea. Maximum yield: Paaloa soil, 18.5 g/plant; Keahua soil, 18.1 g/plant.
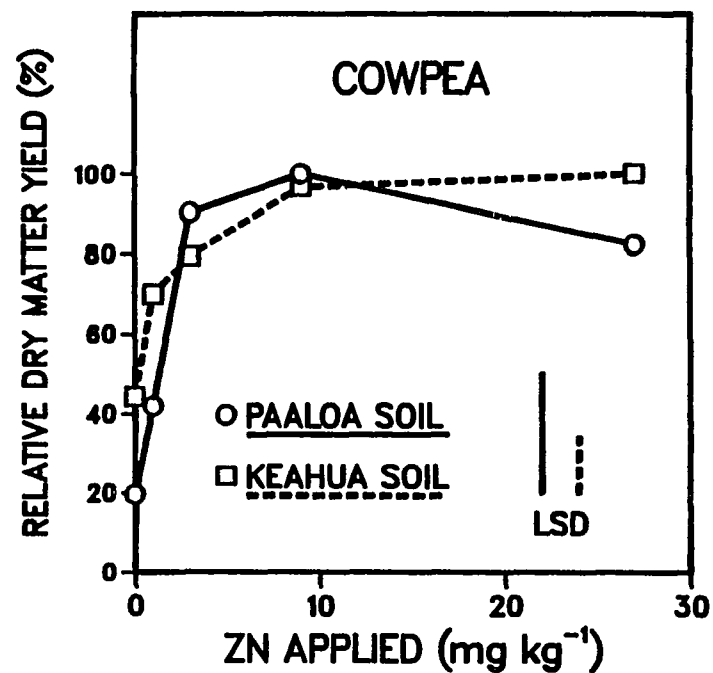
Fig. 27 Relationship between Zn fertilizer rate and dry matter yield of cowpea. Maximum yield: Paaloa soil, 23.6 g/plant; Keahua soil, 22.6 g/plant.
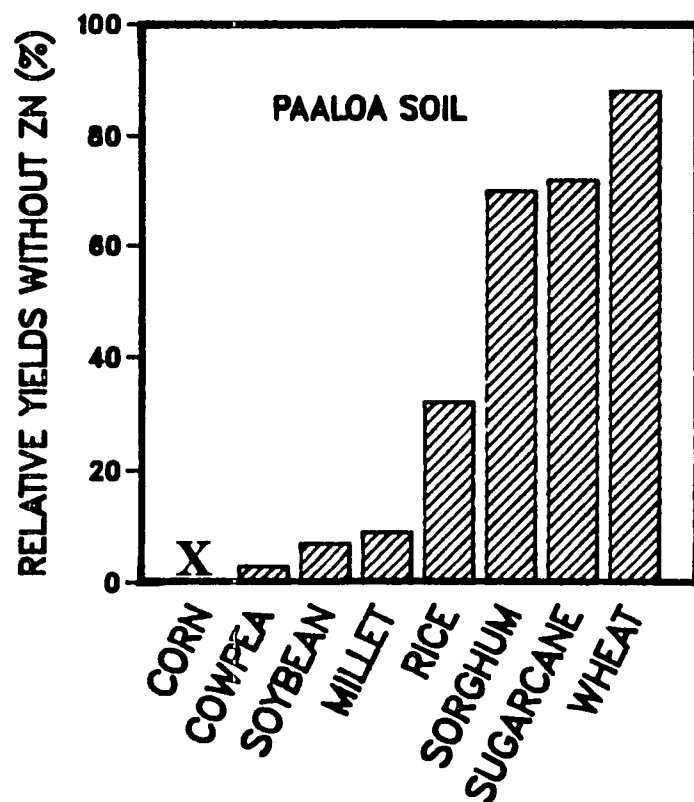
Fig. 28 Relative sensitivity of crop species
to Zn deficiency on Paaloa soil.
(Yields are of grain, except for dry
matter yield of sugarcane after 90
days growth).
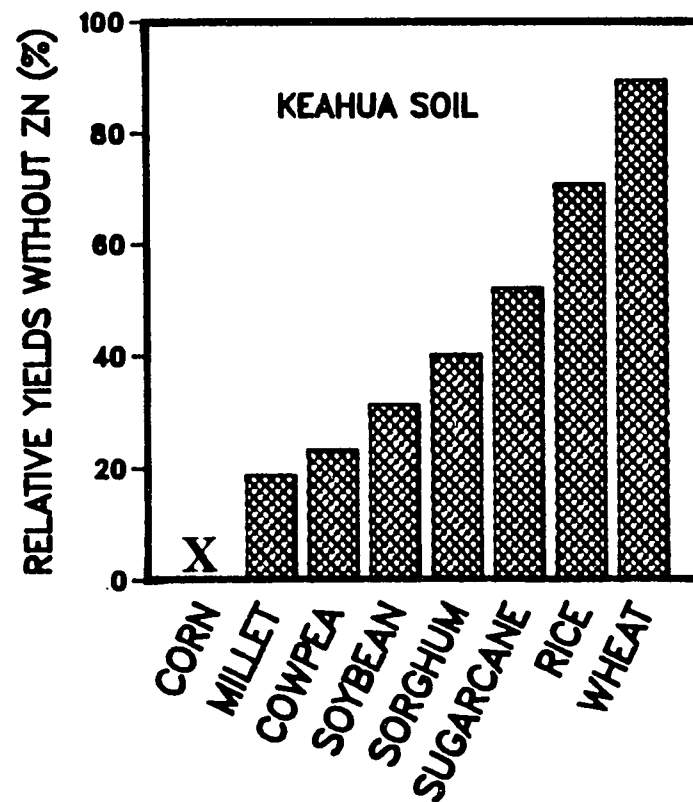
Fig. 29 Relative sensitivity of crop species
to Zn deficiency on Keahua soi.
(Yields are of grain, except for dry
matter yield of sugarcane after 90
days growth).

table gives the sensitivity grouping of crop species.

| Species | Yield without Zn | | Sensitivity |
	Paaloa	Keahua	group
Corn	0	0	Highly sensitive
Cowpea	3	23	Sensitive
Soybean	7	31	Sensitive
Millet	9	19	Sensitive
Rice	32	71	Moderately sensitive
Sorghum	70	40	Moderately sensitive
Sugarcane	72	52	Moderately sensitive
Wheat	88	89	Insensitive

Corn is the crop most severely and widely affected by Zn deficiency in the United States. In addition to its high internal Zn requirements, the very high susceptibility of corn to Zn deficiency may result from its ineffectiveness in extracting soil Zn and by greater dry matter production than other crops. Small grains are seldom affected by Zn deficiency. However in Australia, particularly in Victoria and South and Western Australia, several small grains, including barley, wheat and especially oats, require Zn supplementation (ILZRO, undated).

Zinc deficiency in sorghum has not been reported (Ohki, 1984). Millet did not develop Zn deficiency on a Tulare clay soil; although

beans and corn did. To the knowledge of this author, millet has not been reported to be specially sensitive to Zn deficiency.

Zinc deficiency is one of the most widespread disorders in tropical rice. This crop was severely affected by Zn deficiency on soils where wheat grew normally (Kausar et al., 1976). Varieties of rice differ in tolerance to Zn deficiency. Colombian and Pakistani varieties are tolerant whereas most International Rice Research Institute (IRRI) varieties are not (Centro International de Agricultura Tropical (CIAT), 1971; Chaudhry et al., 1977b). The variety used for this investigation, M101, was only moderately sensitive to Zn deficiency; perhaps because of higher than average efficiency for Zn absorption (Bowen and Perreira, 1984).

That wheat is quite tolerant of low Zn is well known (Kausar et al., 1976; Safaya and Malakondiah, 1981; and ILZRO, undated). Results of the present study agree with most reports. However a deficiency of Zn in field-grown wheat was reported in Yolo County, California and application of 12 kg Zn/ha increased grain yield by 500 kg/ha. The DTPA-extractable Zn of the soil, a Bacon clay loam, was 0.2 mg Zn/kg (Kearney and Zelinski, undated).

Although sugarcane has been considered tolerant of low Zn (Clements, 1980), it was classified as moderately sensitive in the present study. So low extractable soil Zn, as was in the experimental soils (Table 3), almost assures response for all but the most insensitive plants. Although varietal variation in sugarcane sensitivity has not been reported, the sugarcane variety used in this

investigation was susceptible to Maui sugarcane growth failure (Hagihara and Bosshart, 1984). Therefore, the sensitivity of sugarcane to Zn deficiency in the present investigation may be a varietal characteristic -- in which case Clements may have been justified in his evaluation.

In this study, soybean (cv. Davis) was highly sensitive to Zn deficiency (Fig. 28, 29). Although Viets et al. (1954), Moraghan (1984), and ILZRO (undated) rank soybean as very sensitive, few field responses have been reported. The response of soybean to Zn fertilizer is strongly affected by cultivar (Banks, 1982; Rose et al., 1981).

Studies on Zn nutrition of cowpea are rare. In one recent study (Safaya and Malakondaiah, 1981), however, cowpea was more sensitive than corn or sorghum. Andrew et al. (1981) reported that cowpea was moderately sensitive to Zn deficiency as compared with nine other tropical and subtropical pasture and forage legumes. In the present study cowpea and soybean were classed as sensitive to Zn deficiency.

Rates of Zn fertilizer for near-maximum (95%) yields are reported in Table 6. Requirements were generally greater for the more sensitive crops. Fertilizer requirements for dry matter production were less than for grain production. In the case of millet, for example, 0.5 mg Zn/kg soil was needed to obtain near-maximum dry matter yield; and 2.5 mg Zn/kg soil was required for near-maximum grain production. The high Zn requirement for grain production relative to the requirement for vegetative growth leads to the belief that Zn is specifically involved in grain formation and development.

Table 6 Fertilizer Zn requirements for near-maximum yield of cereal, legume, and sugar crops.

Crop species	Fertilizer requirements (mg Zn/kg soil)	
	Grain yield	Dry matter yield
Corn	6.5	7.0
Sorghum	1.5	0.0
Millet	2.5	0.5
Rice	3.0	2.0
Wheat	0.5	0.5
Soybean	6.0	5.0
Cowpea	7.5	6.0
Sugarcane	−	4.0

* Grain yield, except for dry matter yield of sugarcane after 90 days growth

2. Deficiency Symptoms of Zinc in Individual Crops

Plants affected by Zn deficiency are often chlorotic in the interveinal areas of the leaf. These areas turn pale green, yellow, or even white. In monocots, and particularly in corn, broad chlorotic bands form on either side of midribs but do not extend to leaf margins.

In the present investigation all crops developed deficiency symptoms in the absence of Zn fertilizer. In highly sensitive crops, deficiency symptoms persisted even with lower rates of Zn fertilizer and were completely alleviated only with high doses of Zn.

a. Corn

The corn plants grown on Zn-deficient soils exhibited text book type deficiency symptoms. Just three days after germination, leaf margins turned necrotic starting from the leaf tips. Zinc deficient seedlings were much weaker and stunted, with thinner stems and leaves, as compared with Zn-fertilized ones. Typical white-bud symptoms developed along with wide chlorotic bands on both sides of midribs. The growing buds of the seedlings became rotten, sticky, and necrotic. The leaf sheath became stuck around the emerging leaves which constitute the spindle. Such plants collapsed at about two weeks of age. The dry weight of 15-day old corn seedlings, as affected by Zn fertilizer rates, is presented in Fig. 30.

The seedlings grown on soils fertilized with 1 and 3 mg Zn/kg soil also exhibited severe symptoms of Zn deficiency. The symptoms were in the form of interveinal chlorosis and broad chlorotic bands on both
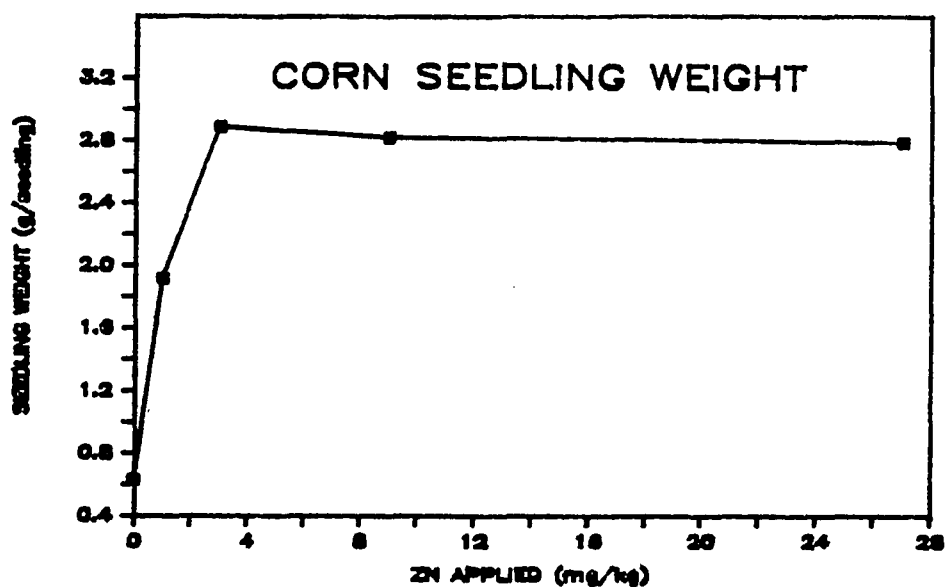
Fig. 30 Relationship between Zn fertilizer rates and dry weight of corn seedlings.
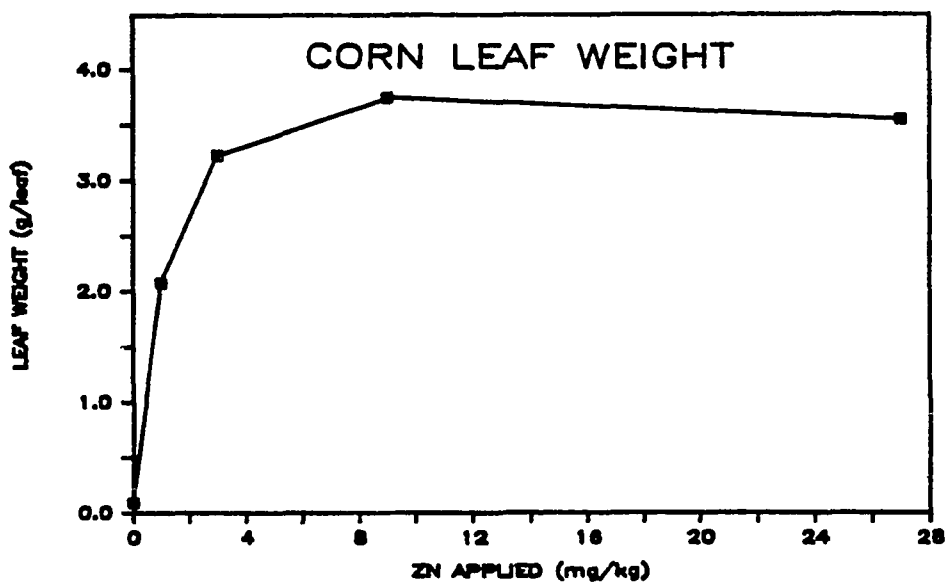
Fig. 31 Relationship between Zn fertilizer rates and dry weight of ear-leaf of corn.
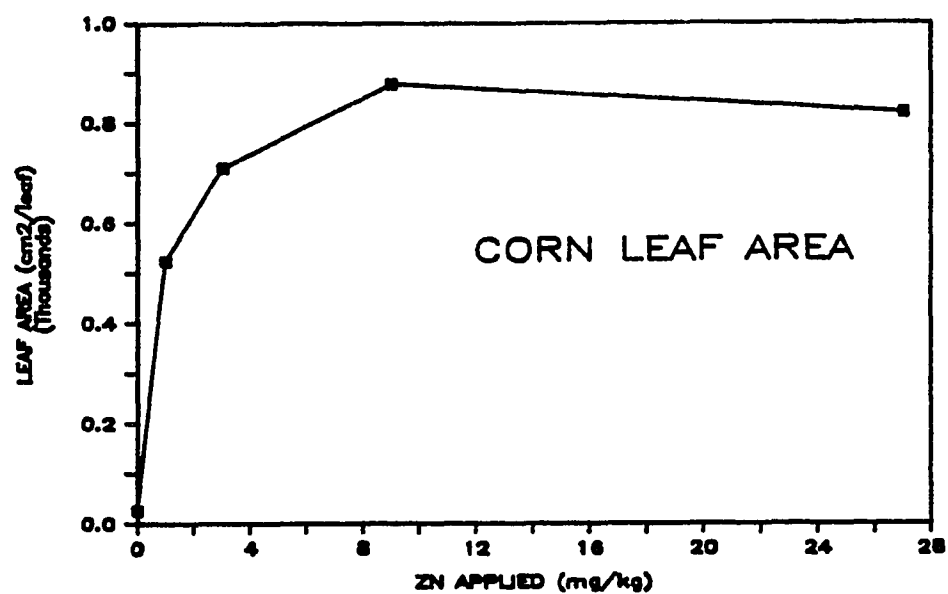
Fig. 32 Relationship between Zn fertilizer rates and area of ear-leaf of corn.
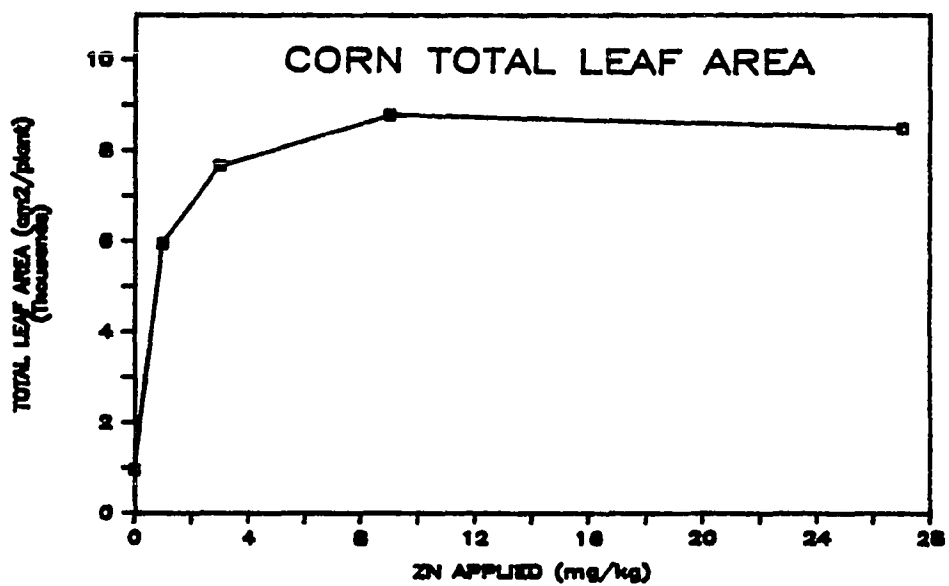
Fig. 33 Relationship between Zn fertilizer rates and total leaf area of corn.
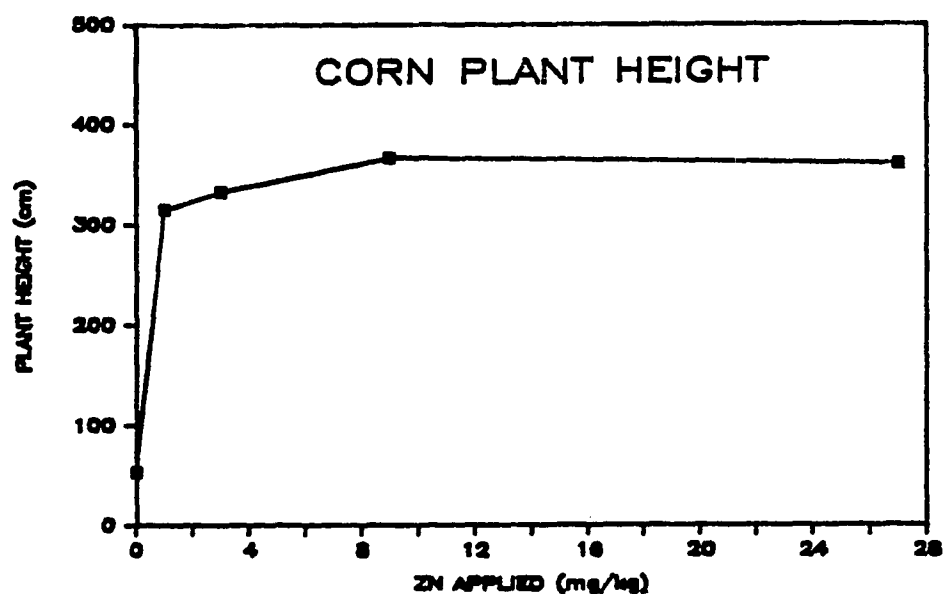
Fig. 34   Relationship between Zn fertilizer rates and plant
height of corn.
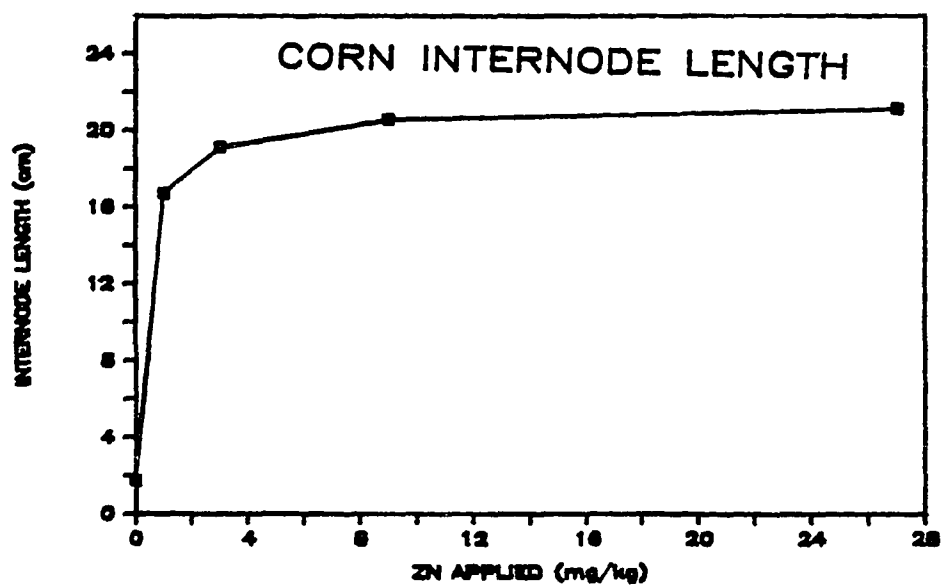
Fig. 35   Relationship between Zn fertilizer rates and
internode length of corn.

Table 7   Effect of soil Zn status on the flowering and maturity
of crop species.

Crop species	Zn applied (mg/kg)	Days to flowering/ heading/silking		Days to maturity	
		Paaloa soil	Keahua soil	Paaloa soil	Keahua soil
Corn	0	–	–	–	–
	1	48	48	90	90
	3–27	43	43	90	90
Sorghum	0	72	72	112	112
	1–27	42	42	91	91
Millet	0	35	30	81	107
	1–27	32	27	81	81
Rice	0	67	67	125	125
	1–27	65	65	125	125
Wheat	0	48	48	109	96
	1–3	41	41	101	96
	9–27	41	41	96	87
Soybean	0	42	42	121	121
	1–9	39	39	121	121
	27	39	39	129	129
Cowpea	0	48	48	86	86
	1–27	33	33	69	69

sides of the midrib, confined mostly to the lower leaves. At about 35 days of age, some of the low Zn-fertilized plants developed crook-neck symptoms.

Leaves of the Zn-deficient plants were much smaller than those of Zn-fertilized plants (Fig. 31, 32). The area of the ear-leaf was a good indicator of the total leaf area of corn plants (Fig. 32, 33). Zinc deficient plants were short (Fig. 34) and their internodes were shorter than Zn-fertilized plants (Fig. 35). Similar symptoms of Zn deficiency in corn were described by Chapman (1966), ILZRO (undated), and Gunderson et al. (1965).

The plants fertilized with the lowest level of Zn (1 mg Zn/kg), tasseled and silked about five days late as compared with plants fertilized with higher rates of Zn. However, plants of all Zn treatments matured at approximately 90 days (Table 7).

b. Sorghum

Zinc deficient sorghum plants developed well-defined deficiency sypmtoms. Symptoms were similar to corn except for the following:

Symptoms began as bronzing on lower leaves, from leaf tip down the leaf blade when plants were approximately two weeks old. Bronzing then spread slowly toward midribs. Ultimately leaf tips and margins became necrotic. Only the lower one-half of leaves were affected by bronzing and reddish-purple coloration. The two lowest leaves of Zn-deficient plants died. The upper leaves of Zn-deficient plants were light green in color. The dry weight of sorghum seedlings at 21 days of age, as affected by the rate of Zn fertilizer, is presented in Fig. 36.
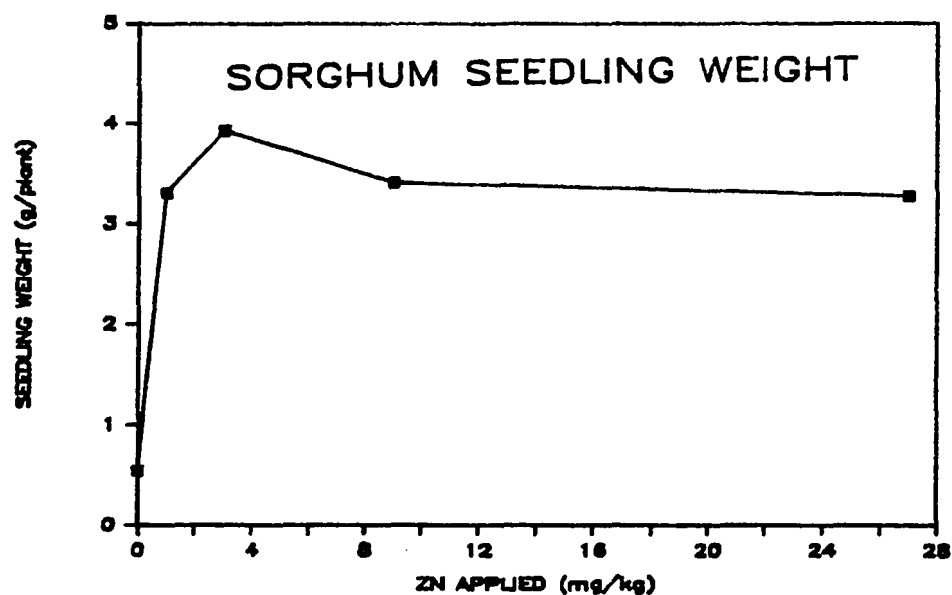
Fig. 36 Relationship between Zn fertilizer rates and dry weight of sorghum seedlings.
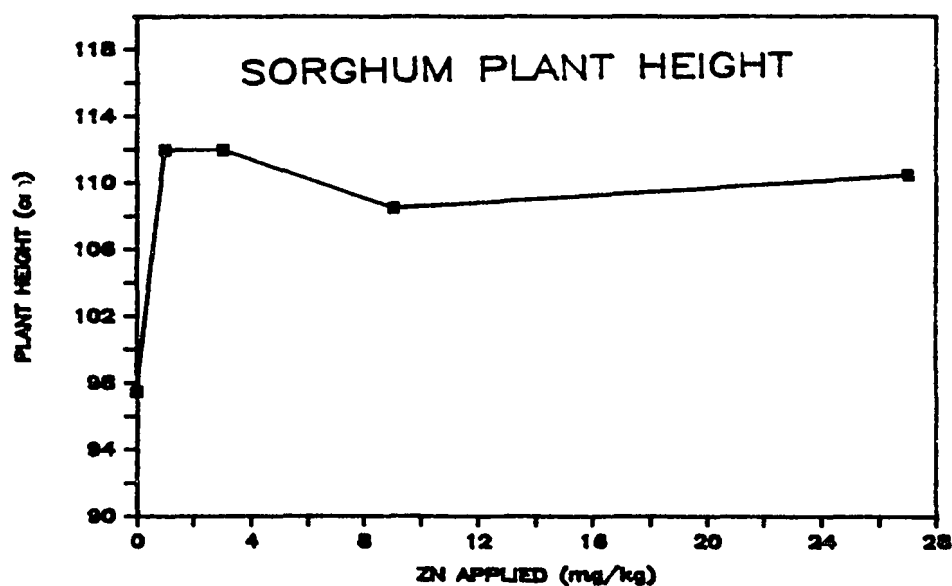
Fig. 37 Relationship between Zn fertilizer rates and plant height of sorghum.

Fig. 38   Relationship between Zn fertilizer rates and weight
          of most recently matured leaf of sorghum.
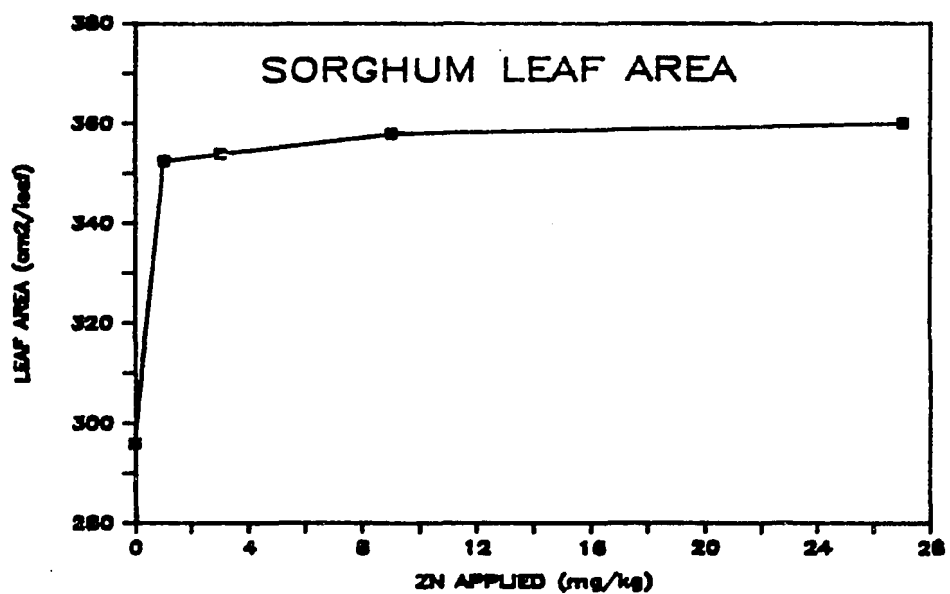
Fig. 39   Relationship between Zn fertilizer rates and area
          of most recently matured leaf of sorghum.

Internode length was drastically reduced by Zn deficiency which reduced

plant height (Fig. 37). Deficient plants developed a rossett type of

appearance. Ohki (1984) also described similar symptoms of Zn

deficiency in sorghum.

In sorghum, deficiency symptoms were less severe even with

the lowest Zn-fertilizer rate. These plants were much healthier

and bore broader and larger leaves (Fig. 38, 39), but leaf color

was light green. No deficiency symptoms developed if plants

were fertilized with rates of fertilizer greater than 1 mg Zn/kg.

Heading of sorghum plants was drastically delayed by Zn

deficiency. Whereas all of the Zn-fertilized plants (1 to 27 mg/kg)

headed at six weeks of age, those without Zn fertilizer headed one

month later (Table 7). Heads of Zn deficient plants were small, bore

few grains and 21 days late in maturity (Table 7). Welch et al.

(1967) reported similar results.

c. Millet

Approximately two weeks after germination, millet seedlings grown

on Zn deficient soils developed deficiency symptoms. They were weaker,

with fewer tillers, narrower leaves, and yellowish green appearance as

compared with seedlings grown on soils well supplied with Zn. Dry

weight of 24 day-old millet seedlings, as affected by Zn fertilization,

is presented in Fig. 40. The dry weight and area of the most recently

mature leaves of the Zn deficient plants were much less than those of

Zn fertilized plants (Fig. 41, 42). The leaves were yellow-green and

a few of the lower leaves were bronzed. The tips of the lower leaves
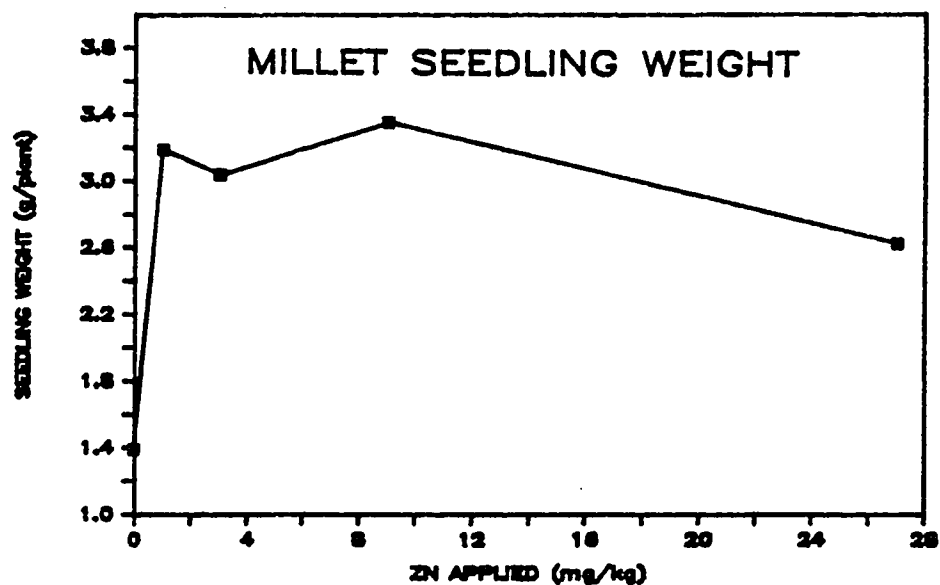
Fig. 40   Relationship between Zn fertilizer rates and dry
weight of millet seedlings.

Fig. 41   Relationship between Zn fertilizer rates and dry
weight of most-recently matured leaf of millet.

Fig. 42   Relationship between Zn fertilizer rates and area
of most-recently matured leaf of millet.
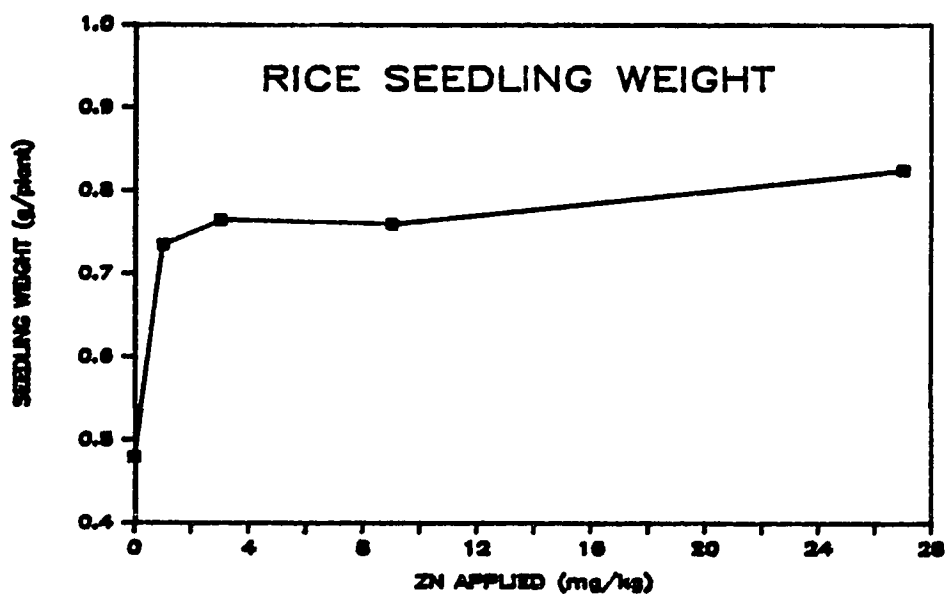
Fig. 43   Relationship between Zn fertilizer rates and dry
weight of rice seedlings.

became necrotic extending down the leaf blade, primarily on the leaf
margins. After approximately four weeks the bronzing became severe on
lower leaves and spread to upper leaves. The lower two or three leaves
died and except for a few topmost leaves, tips of leaves withered in
varying degree.

Most of the symptoms were eleminated by one mg Zn/kg; except
for slight bronzing and tip withering, of the lower three or four
leaves of each tillers.

Plant heading was delayed five days by Zn deficiency on both
soils. On Keahua soil crop maturity was delayed by 26 days (Table 7).
Crop maturity was not delayed on Paaloa soil.

The heads of Zn-deficient plants were short and bore few grains.
Head size and filling increased with increasing rates of Zn fertilizer;
so much so that results could be classed as spectacular.

At maturity, almost all of the leaves and stems of Zn deficient
plants were severely bronzed. Most of the leaves were necrotic, with
necrosis extending from the leaf tips down the leaf blades. The lower
leaves were affected more than upper ones. Milder symptoms were also
exhibited by plants fertilized with one mg Zn/kg. Plants growing in
soils with higher Zn levels did not have these symptoms.

d. Rice

Zinc deficient rice plants were light green in color and their
upper leaves developed a mild interveinal chlorosis. The lower leaves
of these plants were slightly bronzed with rusty- brown lesions. These
are typical symptoms of Zn deficiency in rice (Chaudhry et al., 1977a;

Cox and Wear, 1977). The lowest one to three leaves died. The response of rice to Zn fertilizer at the seedling stage is presented in Fig. 43. Zinc deficient plants were weaker, stunted, produced fewer tillers, and narrower leaves than Zn-fertilized plants. Dry weight and area of ear-leaves, as affected by Zn fertilizer, are presented in Fig. 44 and 45.

Although rice is known for its susceptibility to Zn deficiency, the cultivar M101 used in these studies did not show severe symptoms. Varieties of rice differ markedly in sensitivity to Zn deficiency and the development of its symptoms (chaudhry et al., 1977b). M101 is a frequently-grown variety of rice in California. It is resistant to Zn deficiency (Bowen and Perreira, 1984). Zinc deficiency in rice mostly occurs in flooded soils. In this study, rice was grown as an "upland" crop because the soils used contain large amounts of iron and manganese oxides. The mild Zn deficiency observed may have been related to the moisture regime.

Ear emergence of Zn-deficient rice plants was approximately two days late, but plants of all the Zn treatments matured at the same age, 125 days (Table 7).

e. Wheat

At two to four week age, plants grown on Zn-deficient soil turned light green in color with small and narrow leaves as compared with those of Zn-fertilized plants. The Zn deficient wheat seedlings were weaker than the Zn-fertilized ones (Fig. 46). Leaves of deficient plants were smaller in size than those of Zn-fertilized plants (Fig.
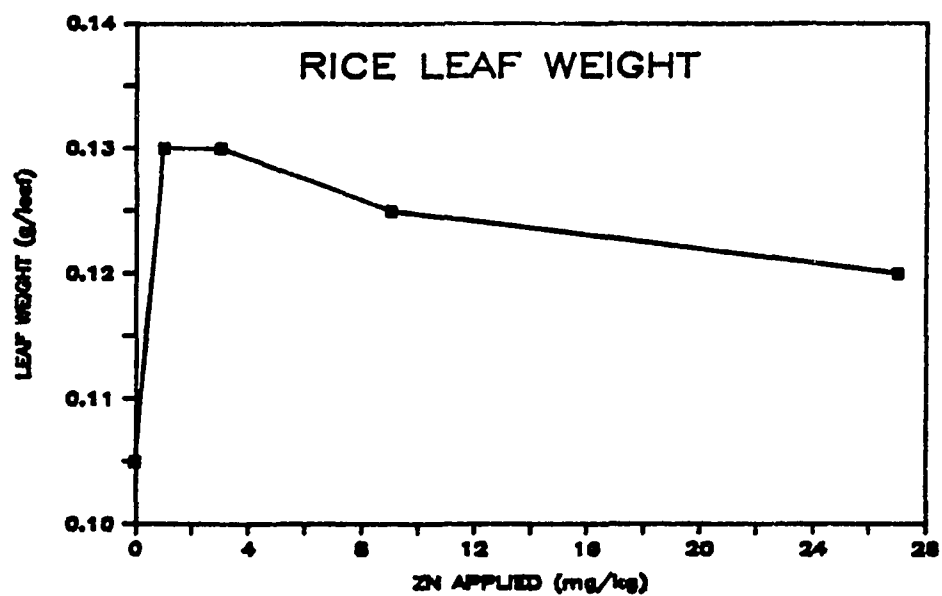
Fig. 44 Relationship between Zn fertilizer rates and dry weight of ear-leaf of rice.
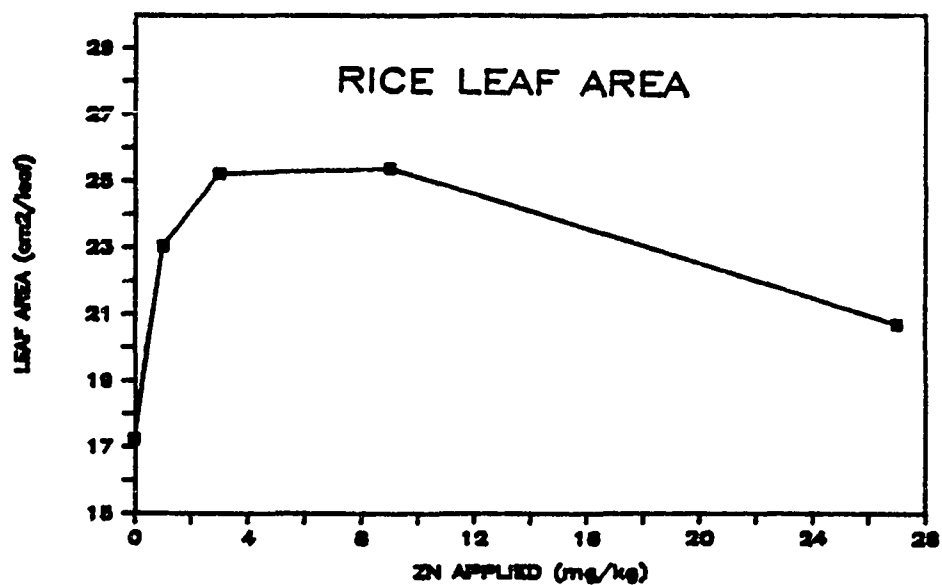
Fig. 45 Relationship between Zn fertilizer rates and area of ear-leaf of rice.
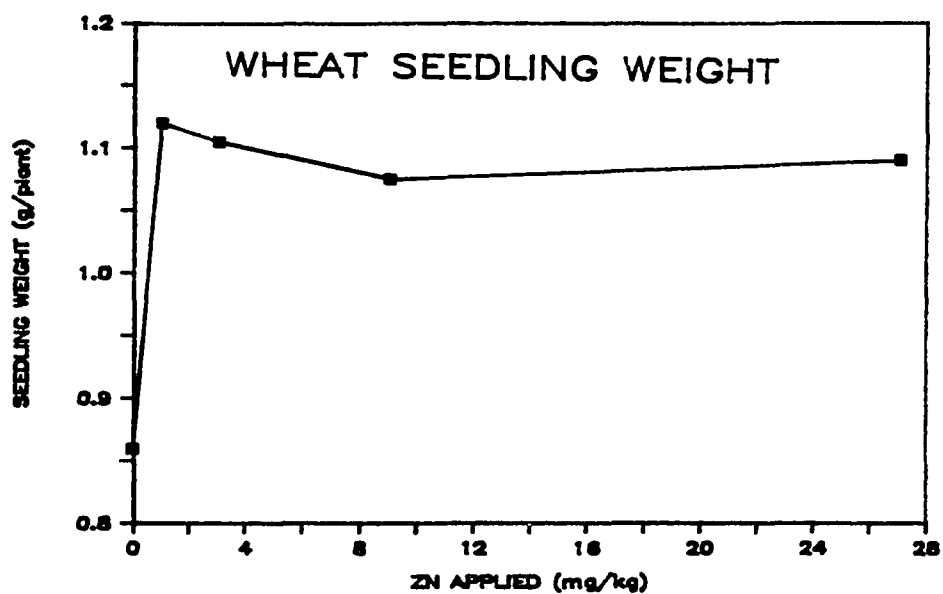
Fig. 46   Relationship between Zn fertilizer rates and dry
weight of wheat seedlings.
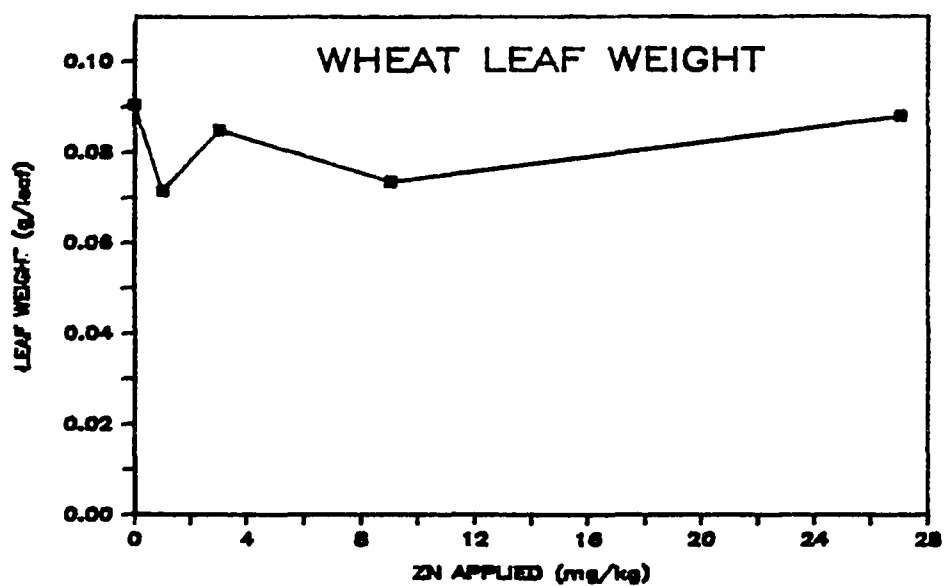
Fig. 47   Relationship between Zn fertilizer rates and dry
weight of ear-leaf of wheat.
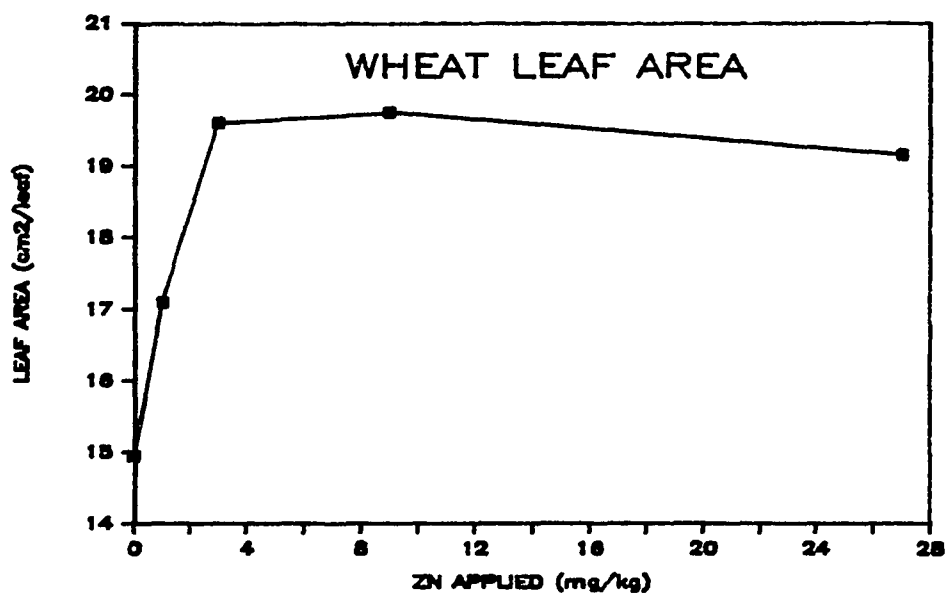
Fig. 48   Relationship between Zn fertilizer rates and area of
          ear-leaf of wheat.
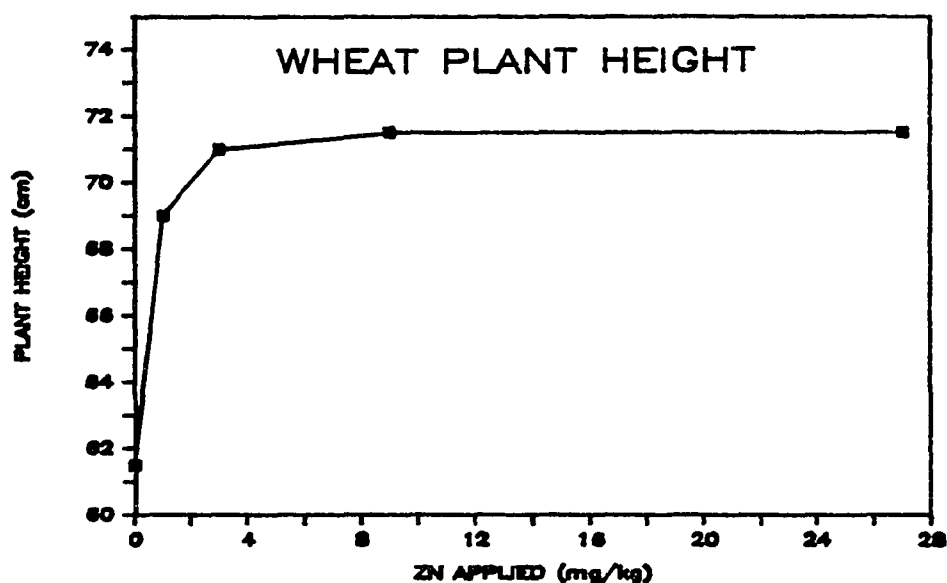
Fig. 49   Relationship between Zn fertilizer rates and height
          of wheat plants.

47, 48). Without Zn application, the lower two to three leaves of each tiller turned chlorotic and then necrotic. The necrosis appeared quite irregularly; it began at the leaf tip or base and extended toward the opposite end of the leaf on one or both sides of the midrib. On some leaves the symptoms began as small irregular patches in interveinal areas of lower leaves. Those later enlarged and coalsced resulting in a white-green mottling that spread down the blade of the already affected leaves. Chlorotic areas also spread to the leaf sheaths down the next node. As necrosis proceeded, leaves often collapsed across the midrib along the severely affected areas and became flaccid and dried. Within a few days the leaf sheaths, as well as the leaf blades, died on one or both sides of the midrib. These symptoms were confined to the lower leaves. The upper leaves were green and healthy. Similar symptoms of Zn deficiency in wheat have been described (ILZRO undated; Shukla and Raj, 1974).

Symptoms were less noticeable in plants fertilized with 1 mg Zn/kg soil, and were completely absent in plants produced by higher Zn treatments.

Although wheat tolerated Zn deficiency, plants on deficient soils were short (Fig. 49). Heading was delayed for seven days and maturity for 12 days due to Zn deficiency (Table 7). A progressive increased time was required to reach maturity with a decrease in soil Zn. These delays did not seriously depress yield in this experiment. But, if factors such as drought/frost are important near the time of harvest, then Zn deficiency may be more important than is indicated here.

f. Sugarcane

The sugarcane grown in the unfertilized subsoils developed stress symptoms that resembled some of the symptoms of Maui growth failure, i.e. irregular broad light-green to yellow bands of tissue on both sides of the midrib (Martin, 1938; Hagihara and Bosshart, 1984). Symptoms were most severe on the lower leaves of secondary shoots. Some lower leaves developed an interveinal necrosis, which began as a chlorosis on both sides of the midrib, then turned into bronzing, and finally resulted in necroses.

Zinc-deficient plants produced slender tillers. The growth index (fresh weight of leaf sheaths no. 3, 4, 5, and 6) increased with increasing rates of Zn fertilizer (Fig. 50).

Symptoms resembled those described by Juang et al. (1974). According to Clements (1980), Zn has limited mobility in sugarcane and as a result young blades contain more Zn than old blades. Therefore, we presume that the appearance of deficiency symptoms on lower leaves resulted from movement of Zn from older leaves to new growth. Plants supplied with Zn grew vigorously and produced broad green leaves. Clements (1980) used "fourth generation" minus-Zn setts to grow plants with a sheath level of 4.0 mg Zn/kg. These plants grew slowly and developed a single broad, lightly-colored stripe taking up the middle third of the left half of the bottom leaf blade. The spindle developed the most severe symptoms; it emerged but growth was defective. The edges of the young leaves were almost white from the tip downward to
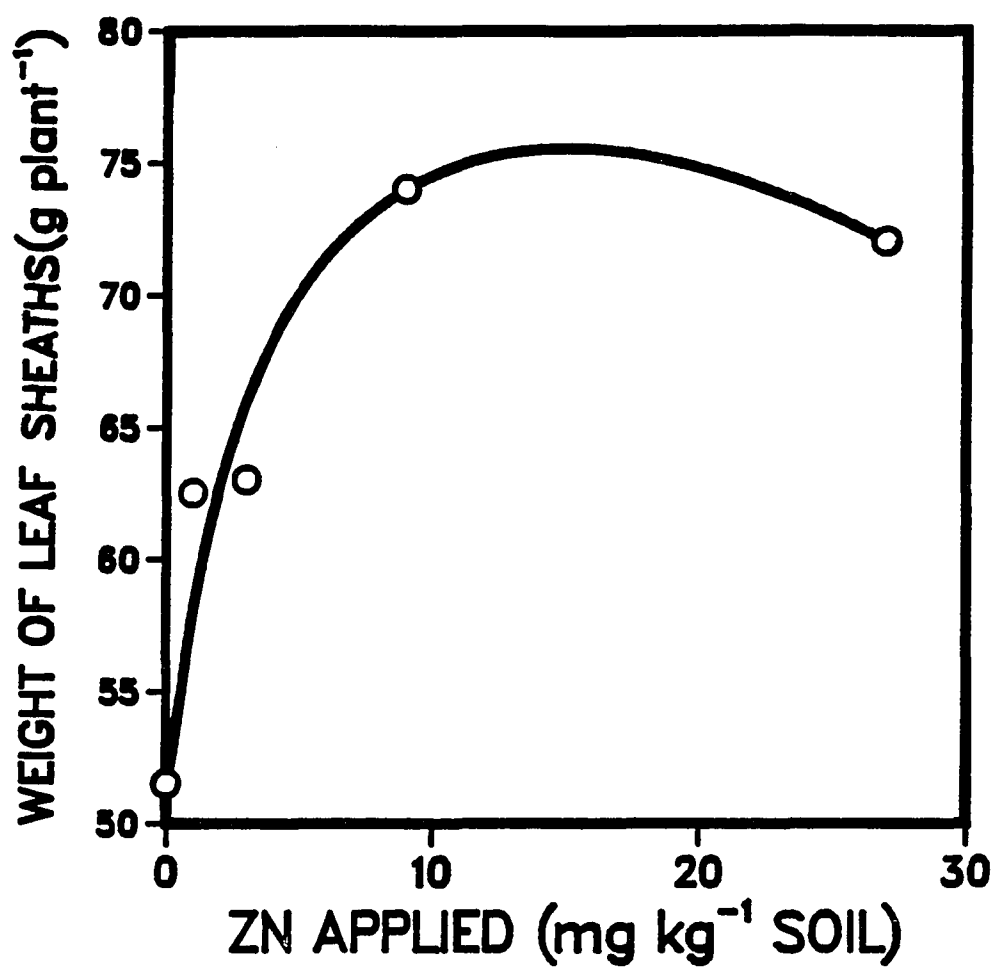
Fig. 50 Relationship between Zn fertilizer rate and growth index
(weight of fresh leaf sheaths) of sugurcane.

approximately one-third of the leaf length. The edges of the two top blades were frequently torn, and the young leaves tended to furl. Such severe symptoms should not be expected in the field nor were they noted in the experiments described here.

g. Soybean

Zinc deficiency symptoms in soybean appeared initially on the young developing leaves as a slightly rugose and chlorotic appearance that increased with time. Older leaves developed severe interveinal chlorosis and finally abscissed. The upper leaves were light green in color with raised interveinal areas. Zinc deficient plants were weaker, stunted and less branched. Leaves of the deficient plants were small (Fig. 51, 52). There appears to be two phases of Zn deficiency: the development of leaf rugosity on young developing leaves, and interveinal chlorosis in older leaves of plants supplied with small or decreasing amount of Zn. Similar symptoms were reported on soybean by Ohki (1977), Chapman (1966) and ILZRO (undated). Viets et al. (1954) reported that lower leaves of Red Mexican bean (Phaseolus vulgaris) were affected more severely than young terminal growth. Observations made in the present study agree with their report. In this study, leaf rugosity, in addition to interveinal chlosoris, was considered as a major expression of Zn deficiency.

Zinc deficiency reduced top dry weights (Fig. 25), plant height, and the number of flowers and branches. Deficiency symptoms were completely alleviated in plants fertilized with 9 and 27 mg Zn/kg soil.

A low Zn concentration may induce a high concentration of Mn in
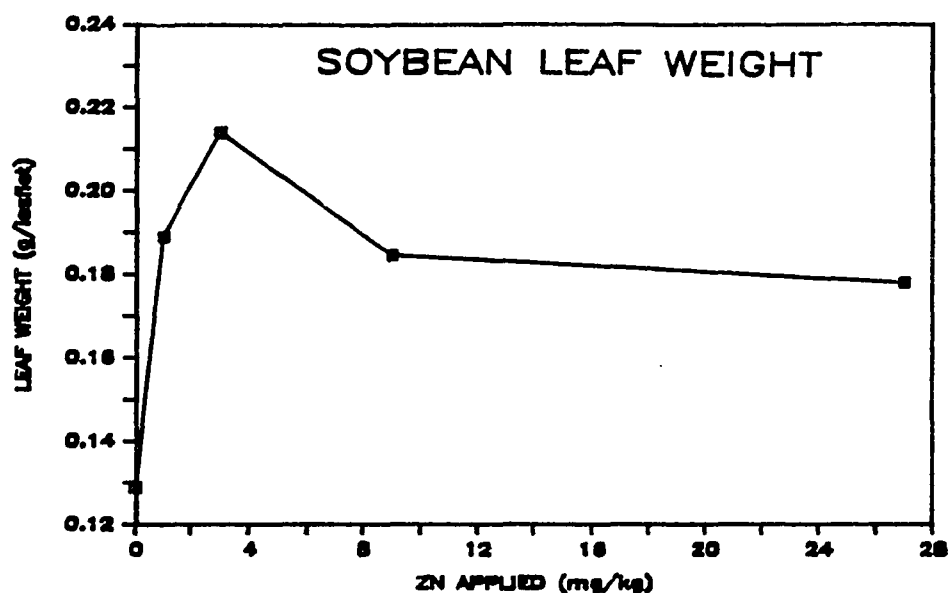
Fig. 51 Relationship between Zn fertilizer rates and weight
of most recently matured leaflet of soybean.
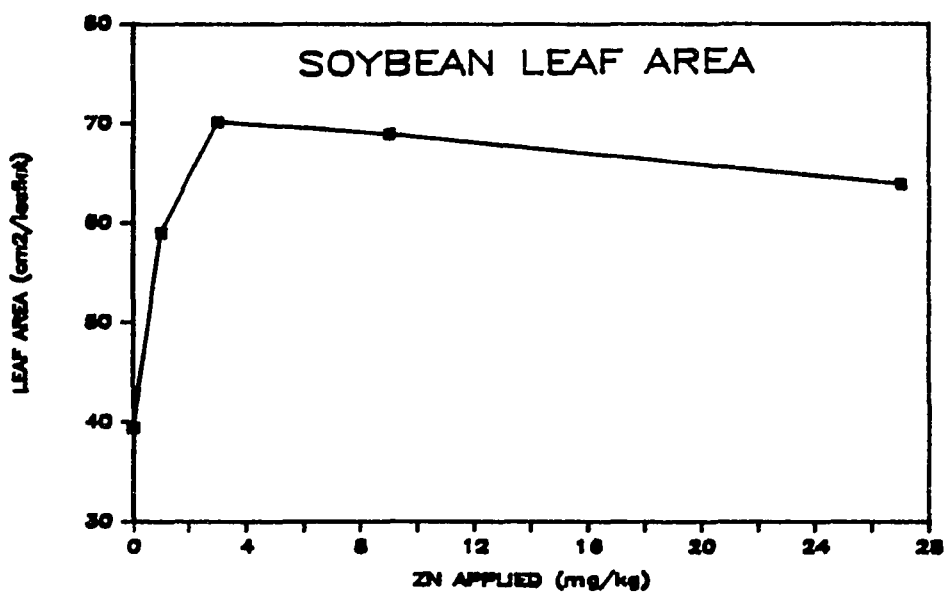
Fig. 52 Relationship between Zn fertilizer rates and area
of most recently matured leaflet of soybean.

Table 8   Effect of Zn fertilization on Mn contents in
          soybean leaves.

Soil	Zn applied (mg/kg soil)				
	0	1	3	9	27
	------------(Mn conc, mg/kg)------------				
Paaloa	62	24	19	23	18
Keahua	151	133	121	96	98

Table 9   Manganese contents in foliar tissue grown on
          Paaloa and Keahua soils.

Crop species	Zn applied (mg/kg)	Mn conc in leaves (mg/kg)	
		Paaloa soil	Keahua soil
Corn	1	53	481
	9	29	151
Sorghum	0	38	185
	9	23	86
Millet	0	33	172
	9	28	74
Rice	0	93	917
	9	43	670
Wheat	0	44	176
	9	38	110
Soybean	0	62	151
	9	23	96
Cowpea	0	34	794
	9	18	543
Sugarcane leaf blades	0	13	780
	9	12	370
leaf sheaths	0	4.4	520
	9	5.1	342

blade tissue (Ohki, 1977). The severe rugosity of the young leaves of soybean plants grown with low Zn supply resembled Mn toxicity symptoms described by Ohki (1977) and Carter et al. (1975). Ohki (1984) determined up to 375 mg Mn/kg tissue in leaves when the Zn concentration was 15 mg/kg. Such Mn concentrations are greater than the critical level of 160 mg Mn/kg reported by Ohki (1976). In the present studies Mn concentration in soybean leaves grown on Keahua soil (Table 8, 9) was only slightly less than the toxic level reported by Ohki (1976), but considerably less than the 250 mg Mn/kg reported by Jones (1972). Paaloa soil is developed under high rainfall. Higher Mn availability in Keahua soil, than Paaloa soil, seems to be related to low rainfall. Zinc concentration was exceedingly low at lower rates of Zn fertilization. Therefore, all the symptoms described above appear to be the result of Zn deficiency rather than of Mn toxicity.

Plants grown without Zn fertilizer flowered three days after the Zn-fertilized plants (Table 7). But, in contrast with other crops, plants fertilized with 27 mg Zn/kg, matured eight days after the plants of other Zn treatments.

h. Cowpea

The Zn deficient plants were extremely weak. Their leaves were small, chlorotic, bronzed, and eventually necrotic starting from leaf tips and proceeding along the margins. Leaf veins, including midribs, lost their green color and turned yellowish-white with time. These symptoms were confined mostly to lower leaves. Many such leaves abscissed prematurely. Later, upper leaves also developed the above
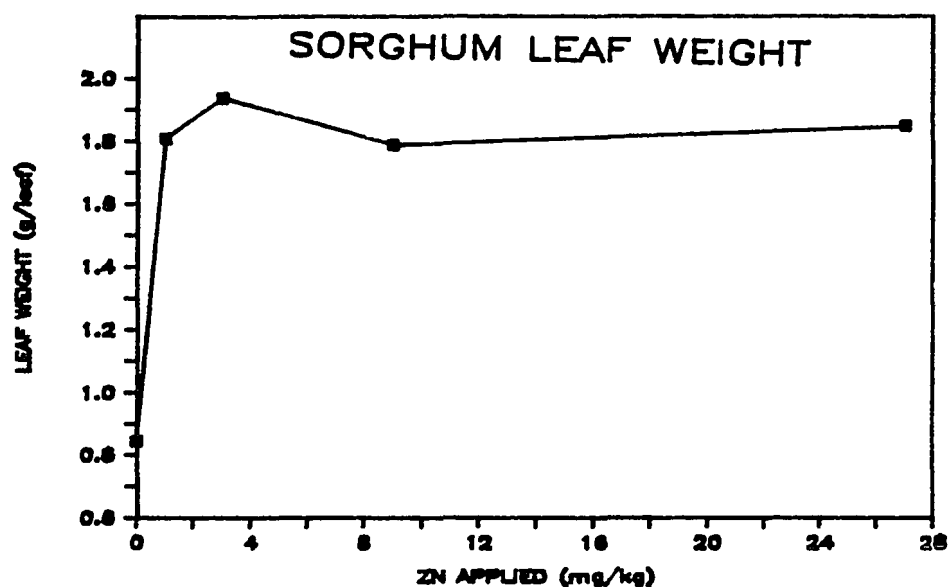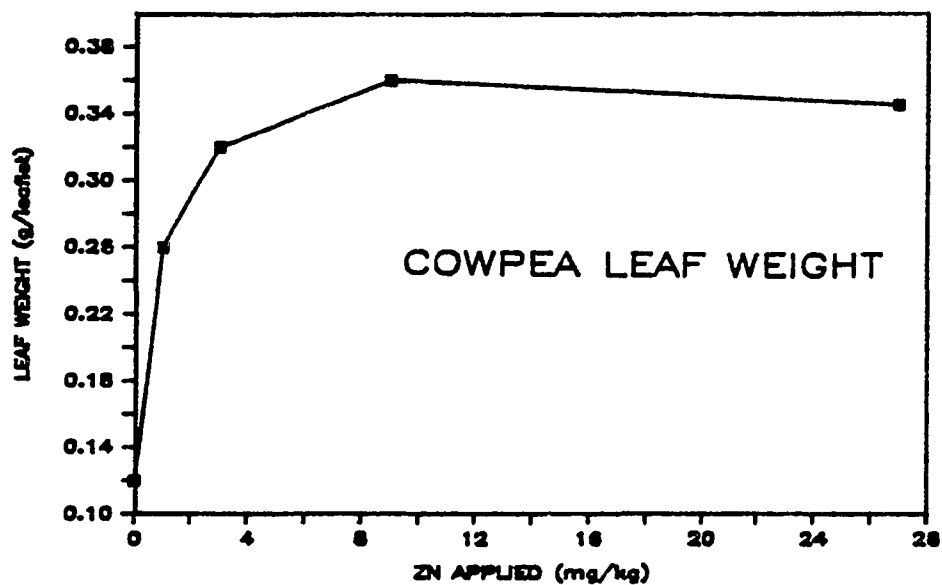
Fig. 53 Relationship between Zn fertilizer rates and dry
weight of most recently matured leaflet of cowpea.
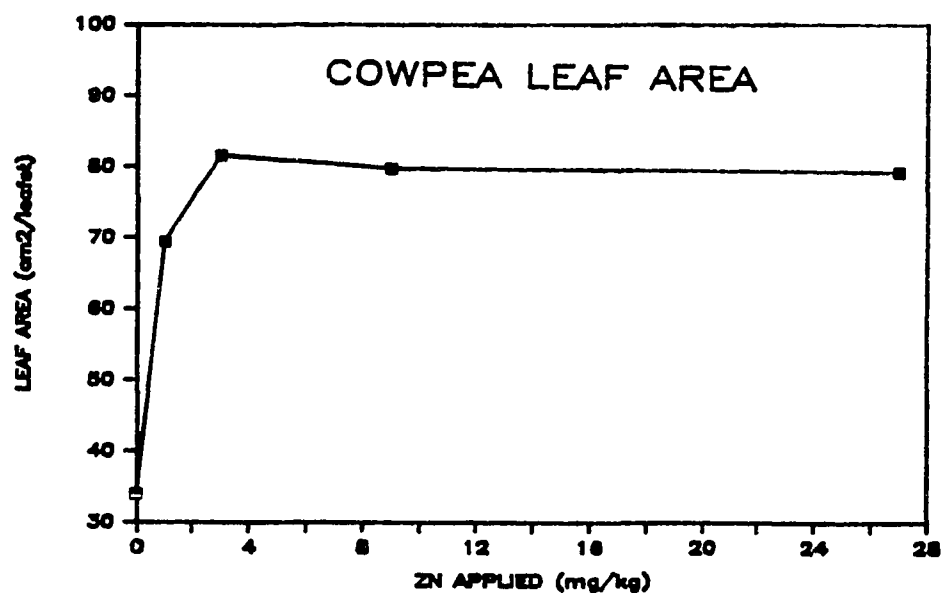
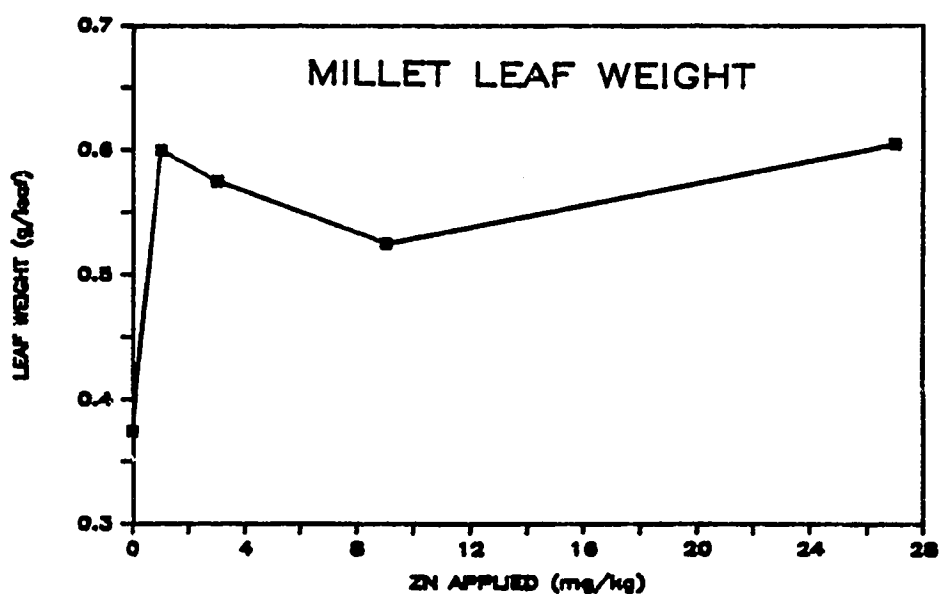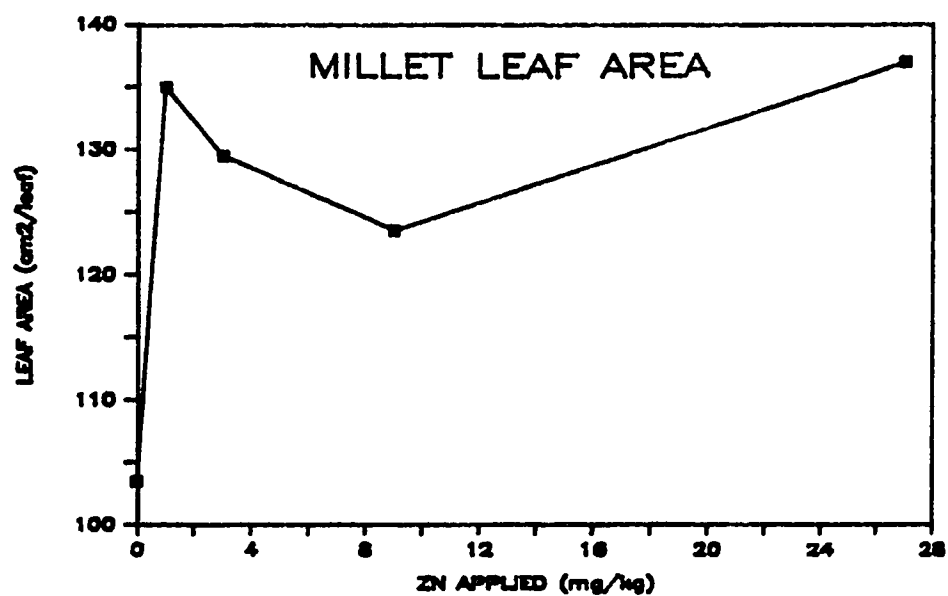Fig. 54 Relationship between Zn fertilizer rates and area
of most recently matured leaflet of cowpea.

symptoms and were curled backwards. Safaya and Malakondaiah (1981) described almost identical symptoms of Zn deficiency in cowpea.

The symptoms persisted in plants fertilized with lower rates of Zn, but an increase in the amount of Zn fertilizer reduced the severity of the symptoms. It improved plant growth, enlarged leaf size (Fig. 53, 54), and decreased leaf fall. The symptoms disappeared completely and the plants attained maximum growth and vigor with the application of nine mg Zn/kg soil.

Zinc deficiency delayed crop flowering by seven days and maturity by 17 days (Table 7).

3. Mobility and Redistribution of Zinc within Plants

Zinc mobility within plants is generally considered intermediate as compared with other nutrients (Lindsay, 1972; Collins, 1981). Zinc concentration in xylem fluids usually exceeds the Zn level supplied to roots (Collins, 1981). This indicates that after its absorption Zn is redistributed within the plant. Some investigators believe that Zn and some other heavy metals (Cu, Fe, Mn, Mo) are mobile in the phloem and that mobility varies with plant species (Epstein, 1971). Loneragan (1975) believe that the degree of mobility of micronutrients may be dependent upon environmental conditions and plant growth stages.

Massey and Loeffel (1967) estimated that Zn accumulation during the development of corn ears exceeded total uptake by 50% during that period. The excess Zn came from the adjacent stem and leaf tissues. The level of Zn supply determined the extent of Zn translocation. When

given luxury supplies of Zn, several plant species mobilized appreciable quantities of Zn from old leaves to developing inflorescence and grain, but under conditions of Zn deficiency the same species mobilized little, if any, Zn from old leaves, even when they were senescing from Zn deficiency (Loneragan, 1975).

In the present study, Zn deficiency symptoms were confined mostly to the lower leaves of sorghum, millet, wheat, sugarcane, soybean, and cowpea. The upper leaves of Zn-deficient plants, of the above species, did not develop any symptoms. It is presumed that the appearance of deficiency symptoms on the lower leaves resulted from movement of Zn from the older leaves to the new growth. Deficiency symptoms in corn and rice were noted on both old and young leaves. However, symptoms were more severe on old leaves. The observations agree with data of Jones (1970) who reported that the Zn concentration of the upper leaves of corn was higher than the lower leaves.

These observations suggest that Zn is mobile within plants and that mobility is greater in sorghum, millet, wheat, sugarcane, soybean, and cowpea, than in corn and rice.

4. Internal Zinc Requirements

Plant composition is an indicator of the nutrient status of plants, which in turn reflects the adequacy of soil nutrient supplies, efficiency of applied fertilizers, etc. Usually plant analysis is useful as a diagnostic tool for future correction of problems. In the case of young plants, analysis can be used for immediate remedial

fertilizer applications. Results of plant analysis combined with soil
test information allow fertilizer practices to more closely meet the
needs of the soil-plant system.

a. Discrepancies between plant zinc data obtained by dry-ashing and
   wet-digestion techniques

In estimating the concentration of nutrients in plant tissues, the
nutrients are first brought into solution. This can be achieved either
by wet-digestion or dry-ashing.

Wet-digestion can be accomplished using various combinations of
nitric acid, sulfuric acid, and perchloric acid. Dry-ashing procedures
vary in temperature and duration of ashing. The recommended ashing
temperature usually does not exceed 550° C. and the duration of
ashing is two to eight hours. Most preparations for analysis on
emmission spectrographs use dry-ash procedures. Analyses by colori-
metric, flame emmission, or atomic absorption spectroscopy techniques
generally rely on wet-digestion (Jones and Steyn, 1973). Although
some analysts prefer wet-digestion, dry-ashing is considerably easier
to do. Advantages of wet-digestion include: a) low temperature, which
limits volatilization; b) a final liquid condition, which lessens
retention losses; and c) rapid oxidation. However, wet-digestion is
time-consuming and there is greater risk of losses (spillage) or
contamination from reagents. Moreover, wet-digestion of large samples
is difficult and possible health hazards are involved including the
danger of $HClO_4$ explosions.

Advantages of dry-ashing are: few reagents added, relatively short

operator's time per sample, and ease in handling large samples. There are some disadvantages however. Some elements are lost by volatilization and retention on amorphous silica and on the ashing container, and oxidation may be time-consuming.

Gorsuch (1959) used radioactive isotopes to determine loss and recovery of a number of nutrients by wet- and dry-ashing procedures. Zinc retention occurred when silica crucibles were used for dry-ashing. Platinum crucibles were the best, and vitreous silica crucibles were satisfactory if properly handled.

The merits of wet- versus dry-ashing have yet to be resolved. The choice of an ashing procedure is usually determined by the type of plant material, the element being determined, and the equipment available.

All of the plant tissue samples from greenhouse experiments, seedlings, leaves, and seeds, were both dry-ashed and wet-digested. Zinc concentrations, in both cases, were measured by atomic absorption spectrophotometry. The Zn data obtained by dry-ashing, along with its ratio to wet-digested Zn contents, are presented in Appendix Tables 4 to 11. Less Zn was recovered by dry-ashing than by wet-digestion. In general, the differences were greater for foliar tissues than for seeds.

Zinc concentrations of corn leaves obtained by wet-digestion were 1.09 to 1.25 times greater than those obtained by dry-ashing (Appendix 4). Similarly, Zn contents of soybean leaves determined by wet-digestion were 1.10 to 1.21 times greater than those determined by

dry-ashing (Appendix 10). Generally, differences were greater for

plants that received no Zn fertilizer than for high Zn fertilized

plants. When plants are dry-ashed, Zn and other heavy metals

presumably are retained by amorphous silica. The discrepancy seems to

be associated with silica contents of tissues. Silica contents of corn

leaves were 1.92% at 1 mg Zn/kg soil and 1.35% at 9 mg Zn/kg soil

(Table 10). Greater differences in Zn content between dry-ashed and

wet-digested soybean leaves (Appendix 10) were associated with greatest

silica content (Table 10). In sugarcane, the discrepancy between Zn

contents determined by these two ashing procedures was generally

greater for leaf blades than leaf sheaths (Appendix 9). The silica

content of sugarcane leaf blades was greater than leaf sheaths (Table

10). The ashes of plant materials which contained more silica were

darker in color (more carbon) than ashes of low silica containing

material. High amounts of silica presumably hinder complete oxidation

of plant materials. Sedberry et al. (1971) reported that dry ashing

consistently yielded lower Zn concentrations from rice tissue obtained

by dry-ashing than by acid-digestion of tissue. Rice is typically very

high in silica. According to Jones (1972), the method of analysis

following wet- or dry-ashing may be a primary factor in differences

obtained. This was not true in the present investigation because Zn

determinations were made by atomic absorption spectrophotometry in both

cases. Differences between Zn contents of seeds determined by dry- and

wet-ashing procedures were generally not as great as for foliar tissues

(Appendix 4 to 10). A probable explanation is that seeds contain

Table 10   Silica contents in foliar tissue and seeds
grown on Keahua soil.

Crop species	Zn applied (mg/kg)	SiO_2 concentration (%) Leaves	Seeds
Corn	1	1.35	0.06
	9	1.02	0.06
Soybean	0	0.39	0.08
	9	0.25	0.05
Sugarcane leaf blades	0	2.78	
	9	1.95	
leaf sheaths	0	2.17	
	9	1.79	
Sorghum	0		0.11
	9		0.07
Millet	0		0.15
	9		0.04
Rice	0		0.24
	9		0.17
Wheat	0		0.09
	9		0.07
Cowpea	0		0.12
	9		0.06

little silica (Table 10).

Because more Zn was recovered by wet-digestion than by dry-ashing, the following discussion is be based on data obtained by wet-digestion.

b. Interpretation of analytical data

Difficulties have been encountered in using and interpreting plant analyses, although the quantitative association between absorbed nutrients and growth has been studied. In interpreting the results of individual experiments, all available information relevant to the problem under investigation should be considered. Published reports can help make sense out of data that would otherwise be difficult to explain. Snedecor (1946) emphasizes the value of utilizing already accumulated information in the following paragraph.

"Some people adopt a rather slavish attitude toward test of significance, rejecting the hypotheses if chi-square is more than 3.841 and accepting it if chi-square is less. This indicates inadequate appreciation of the nature of the information acquired by sampling. A sample furnishes evidence not proof. This evidence is to be added to that already accumulated from experience and reports of other research. Usually, also, there is collateral information accruing during the progress of the experiment. It is the investigator's responsibility to integrate all that evidence and to reach a decision. He cannot evade this responsibility merely by citing a value of chi-square."

Much of the data from greenhouse studies for determining Zn requirements of crops were difficult to interpret using traditional statistical methods. For example, the critical concentration of Zn in

corn ear-leaves at the early silking stage has been established to be about 20 mg Zn/kg (Jones, 1966; and Boehle and Lindsay, 1969; Jones, 1972); although some other researchers (Melsted et al., 1969; Randhawa and Takkar, 1975; Cox and Wear, 1977) have reported values of 15 to 17 mg Zn/kg. It is generally believed that once the critical value associated with a nutrient deficiency has been established, it applies almost universally, regardless of climate or soil type in which the crop was grown, as long as the sampling techniques and analytical methods were comparable throughout (Reisenauer, 1983). This concept is not affirmed by this study.

In the present study, estimation of a critical Zn level in corn ear-leaves was not straight-forward. Three different approaches were used (Fig. 55 a, b, c). When two curves were drawn by joining the points of each soil separately, two widely different critical levels (48 and 24 mg Zn/kg) were obtained for the two soils, (Fig. 55a). While 24 mg/kg was not much different from the established critical Zn level, a concentration of 48 mg/kg was unlikely. The same variety of corn was grown on both soils. According to information gathered by other researchers, a Zn concentration of about 15 to 20 mg Zn/kg plant tissue should be sufficient for optimum growth of corn. No improvement in plant growth and grain yield is generally expected when Zn concentration of corn leaves increases beyond 20 mg Zn/kg. But the interpretation made in Fig. 55a suggest that corn plants grown on Paaloa soil were deficient in Zn until the Zn concentration in ear-leaves was 48 mg Zn/kg. Remembering the advice of Snedecor and
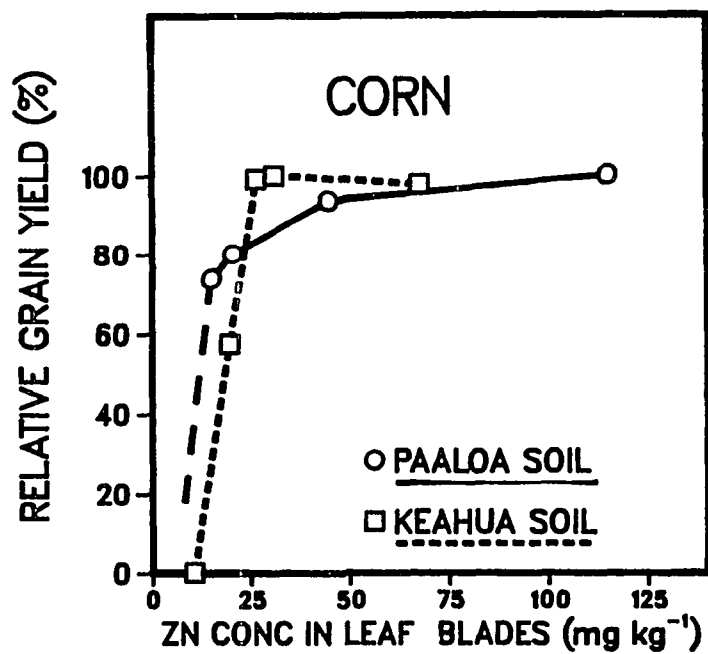
Fig. 55a Relationship between Zn concentration
of ear-leaf and grain yield of corn
(Seperate curve for each soil).
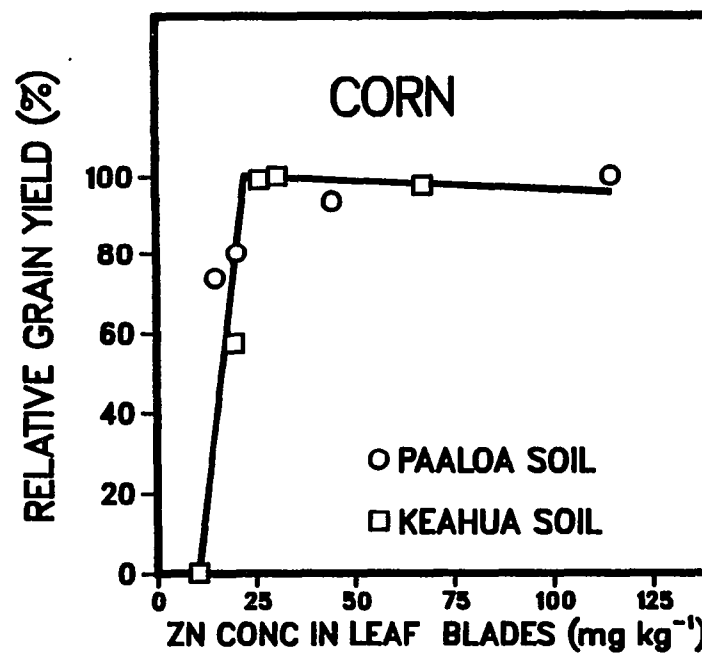
Fig. 55b Relationship between Zn concentration
of ear-leaf and grain yield of corn
(Linear response plateau).
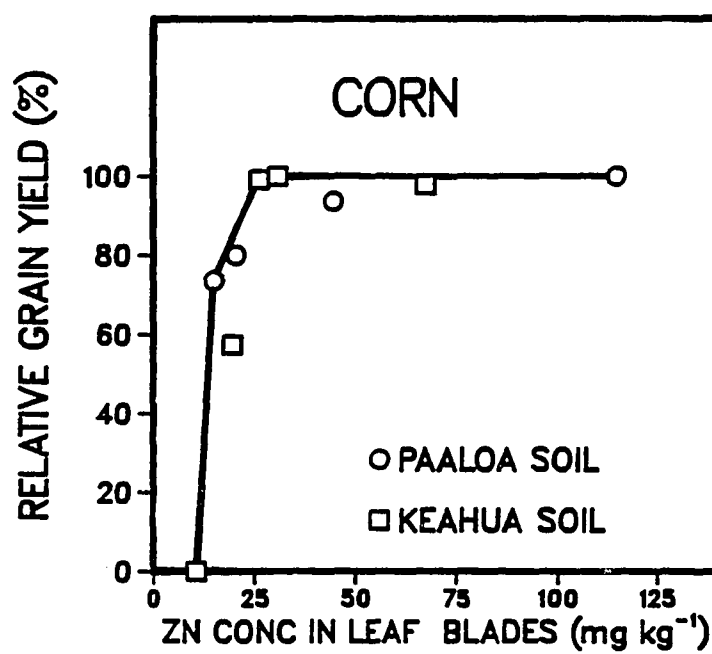
Fig. 55c   Relationship between Zn concentration
            of ear-leaf and grain yield of corn
            (Response envelope).

keeping in view the information gathered by previous researchers over many years, the data were replotted by two other techniques (Fig. 55 b, c). The approaches used in the later plots gave the same value, 24 mg Zn/kg, for both soils, a value that was approximately equal to critical values already established. Response envelope or response boundary techniques of plotting data of this sort have been employed in recent years by several investigators (Cornforth and Steele, 1981, Kang and Fox, 1980, Worku et al., 1982; Fox et al., 1985). The chief concern in using this technique in the present work was that the number of data points were few.

A critical value of 24 mg Zn/kg obtained by the response envelope technique is a reasonable estimate as judged by published data. Even this value is a little greater than the commonly reported value of 20 mg Zn/kg. There are several possible reasons for this higher estimate. First, crop varieties vary with respect to their Zn requirements (Brown et al., 1972). This is true for corn (Halim et al., 1968). Second, leaf tissue sampled in this study was composed entirely of leaf blade lamina, excluding midribs. Zinc concentration of midribs is about half than that of leaf blades (Jones, 1970). Third, while critical levels reported in the literature were usually estimated for 85 or 90% yield, the levels reported here were based on 95% of the maximum yield.

If 24 mg Zn/kg is the critical level of Zn in corn leaves, why did crop growth and yield increase with Zn concentration on Paaloa soil? Hylton et al. (1967) reported that the critical level of an element can shift rather widely if an interfering or complementary element is

Table 11   Phosphorus contents in foliar tissue grown on Paaloa and Keahua soils.

Crop species	Zn applied (mg/kg)	P conc in leaves (%)	
		Paaloa soil	Keahua soil
Corn	1	0.55	0.66
	9	0.43	0.40
Sorghum	0	1.05	0.73
	9	0.50	0.45
Millet	0	1.28	1.71
	9	0.53	0.47
Rice	0	0.33	0.31
	9	0.29	0.27
Wheat	0	0.57	0.64
	9	0.46	0.47
Soybean	0	2.11	1.41
	9	0.38	0.51
Cowpea	0	2.28	1.68
	9	0.60	0.69
Sugarcane leaf blades	0	0.32	0.34
	9	0.30	0.25
leaf sheaths	0	0.14	0.14
	9	0.14	0.14

Table 12 Iron contents in foliar tissue grown on
Paaloa and Keahua soils.

Crop species	Zn applied (mg/kg)	Fe concentration (mg/kg)	
		Paaloa soil	Keahua soil
Corn	1	174	260
	9	131	154
Sorghum	0	233	209
	9	111	124
Millet	0	275	165
	9	101	83
Rice	0	142	88
	9	62	77
Wheat	0	114	119
	9	59	71
Soybean	0	266	177
	9	92	111
Cowpea	0	178	414
	9	103	375
Sugarcane leaf blades	0	89	79
	9	77	72
leaf sheaths	0	37	41
	9	38	32

Table 13   Effect of Zn fertilization on Cu contents in
corn leaves.

Soil	Zn applied (mg/kg soil)				
	0	1	3	9	27
	------------(Cu conc, mg/kg)------------				
Paaloa	–	17.8	16.1	13.9	19.9
Keahua	9.6	7.0	6.3	6.5	5.3

Table 14   Copper contents in foliar tissue grown on
Paaloa and Keahua soils.

Crop species	Zn applied (mg/kg)	Cu conc in leaves (mg/kg)	
		Paaloa soil	Keahua soil
Corn	1	17.8	9.6
	9	13.9	6.5
Sorghum	0	11.7	6.6
	9	9.8	4.5
Millet	0	27.0	9.0
	9	16.5	8.3
Rice	0	13.2	6.2
	9	10.7	5.1
Wheat	0	12.9	5.7
	9	11.3	4.9
Soybean	0	10.8	5.7
	9	7.5	4.5
Cowpea	0	16.7	13.6
	9	11.3	5.3
Sugarcane leaf blades	0	8.5	4.2
	9	7.5	3.8
leaf sheaths	0	4.2	3.2
	9	4.8	2.9

present. For example, the critical level of K for Italian ryegrass was between 0.8 to 3.5%, depending on the concentration of Na in the blade tissue. This does not invalidate the concept but does illustrate the importance of interpretation. The critical level of Zn can be greatly influenced by the presence of other minerals. For example, high concentrations of Mn in corn leaves resulted in high Zn requirements (Fuehring and Soofi, 1964). In this study, Mn content was not a factor because Mn contents of plants grown on Paaloa soil were much lower than those grown on Keahua soil (Table 8, 9). An increase in Zn requirements of plant tissue due to high P or Fe levels was also unlikely because P and Fe contents of plants grown on Paaloa soil were not much greater than Keahua soil (Table 11, 12). Plants grown on Paaloa soil contained higher levels of Cu than plants on Keahua soil (Table 13, 14). It appears that excess availability of Cu in Paaloa soil may have interfered with an otherwise adequate Zn level. These observations are in keeping with the organic matter content and weathering of Paaloa soil. Further studies are needed to test this hypothesis.

c. Critical zinc levels in plant tissue

i. Seedlings

Critical Zn concentrations in seedlings of cereals associated with 95% of maximum grain yield were estimated from Fig. 56 to 60 and the values obtained are listed in Table 15. Critical Zn levels for corn, sorghum, rice and wheat were approximately the same, ranging from 18 to 23 mg Zn/kg. A much higher value, 40 mg/kg, was obtained for millet.

Fig. 56 Relationship between Zn concentration in seedling and grain yield of corn.

Fig. 57   Relationship between Zn concentration
          in seedling and grain yield of sorghum.

Fig. 58   Relationship between Zn concentration
          in seedling and grain yield of millet.

Fig. 59 Relationship between Zn concentration in seedling and grain yield of rice.

Fig. 60 Relationship between Zn concentration in seedling and grain yield of wheat.

Table 15   Critical levels of Zn in plant tissue *
(wet-digested), for 95% relative yield*.

Crop species	Zn concentration (mg/kg)		
	Seedling	Leaves	Seeds
Corn	18	24	18
Sorghum	23	19	10
Millet	40	24	15
Rice	20	19	15
Wheat	19	17	15
Soybean		22	43
Cowpea		21	36
Sugarcane		18 (blades) 14 (sheaths)	

* Grain yield except for dry matter yield of sugarcane after 90 days growth.

Cox and Wear (1977) reported a critical Zn level for young corn plants (five to six leaf stage) to be approximately 20 mg Zn/kg. For sorghum seedlings, Lockman (1972) estimated a critical Zn level of approximately 30 mg Zn/kg. Kausar et al. (1976) reported 17.4 mg Zn/kg as the critical Zn concentration in rice plants at the preflowering stage.

In this study, the critical Zn level in wheat seedlings was 19 mg Zn/kg (Table 15). Shukla and Raj (1974) also estimated a value of 19 mg Zn/kg for eight week old wheat shoots. Radjagukguk et al. (1980) reported a critical Zn level of 20 mg Zn/kg in six week old wheat tops and Kausar et al. (1976) reported 14.5 mg Zn/kg for wheat plants at the preflowering stage. This magnitude of difference could scarcely be the result of using different varieties alone.

Zinc contents are usually highest in very young seedlings and decrease with age (Carroll and Loneragan, 1968). Critical Zn levels in seedlings of cereal crops, except corn, were higher than that in foliar tissues sampled at later growth stages (Table 15). Lindsay (1972) thought that decreases in Zn content with age often occur due to depletion of available Zn in the soil or nutrient solution.

ii. Leaf tissue

Critical Zn levels in leaf tissues were estimated from Figure 55c and 61 to 68 and values obtained are presented in Table 15. A plot of Zn concentration in the flag leaf versus grain yield of sorghum, by the response envelop technique, resulted in a sickle-shaped curve and a
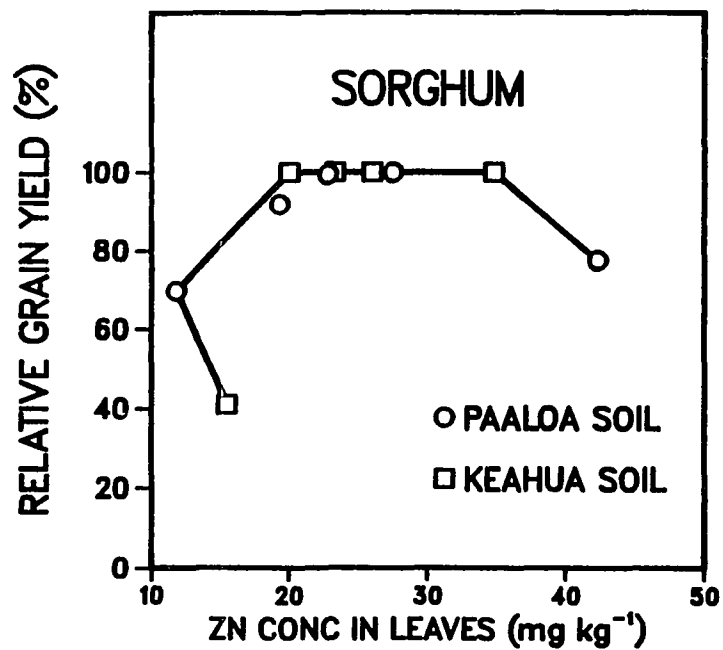
Fig. 61 Relationship between Zn concentration in flag-leaf and grain yield of sorghum.
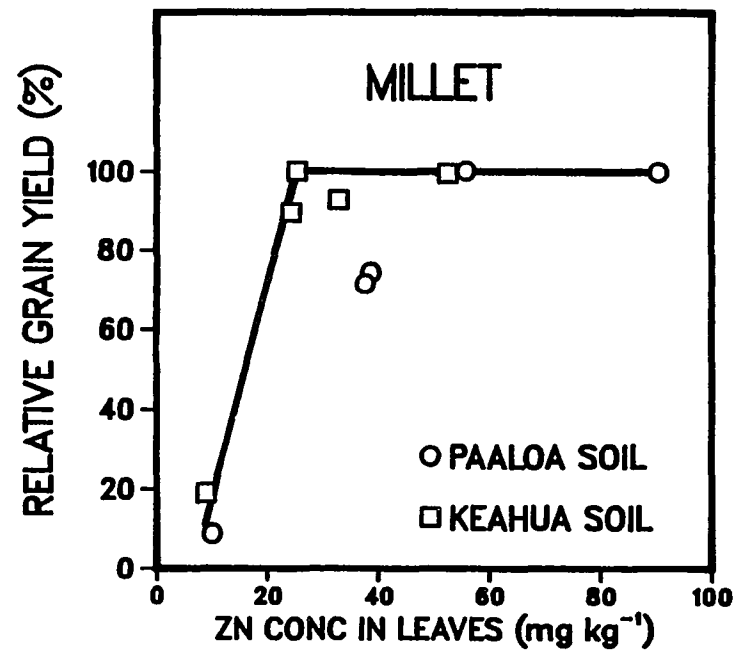
Fig. 62 Relationship between Zn concentration in flag-leaf and grain yield of millet.
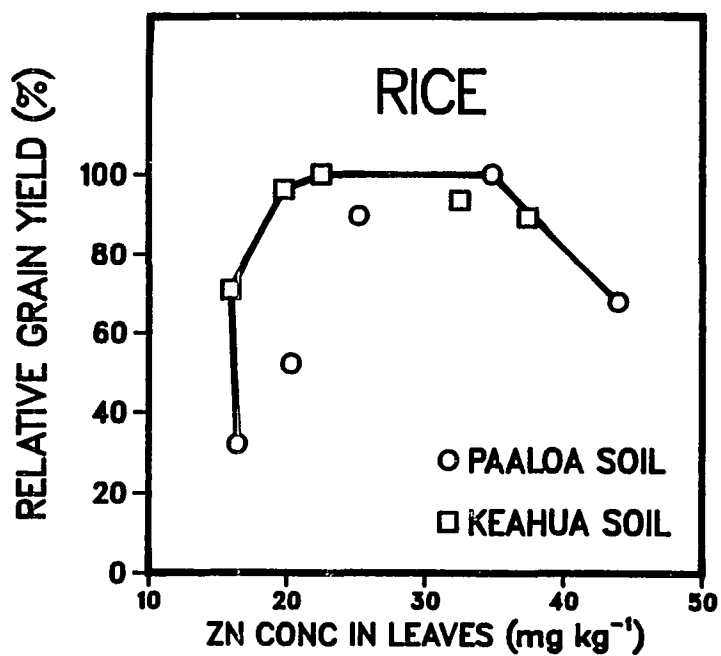
Fig. 63 Relationship between Zn concentration in ear-leaf grain and yield of rice.
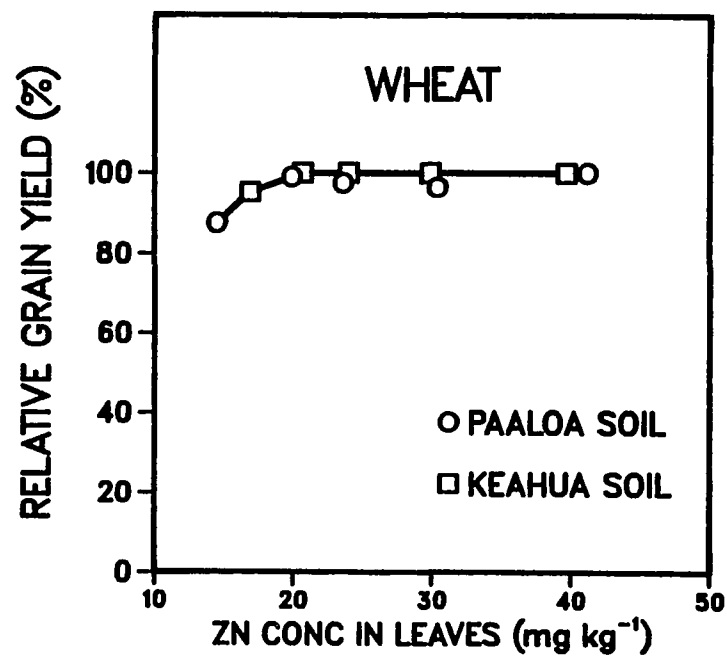
Fig. 64 Relationship between Zn concentration in ear-leaf and grain yield of wheat.
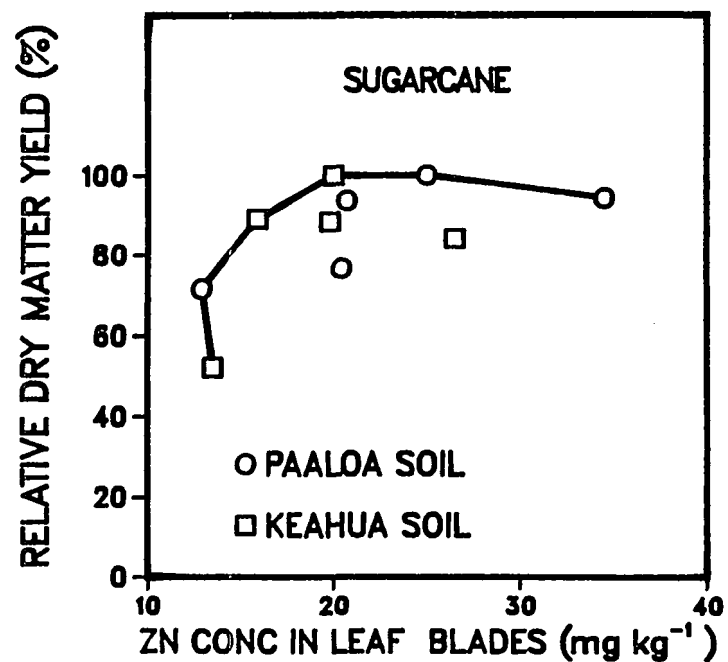
Fig. 65 Relationship between Zn concentration
in leaf blades and dry matter yield
of sugarcane.
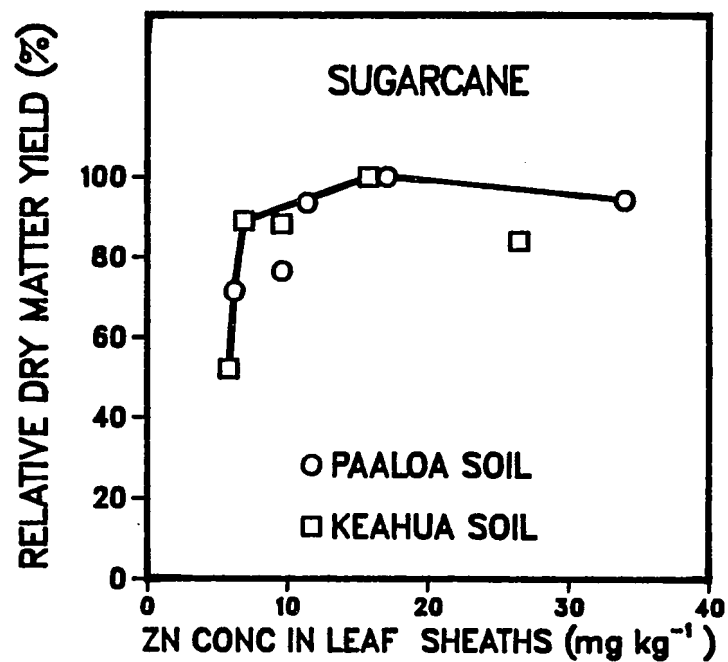
Fig. 66 Relationship between Zn concentration
in leaf sheaths and dry matter yield
of sugarcane.
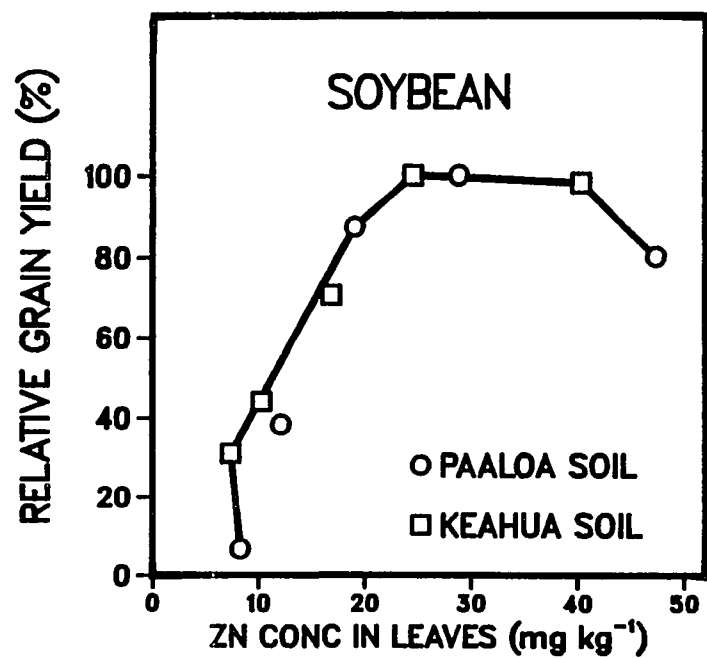
Fig. 67 Relationship between Zn concentration
in most recently matured leaflet and
grain yield of soybean.
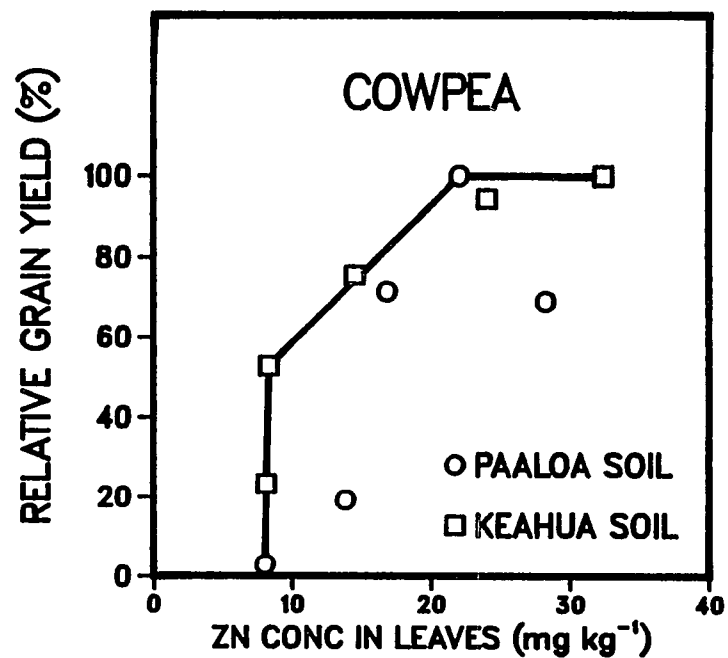
Fig. 68 Relationship between Zn concentration
in most recently matured leaflet and
grain yield of cowpea.

critical level of 19 mg Zn/kg (Fig. 61). The lowest yield was associated with higher than minimum Zn concentration of the leaf tissue. When yields are limited by deficiency of a nutrient, yield reductions may sometimes cause relatively higher concentration of that nutrient in plant tissues. Similar sickle-shaped response curves were obtained by Nishimoto et al. (1975) in estimating P requirements of chrysanthemums.

Critical Zn levels in leaves were higher for corn and millet than for other crops (Table 15). In several areas of the United States, corn develops deficiency symptoms when leaves contain less than 15 to 20 mg Zn/kg (ILZRO, undated). In Michigan, the critical Zn range was somewhat higher, 16 to 25 mg Zn/kg.

The critical Zn concentration for sorghum flag leaves was 19 mg Zn/kg (Table 15). Lockman (1972) reported a value of 15 mg Zn/kg for the third leaf at bloom growth. Chapman (1966) and Ohki (1984), however, list a value of 10 mg Zn/kg for the 2nd leaf from the top of sorghum at heading stage. The higher critical value in this study may be a result of the sampling of leaf lamina excluding the midrib. Midribs of sorghum leaves, like corn, (Jones, 1970) may contain less Zn than leaf laminas.

The critical Zn level in the ear leaf of rice was also 19 mg Zn/kg (Table 15). Other reported Zn values range from 15 to 25 mg Zn/kg (Cox and Wear, 1977; Chaudhry et al., 1977a, b). An earlier report (IRRI, 1969), however, lists 10 mg Zn/kg for leaf blades of rice. This discrepancy may be the result of asking technique; dry-ashing by the

International Rice Research Institute and acid-digestion by Pakistan.

Critical Zn levels in ear leaves of wheat were the lowest of all species, 17 mg Zn/kg. Randhawa et al. (undated) reported a value of 20 mg/kg for wheat in India. The response curve for wheat is so nearly flat that little confidence should be placed in this small difference.

In sugarcane, a concentration of 18 mg Zn/kg in the first visible dewlap leaf and 14 mg/kg in leaf sheaths, no. 3, 4, 5, and 6, was associated with near-maximum yield (Fig. 65, 66). Juang et al. (1974) reported a critical level of 20 mg Zn/kg in young sugarcane leaf blades. For leaf sheaths, a critical Zn concentration of 10 mg Zn/kg was reported by Bowen (1983) and Clements (1980). Their data were obtained by dry-ashing which recover Zn less effectively than wet-digestion (Appendix 9). Zinc concentrations of leaf sheaths obtained by wet digestion were 1.1 to 2.7 times greater than those obtained by dry ashing; the discrepancy being greatest in plant materials with high silica contents (Appendix 9; Table 10). Similarly, analysis of leaf blades by both methods resulted in 1.4 to 2.1 times more Zn by wet digestion than by dry ashing. Therefore, it is likely that the higher estimates for leaf sheaths in this study were caused by more effective recovery of Zn.

Critical Zn level in the most recent fully-expanded leaf of soybean at 50% flowering was 22 mg Zn/kg (Table 15). Small and Ohlrogge (1973) and Jones (1966) reported 21 mg/kg for top mature leaves of soybean at the initial bloom stage. Viets et al. (1954) reported a value of 19 mg Zn/kg and Ohki (1977, 1978) and Melsted et

al. (1969) reported 15 mg/kg for the youngest mature leaves of soybean.

The critical Zn level in the most recently matured leaves of cowpea was 21 mg Zn/kg (Table 15). Andrew et al. (1981) reported 17 mg Zn/kg for cowpea tops at a preflowering stage. Safaya and Malakondaiah (1981), however, give a value of reported 40 mg Zn/kg for 67 day old cowpea shoots, a value that is probably in error.

5. Seeds as Diagnostic Tissues for Zinc Analyses

Contrary to general belief (Jones, 1972; Small and Ohlrogge, 1973), Zn composition of seeds is not constant. In fact, Zn content of seeds varies widely among crop species and within the same species (Table 16). Zinc concentrations of seeds are influenced by the Zn status of soils on which they grow. The range of Zn concentration in seeds of corn, sorghum, and millet, was smaller than in their leaves. Seeds and leaves of rice have similar ranges. Although wheat was comparatively insensitive to Zn deficiency and did not respond significantly to Zn fertilization (Fig. 28, 29), its seeds varied dramaticlly in Zn composition. In fact Zn variability in wheat seeds was greater than in associated leaves (Table 16).

The variability of Zn concentration in wheat seeds and in soils collected from wheat fields of eastern Colorado in presented in Table 17. Seeds sampled from 41 locations in Colorado range from 12 to 60 mg Zn/kg. AB-DTPA-extractable Zn in associated soils range from 0.3 to 6.0 mg Zn/kg. The relationship between Zn contents of soils and of

Table 16   Range of Zn contents in leaves and seeds
(wet-digested) grown in greenhouse.

Crop species	Zn concentration (mg/kg) Leaves	Seeds
Corn	11 - 115	17 - 45
Sorghum	12 - 42	6 - 28
Millet	9 - 90	13 - 51
Rice	16 - 44	12 - 44
Wheat	15 - 41	14 - 71
Soybean	7 - 47	23 - 68
Cowpea	8 - 32	16 - 54
Sugarcane	13 - 45 (blades) 6 - 34 (sheaths)	

Table 17   Range of Zn contents in soils and associated
wheat seeds collected from Colorado.

Seed/soil	Zn concentration (mg/kg)
Wheat seed	12 - 60
AB-DTPA-extr. soil Zn	0.3 - 6.0
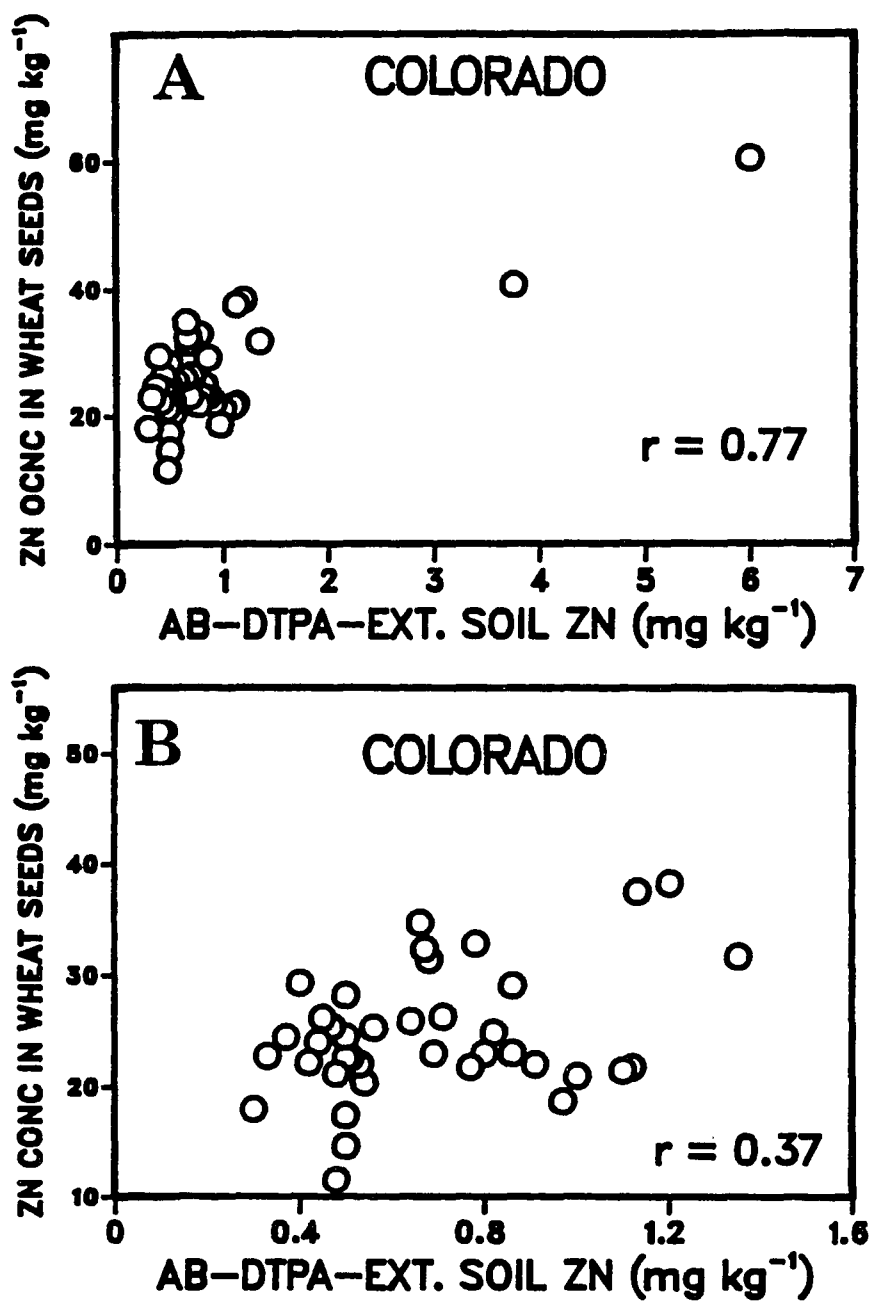
Fig. 69 Relationship between AB-DTPA-extractable soil Zn
and Zn concentration in wheat seeds, Colorado:
(a) 41 sample locations; (b) 39 samples (two
high-Zn locations excluded).

seeds is shown in Fig. 69 a, b. A correlation coefficient of 0.77

between soil and seed Zn (Fig. 69 a) indicates that the Zn content of

wheat seeds was largely determined by the Zn status of soils. If two

locations of very high Zn status were excluded, the correlation

coefficient, however, dropped to 0.37 (Fig. 69 b).

Zinc concentration variability in the seeds of soybean and cowpea

was greater than their leaves. Seeds of both the legumes have greater

Zn concentration than leaves. For analytical precision, seeds of these

legumes are better tissue than leaves.

Critical Zn levels in seeds of all crops estimated from Fig. 70

to 76 are presented in Table 10. Critical levels range from 10 mg

Zn/kg for sorghum seeds to 43 mg Zn/kg for soybean. The level was 18

mg Zn/kg for corn seeds, and 15 mg Zn/kg for the seeds of millet, rice,

and wheat. Zinc concentration associated with near-maximum yield of

both the legumes, soybean and cowpea, was much higher than that of

cereals (Table 15). The critical Zn level in seeds of legumes were

almost twice the critical level in their leaves (Table 15).

Seed analyses have already been proven valuable for evaluating Mo

(Lavy and Barber, 1963), N (Pierre et at., 1977a, b) and S (Fox et al.,

1977) status of soils. The results of this study suggest that seed

composition can also be used to evaluate the Zn status of soils. The

use of seeds rather than leaves as index tissue has several possible

advantages including:

1. Seed samples are more easily secured, cleaned and processed .

2. Time of sampling is not critical. Seed samples can be collected
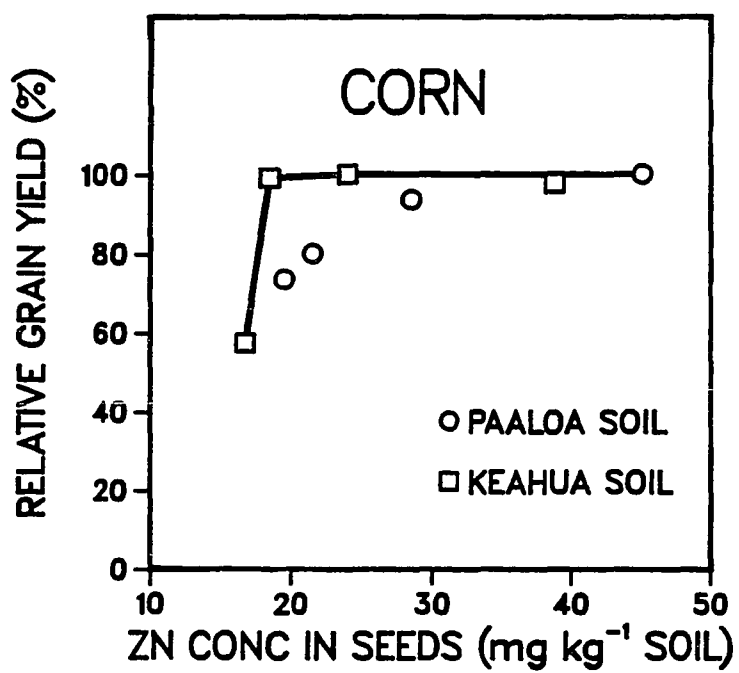
Fig. 70   Relationship between Zn concentration
in seeds and grain yield of corn.
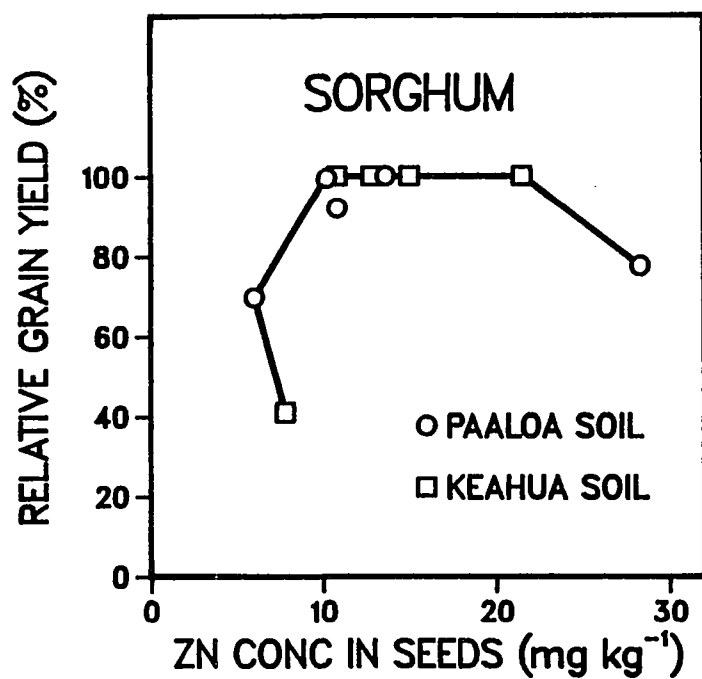
Fig. 71   Relationship between Zn concentration
in seeds and grain yield of sorghum.
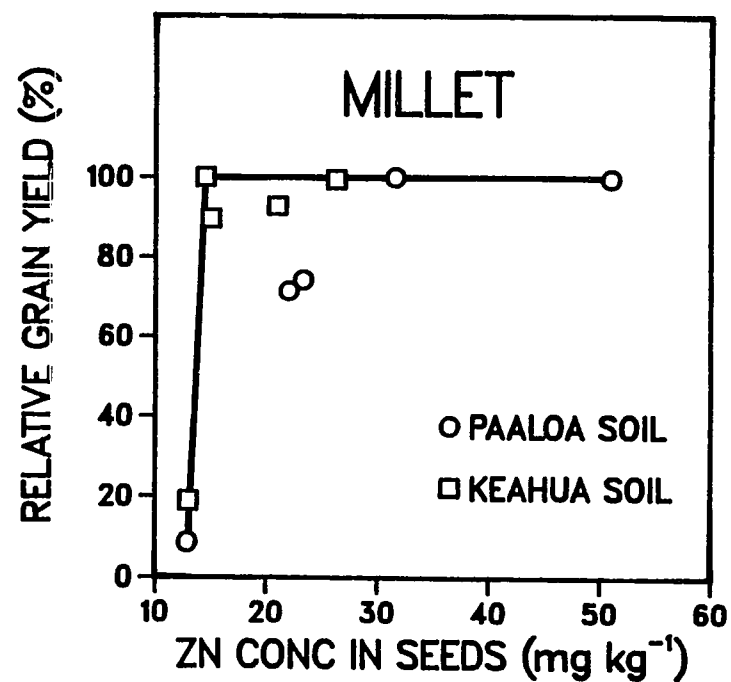
Fig. 72   Relationship between Zn concentration
in seeds and grain yield of millet.
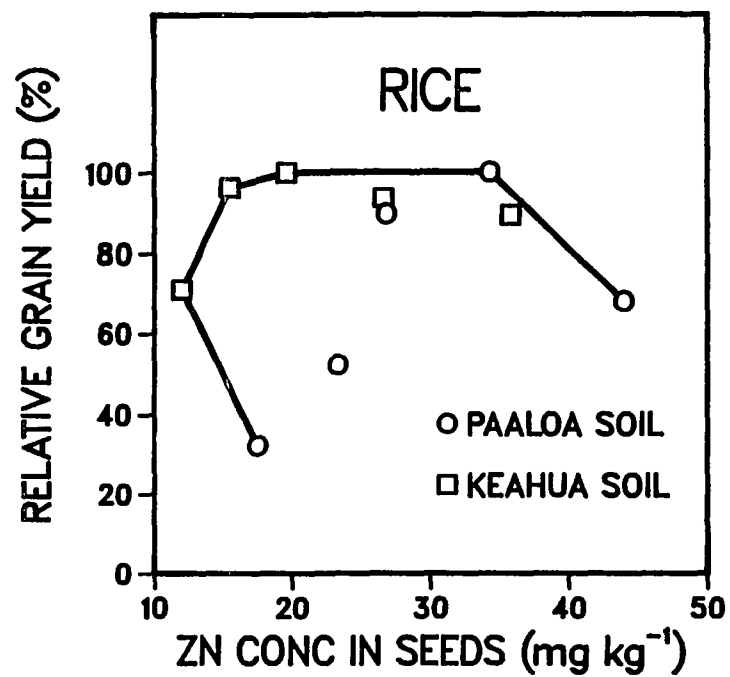
Fig. 73 Relationship between Zn concentration
in seeds and grain yield of rice.
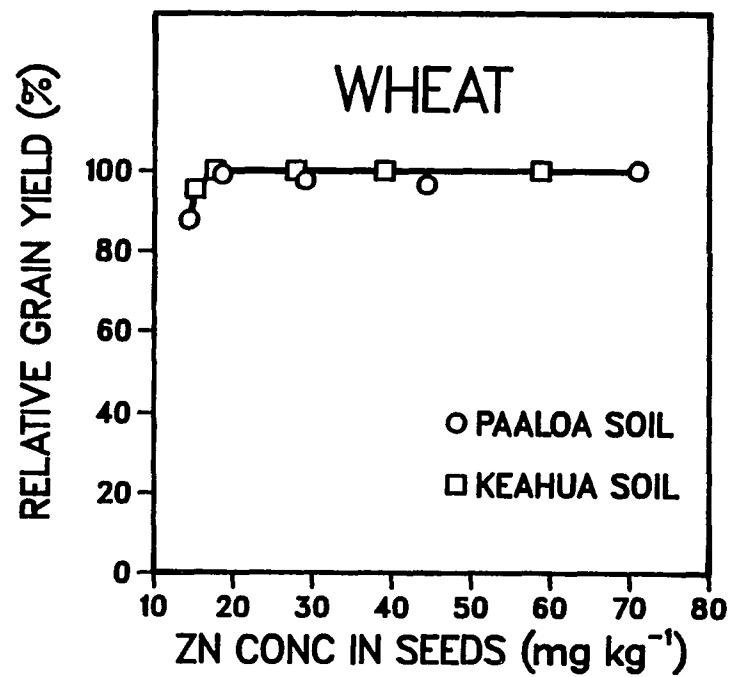
Fig. 74 Relationship between Zn concentration
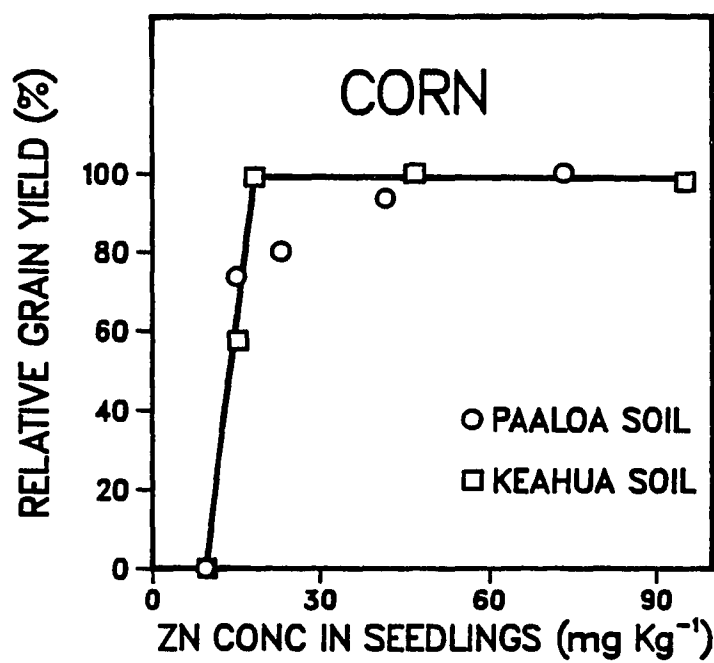in seeds and grain yield of wheat.
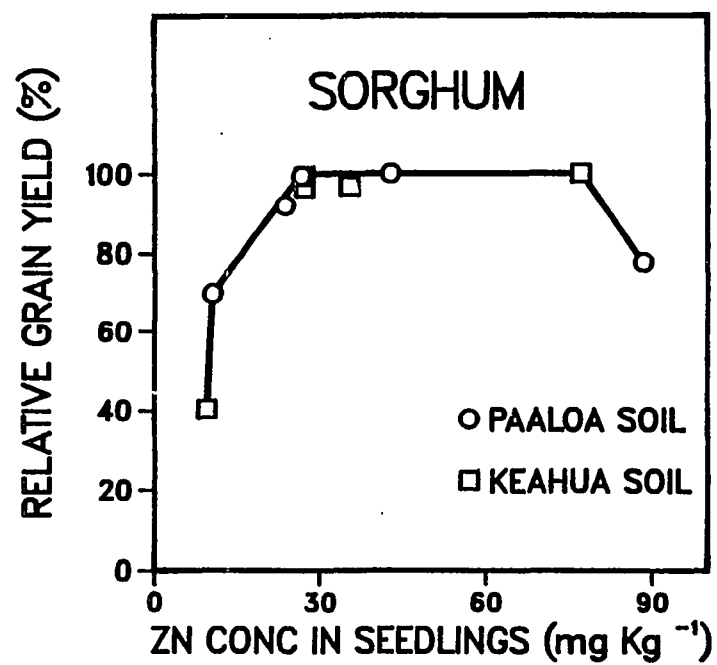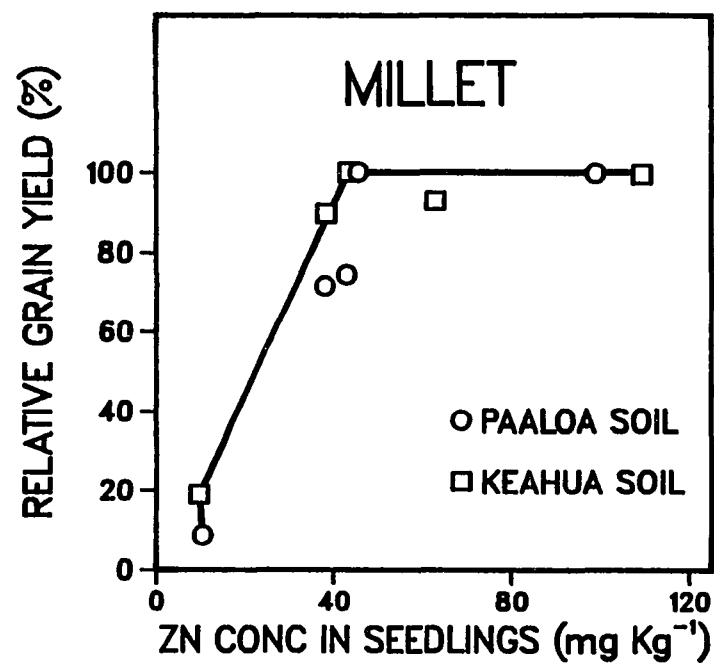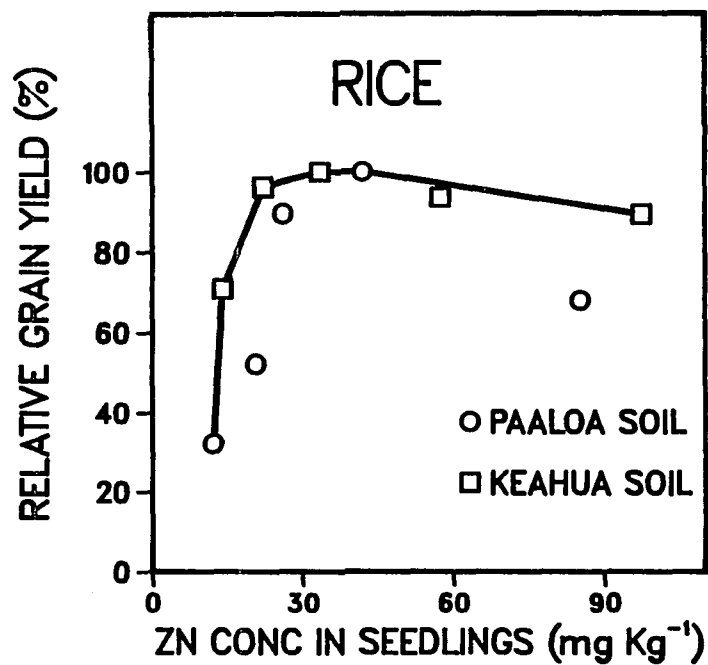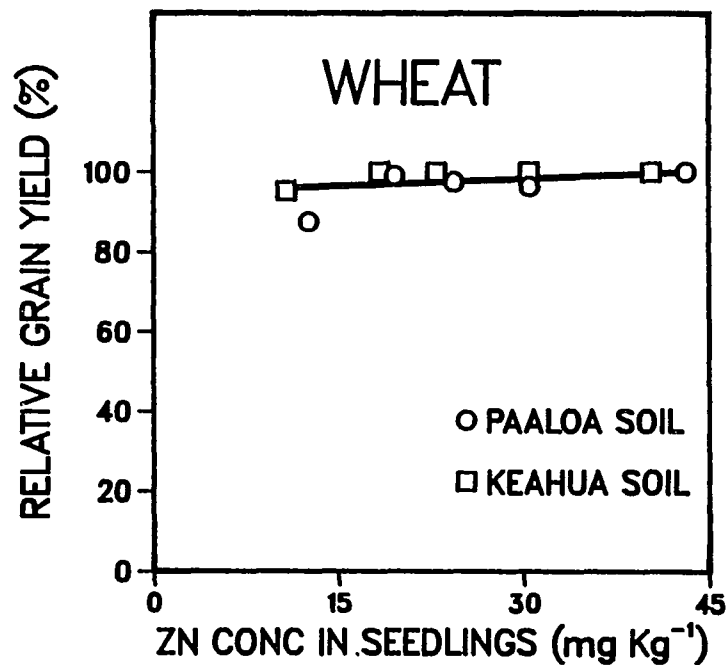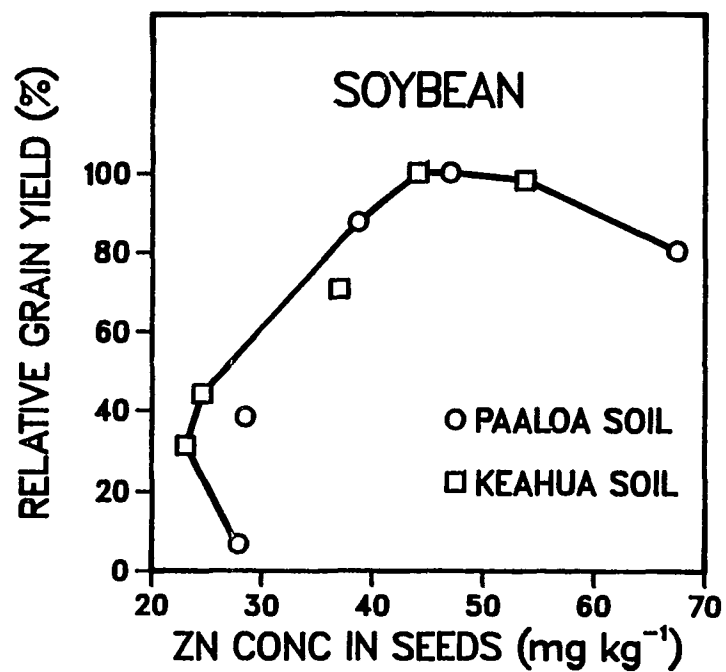
Fig. 75 Relationship between Zn concentration
in seeds and grain yield of soybean.
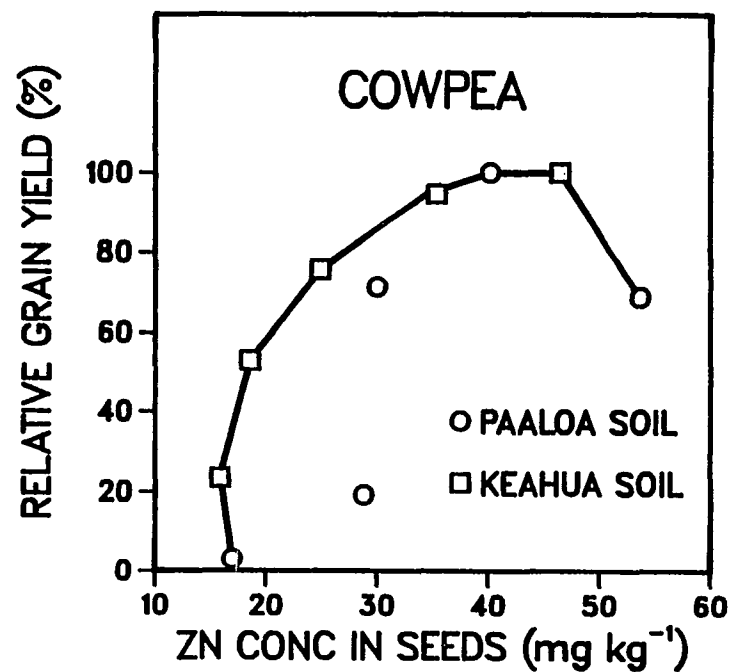
Fig. 76 Relationship between Zn concentration
in seeds and grain yield of cowpea.

any time of the year in different areas.

3. Seeds contain less silica and can be analyzed by dry-ashing.

6. External Zinc Requirements

In this study, Zn concentrations in soil solutions were estimated

from Zn sorption curves (Fig. 77). Soil solution Zn concentration of

deficient soils ranged from 0.03 to 0.04 mg Zn/L. Paaloa soil sorbed

more Zn than Keahua soil. Differences in minerology of the soils may

be responsible for this. Soils containing constant charge colliods

absorb more Zn than soils with variable charge colliods (Saeed and Fox,

1979). A relatively rapid increase in soil solution Zn concentration

of Keahua soils with Zn fertilization (Fig. 77) may be responsible for

a better response of corn, millet, rice and sugarcane when low levels

of Zn fertilizer (Fig. 13, 17, 19, 23) were added to this soil.

Legumes are known to be more dependent on mycorrhizae than cereals.

Differential response of legumes to low Zn fertilizer rates may be due

to differences in mycorrhizal status of plants. Zinc is frequently

mentioned as being influenced by mycorrhizae (Mosse, 1981).

In the greenhouse studies, near-maximum yield of all the crops was

recorded when the quantitiy of Zn fertilizer applied was 7.5 mg Zn/kg

or less (Table 6). These rates of Zn application acarcely changed Zn

concentrations in soil solution (Fig. 77).

A variety of analytical techniques have been developed for

characterizing the fraction of micronutrients in soils available for

plant growth. Many of these methods have merit and practical
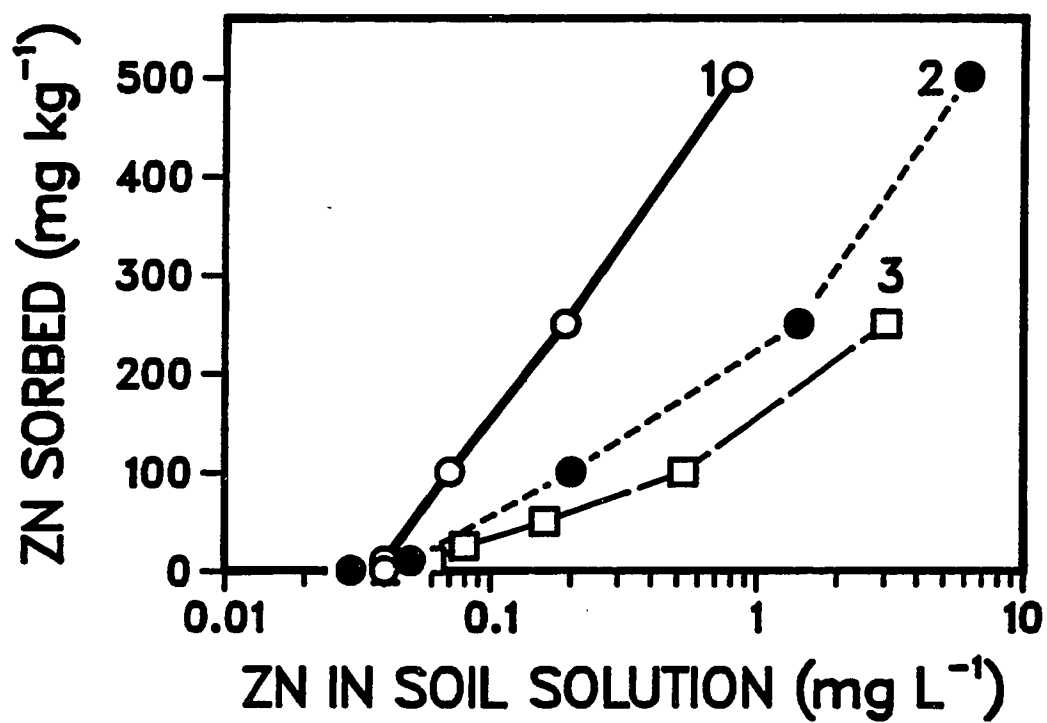
Fig. 77 Zinc sorbed by greenhouse soils in relation to Zn remaining
         in solution (1 = Paaloa subsoil, 2 = Keahua subsoil, 3 =
         Keahua topsoil).

application and were probably developed to overcome analytical problems associated with the low concentration of micronutrients in soil solutions. However, none of the methods successfully evaluate the Zn status of both acid and alkaline soils.

The availability of Zn to plants is governed largely by the solubility of soil minerals and the stability of ionic species in the soil solution (Lindsay, 1979). The soil solution provides an important, immediate nutrient source for plants. Because Zn requirements of plants are small, it is assumed that the Zn concentration in solution does not decrease drastically as a result of cropping, particularly if the soil is well-supplied with this nutrient.

Measurement of Zn concentrations in soil solution offers several advantages over extraction procedures: (a) it can have wide application. Results of analysis of soil types from diverse areas, climates and cultural practices have a basis for more reasonable comparison; (b) results can be compared with data from solution and sand culture experiments, as well as actual soil solution environments; (c) effect of different soil amendments and fertilizer practices on solubility of Zn can be determined.

The concentrations of micronutrients, including Zn, in the soil solution are generally so low that the total quantity present at any one time can sustain relatively little plant growth. To be sufficient for plant growth, Zn needs to be rapidly replenished from the solid phase as it is depleted (Loneragan, 1975).

The concentration and forms of Zn in soil solution has been

studied in relatively few soils. Perhaps the most extensive work was that of Hodgson et al. (1966) on a range of New York and Colorado soils. The concentration of Zn in solution displaced from the surface horizons of these soils ranged from <0.03 to 3 μM (0.000195 to 0.195 mg Zn/L). Concentrations were particularly low in calcareous soils. In general about 50% of Zn was present as complexes.

Bradford et al. (1971) measured the Zn content of soil saturation extracts of 68 soils representing 30 soil series from throughout California. Zinc concentration in saturation extracts of these soils ranged from 0.01 to 0.4 mg Zn/L (mean 0.07 and median 0.04 mg/L). Jeffery and Uren (1983) reported that total concentration of Zn in soil solutions varied very drastically with a change of soil pH. It was 1.8 mg Zn/L at pH 4.4 and 0.012 mg/L at pH 7.5.

Saeed and Fox (1979) used a Zn-sorption technique to measure the Zn concentration of five soils of Hawaii. Zinc concentration in soil solution of those soils ranged form 0.04 to 0.11 mg Zn/L. The soils had been Zn fertilized and levels of extractable Zn were high; DTPA-extractable 5 to 12 mg Zn/kg soil and HCl-extractable 22 to 54 mg Zn/kg soil.

Halvorson and Lindsay (1977) estimated that critical Zn level in soil solution for normal growth of corn plants was about $10^{-10.6}$ M Zn (1.6 X 10^{-6} mg Zn/L). This is much lower than the 10^{-7} M (6.5 X 10^{-3} mg Zn/L) reported by Carroll and Loneragan (1969) from flowing culture experiments. Halvorson and Lindsay suspected that a depletion zone in the free space could have developed in the flowing culture

experiments. They proposed that only free Zn is taken up by the root and the released chelate acts to maintain soluble Zn levels adjacent to the absorbing zones. Salisbury and Ross (1978) also stated that Zn is absorbed largely or entirely as the divalent Zn^{2+} ion.

Ohki (1977, 1984) estimated the critical level of Zn in solution culture to be 0.1 mg Zn/L for soybean and 0.00005 mg Zn/L for sorghum -- values so dissimilar that probably an error is involved.

Although both of the subsoils under study were exceedingly Zn deficient, their soil solution Zn concentration were much greater than the critical Zn levels predicted by solution culture studies (Carroll and Loneragan, 1968; Ohki, 1977, 1984). Furthermore, no appreciable increase in soil solution Zn was recorded with Zn fertilizer rates associated with maximum yield increase of test crops. Thus it appears that measurement of total Zn concentration in soil solution is not helpful in diagnosing the Zn status of soils.

The data suggest that Zn concentration surrounding roots are very quickly decreased by nutrient uptake and that Zn does not readily move back into the rhizosphere by diffusion or otherwise. It is not unusuall for plants to have a higher external P requirement when they grow in soils than when they grow in flowing solution cultures.

In any case, these data suggest that Zn is much less effeciently moved upto and in to the plant roots than P. These kind of P levels are enough to get 1000 to 3000 mg P/kg into many plants. Could it be that Zn absorption sites on roots are more widely apaced than P absorption sites -- then Zn has, on average, further to move by

diffusion to reach an absorption site.

B. Spatial Variability of Zinc in Soils and Crops

Soil properties are continuous variables. Property values at a given location may vary from values of neighboring samples according to direction and distance (Burgess and Webster, 1980a). In so doing, they exhibit spatial dependence within a localized region.

One of the major objectives of this study was to prepare maps indicating the Zn status along with other related properties of soils and associated plants . Soil and plant tissue samples were collected from wheat fields of Colorado and two sugarcane plantations on the island of Maui, Hawaii. Maps for these locations were prepared using geostatistical techniques. Zinc is not considered to be a problem element in wheat fields of Colorado or in sugarcane fields of Hawaii. Thus, Zn is not routinely applied to the soils mapped in this study. Therefore, the maps presented in subsequent sections indicate the native soil Zn status.

Recent developments in statistical theory permit spatial relationships among sample values to be used to interpolate between sample points. These developments are based on the theory of regionalized variables which takes into account both structured and random characteristics of spatially distributed variables to provide quantitative tools for their description and optimal, unbiased estimation.

Such procedures have precedent in soil investigations. For

example, Campbell (1978) used geostatistical methods to compute and display semi-variograms for soil texture and pH of soil derived from loess and glacial-till. In Hawaii, Yost et al. (1982a, b) used geostatistics to determine spatial variability of soil chemical properties and create isarithmic maps of soil properties and fertilizer requirements. Trangmar et al. (1984) computed isarithmic maps of sand, clay, pH, and total P using a fine grid of locations and geostatistical methods.

1. Colorado

The area of Colorado state is 270,000 square kilometers. Eastern Colorado, a little less than half of the state, is mostly under agricultural crops. Wheat is a major crop in eastern Colorado and it comprises more than one half of the harvested area.

Soil and associated wheat grain samples were collected from 41 locations throughout the wheat producing areas of eastern Colorado. Most soils of eastern Colorado are alkaline and calcareous. The pH of surface soils ranged from 6.2 to 8.0 and $CaCO_3$ contents ranged from 0 to 10.2%. pH and $CaCO_3$ content were greater in subsoils than in surface soils (Table 18). Clay content of surface soils varied from 12 to 42%. Soils collected from Colorado belong to three soil orders: Aridisol, Entisol, and Mollisol (Appendix 1).

AB-DTPA-extractable Zn varied widely in both surface soils and subsoils, (Table 18). Extractable Zn in most soils was less than the critical level of 0.9 mg Zn/kg soil proposed by Soltanpour (1985).

Table 18   Mean, range and standard deviation of properties of
soils and wheat seeds, Colorado.

Variable	Mean/ median*	Range	Standard deviation	Distribution

Surface soils (0-15 cm)

Variable	Mean/median*	Range	Standard deviation	Distribution
pH	7.3	6.2-8.0	0.5	normal
E.C. (dS/m)	0.53	0.2-1.4	0.29	-[a]
CaCO$_3$ (%)	1.6	0.0-10.2	2.52	-
O.M.^{3}(%)	1.35	0.7-2.2	0.34	normal
Sand (%)	27	7-79	16	log
Silt (%)	38	9-56	12	normal
Clay (%)	30	12-42	7	normal

AB-DTPA-
extractable (mg/kg)

Zn	0.88	0.33-6.0	0.98	-
Fe	11.2	5.3-27.2	5.3	log
Mn	8.0	3.0-27.8	5.9	log
Cu	3.5	0.9-16.2	3.1	log
P	3.15	0.35-14.7	3.31	log
K	429	167-704	131	normal

Subsoils (30-45 cm)

Variable	Mean/median*	Range	Standard deviation	Distribution
pH	7.6	6.5-8.0	0.4	-
E.C. (dS/m)	0.4	0.2-0.8	0.13	-
CaCO$_3$ (%)	4.8	0.0-16.4	4.7	-
O.M.^{3}(%)	0.94	0.4-1.5	0.24	normal
Sand (%)	25	4-76	15	log
Silt (%)	39	10-67	12	normal
Clay (%)	33	14-45	7	normal

Table 18   Mean, range and standard deviation of properties of
(cont.)   soils and wheat seeds, Colorado.

Variable	Mean/ median*	Range	Standard deviation	Distribution
Subsoils (30-45 cm)				
AB-DTPA-extractable (mg/kg)				
Zn	0.56	0.26-2.5	0.36	-
Fe	7.0	3.1-18.0	3.3	log
Mn	4.4	2.2-20.7	3.8	log
Cu	4.7	1.4-15.0	3.0	log
P	1.30	0.13-16.6	2.72	log
K	393	154-773	152	normal
Wheat Grain				
Zn (mg/kg)	24	12-60	8	log
Fe (mg/kg)	33	24-44	5	normal
Mn (mg/kg)	49	28-81	12	normal
Cu (mg/kg)	5.3	3.0-6.9	1.0	normal
P (%)	0.35	0.25-0.44	0.053	normal
K (%)	0.45	0.34-0.57	0.054	normal
Na (mg/kg)	15.7	5.0-37.5	7.8	-
Ca (mg/kg)	520	370-1430	170	-
Mg (mg/kg)	1700	1430-1880	130	-

* -- Median values are given for lognormally distributed data.
a -- Data did not fit to normal or log-normal distribution.
E.C. -- Electrical conductivity.
O.M. -- Organic matter.
AB-DTPA -- Ammonium bicarbonate-diethylenetriaminepentaacetic acid.

Table 19 Correlation coefficients and levels of significance of some soil and wheat seed properties with soil and seed Zn status, Colorado.

	Topsoil Zn (mg/kg)		Seed Zn (mg/kg)	
	Correlation coefficient (r)	significance	Correlation coefficient (r)	significance
Topsoil				
pH	0.11	0.50	-0.018	0.91
CaCO$_3$ (%)	0.077	0.63	0.054	0.74
Clay (%)	0.038	0.81	0.16	0.33
Zn (mg/kg)	1		0.77	0.0001
Fe (mg/kg)	0.098	0.54	0.035	0.83
Mn (mg/kg)	-0.023	0.89	-0.12	0.46
Cu (mg/kg)	0.40	0.1	0.37	0.017
P (mg/kg)	0.17	0.29	-0.038	0.82
K (mg/kg)	-0.13	0.41	-0.0023	0.99
Subsoil Zn (mg/kg)	0.77	0.0001	0.54	0.0003
Wheat seed				
Zn (mg/kg)	0.77	0.0001	1	
Fe (mg/kg)	0.33	0.034	0.38	0.013
Mn (mg/kg)	0.066	0.68	0.081	0.62
Cu (mg/kg)	0.11	0.51	0.25	0.12
P (%)	0.081	0.61	0.13	0.41
K (%)	-0.13	0.41	-0.064	0.69
Na (mg/kg)	0.104	0.52	0.067	0.68

Table 19 Correlation coefficients and levels of significance of
(cont.)   some soil and wheat seed properties with soil and seed
         Zn status, Colorado.

	Subsoil Zn (mg/kg) Correlation coefficient (r)	significance	Seed Zn (mg/kg) Correlation coefficient (r)	significance
SubSoil				
pH	0.098	0.54	-0.073	0.65
CaCO$_3$ (%)	-0.027	0.87	0.027	0.87
Clay (%)	-0.044	0.79	0.021	0.89
Zn (mg/kg)	1		0.54	0.0003
Fe (mg/kg)	0.18	0.26	-0.086	0.59
Mn (mg/kg)	0.16	0.33	-0.24	0.14
Cu (mg/kg)	0.36	0.022	0.097	0.55
P (mg/kg)	-0.0035	0.98	-0.16	0.31
K (mg/kg)	-0.20	0.21	-0.042	0.79
Topsoil Zn (mg/kg)	0.77	0.0001	0.77	0.0001
Wheat seed				
Zn (mg/kg)	0.54	0.0003	1	
Fe (mg/kg)	0.21	0.18	0.38	0.013
Mn (mg/kg)	0.072	0.66	0.081	0.62
Cu (mg/kg)	0.13	0.41	0.25	0.12
P (%)	-0.20	0.21	0.13	0.41
K (%)	-0.27	0.089	-0.064	0.69
Na (mg/kg)	-0.11	0.48	0.067	0.68

However, the Zn status of some soils was adequate even for sensitive crops. Concentrations of wheat grain Zn also varied widely (Table 18).

Subsoils contained less extractable Zn than topsoils. This is probably a consequence of Zn recycling by plants and, in addition, higher levels of $CaCO_3$ and less organic matter in subsoils (Table 18).

a. Statistical analysis

A correlation matrix between Zn data and other properties of soil and wheat grain is given in Table 19. There was no relationship between soil pH and extractable soil Zn and between soil pH and wheat grain Zn. Zinc contents of topsoils and subsoils were related (r = 0.77).

The correlation coefficient between wheat grain Zn and topsoil Zn was 0.77 and wheat grain Zn and subsoil Zn was 0.54. Correlation coefficient between kriged values of topsoil Zn and kriged values of wheat grain Zn was 0.87.

b. Spatial analysis

Soil and wheat grain properties listed in Table 20 were analyzed for spatial dependence. Parameters associated with semi- variograms of the properties that varied isotopically are listed in Table 20 and the mathematical models fitted to semi-variograms are listed in Table 21.

The semi-variogram of surface soil pH was linear implying that soil pH was nonstationary. However, R^2 of linear fit was only 0.26 (significant at 0.05). Nugget variance was very high (67% of the sill).

Although the sample locations were few and these were scattered

Table 20   Parameter estimates of isotropic semi-variograms[a] of soil properties and composition of wheat seed, Colorado.

Variables	Range (km)	Nugget variance	Sill	% of sill	General variance	Model[b]	R^2 of model[c]
			Surface soil (0-15cm)				
pH	129	0.14	0.21	67	0.21	L	0.26[**]
CaCO$_3$ (%)		No structure					
Sand (%)		No structure					
Silt (%)		No structure					
Clay (%)		No structure					
AB-DTPA-extractable (mg/kg)							
Zn	131	0.045	0.72	6.3	0.96	S	0.64
Fe		No structure					
Mn		No structure					
Cu		No structure					
P		No structure					
K		No structure					
			Subsoil (30-45 cm)				
pH	196	0.046	0.17	27	0.14	L	0.58
CaCO$_3$ (%)		No structure					
Sand (%)		No structure					
Silt (%)		No structure					
Clay (%)		No structure					
AB-DTPA-extractable mg/kg)							
Zn	142	0.0011	0.128	0.9	0.128	L	0.86
Fe	180	0.02	0.22	9	0.16	L	0.88

Table 20 Parameter estimates of isotropic semi-variograms[a]
(cont.)   of soil properties and composition of wheat seed,
           Colorado.

Variables	Range (km)	Nugget variance	Sill	% of sill	General Model[b] variance		R^2 of model[c]

Subsoil (30-45 cm)

Variables	Range (km)	Nugget variance	Sill	% of sill	General Model[b] variance		R^2 of model[c]
Mn	No structure						
Cu	No structure						
P	No structure						
K	No structure						

Wheat seed

Variables	Range (km)	Nugget variance	Sill	% of sill	General Model variance	Model	R^2 of model
Zn (mg/kg)	117	0.0044	0.073	6	0.081	S	0.82
Fe (mg/kg)	No structure						
Mn (mg/kg)	201	16.8	161.1	10	137.74	S	0.82
Cu (mg/kg)	174	0.44	1.00	44	1.00	L	0.32
P (%)	No structure						
K (%)	No structure						
Na (mg/kg)	No structure						
Ca (mg/kg)	No structure						
Mg (mg/kg)	No structure						

a -- Semi-variances for sand, soil Fe, Mn, Cu, P, and wheat grain
     Zn determined on log transformed values.

b -- L = Linear model, M = Mitscherlich (exponential) model,
     S = Spherical model.

c -- $R^2 = (SS_{corrected} - SS_{residual})/SS_{corrected}$.
     R^2 for model fitted up to range. All R^2 values
     significant at $P < 0.01$ unless otherwise indicated.

$$\% \text{ of sill} = \frac{\text{nugget variance}}{\text{sill}} \times 100.$$

Table 21 Mathematical models fitted to isotropic semi-variograms
of soil and wheat grain properties, Colorado.

Variable	Model	Equation
Topsoil pH	L	$\gamma(h) = 0.14 + 0.00038\ h$
Subsoil pH	L	$\gamma(h) = 0.046 + 0.00058\ h$
Topsoil Zn (mg/kg)	S	$\gamma(h) = 0.045 + 0.0082\ h - 0.000000\ h^3$
Subsoil Zn (mg/kg)	L	$\gamma(h) = 0.0011 + 0.00085\ h$
Subsoil Fe (mg/kg)	L	$\gamma(h) = 0.02 + 0.0013\ h$
Wheat grain		
Zn (mg/kg)	S	$\gamma(h) = 0.0044 + 0.00093\ h - (2.29 \times 10^{-8})\ h^3$
Mn (mg/kg)	S	$\gamma(h) = 16.8 + 806\ h - 2983\ h^3$
Cu (mg/kg)	L	$\gamma(h) = 0.44 + 0.00296\ h$

L -- Linear model
M -- Mitscherlich model
S -- Spherical model

over a very large area, almost half the State of Colorado (Fig. 4), good structure was demonstrated in semi-variograms for Zn content of soils and wheat grain. The semi-variogram for topsoil Zn was isotropic spherical (R^2 = 0.64; Fig. 78). The range of spatial dependence was 131 km. In geostatistics, range corresponds to the maximum distance over which sample values are spatially related. Nugget variance was small (Table 24). The semi-variogram for subsoil Zn displayed a linear structure implying nonstationarity in this soil property. The nugget variance was negligible (0.9% of sill). The range of spatial dependence for subsoil Zn was 142 km, which was greater than the range for topsoil Zn. Ahmad (1985) has also reported an increase in the range of spatial dependence for soil pH with an increase in soil depth.

A spherical model gave the best fit to the semi-variogram of wheat grain Zn (Fig. 79). The R^2 value was 0.82 and nugget variance was small (Table 20). The range of spatial dependence was 117 km, which was approximately the range for soil Zn.

No structure or indication of spatial dependence was detected in semi-variograms of other properties of soil and wheat grain. This probably is the result of insufficient sampling points.

c. Kriging

Isarithm maps of soil and wheat grain Zn were prepared by using a block kriging program and computer graphics procedure (Trangmar, 1984; Bridges and Becker, 1976).

The map of Zn status of topsoils indicated two areas with very
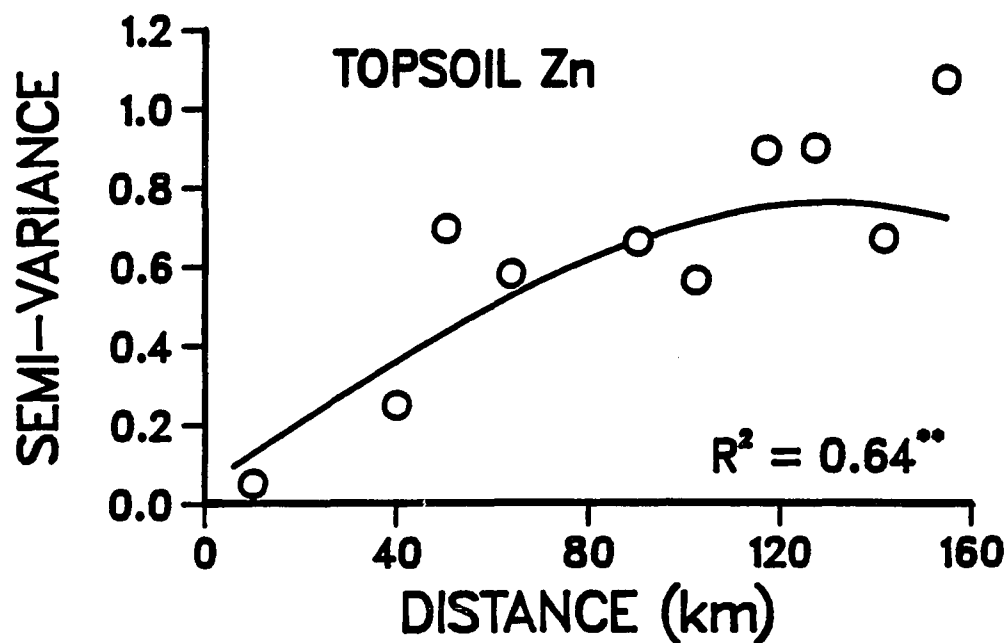
Fig. 78 Isotropic semi-variogram for AB-DTPA-extractable Zn
(mg/kg) in surface soils, Colorado.
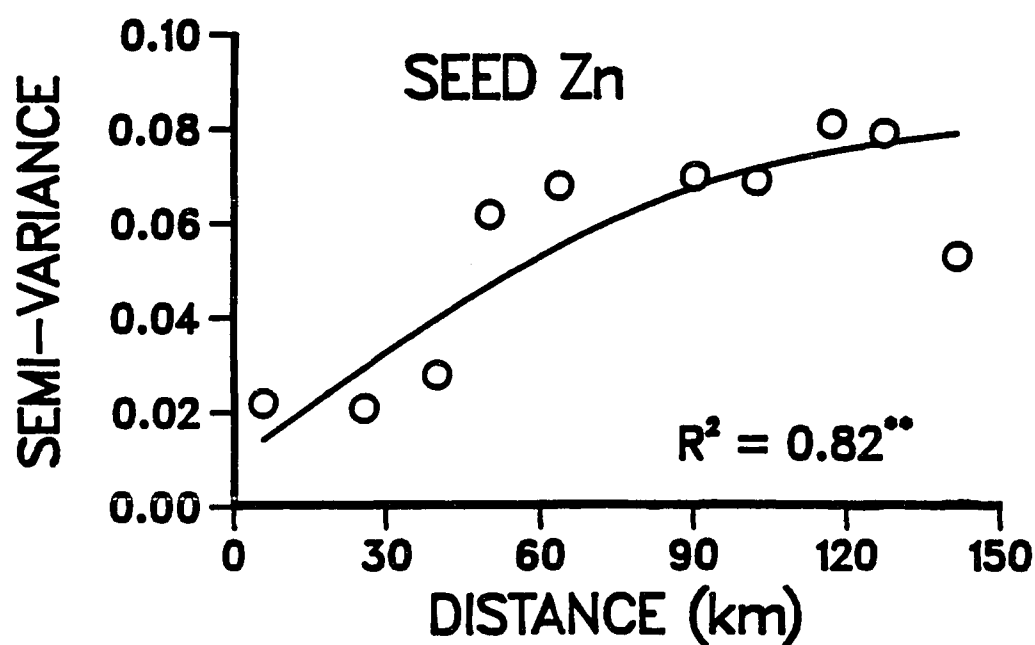
Fig. 79 Isotropic semi-variogram for log transformed values of
Zn concentration (mg/kg) in wheat seeds, Colorado.
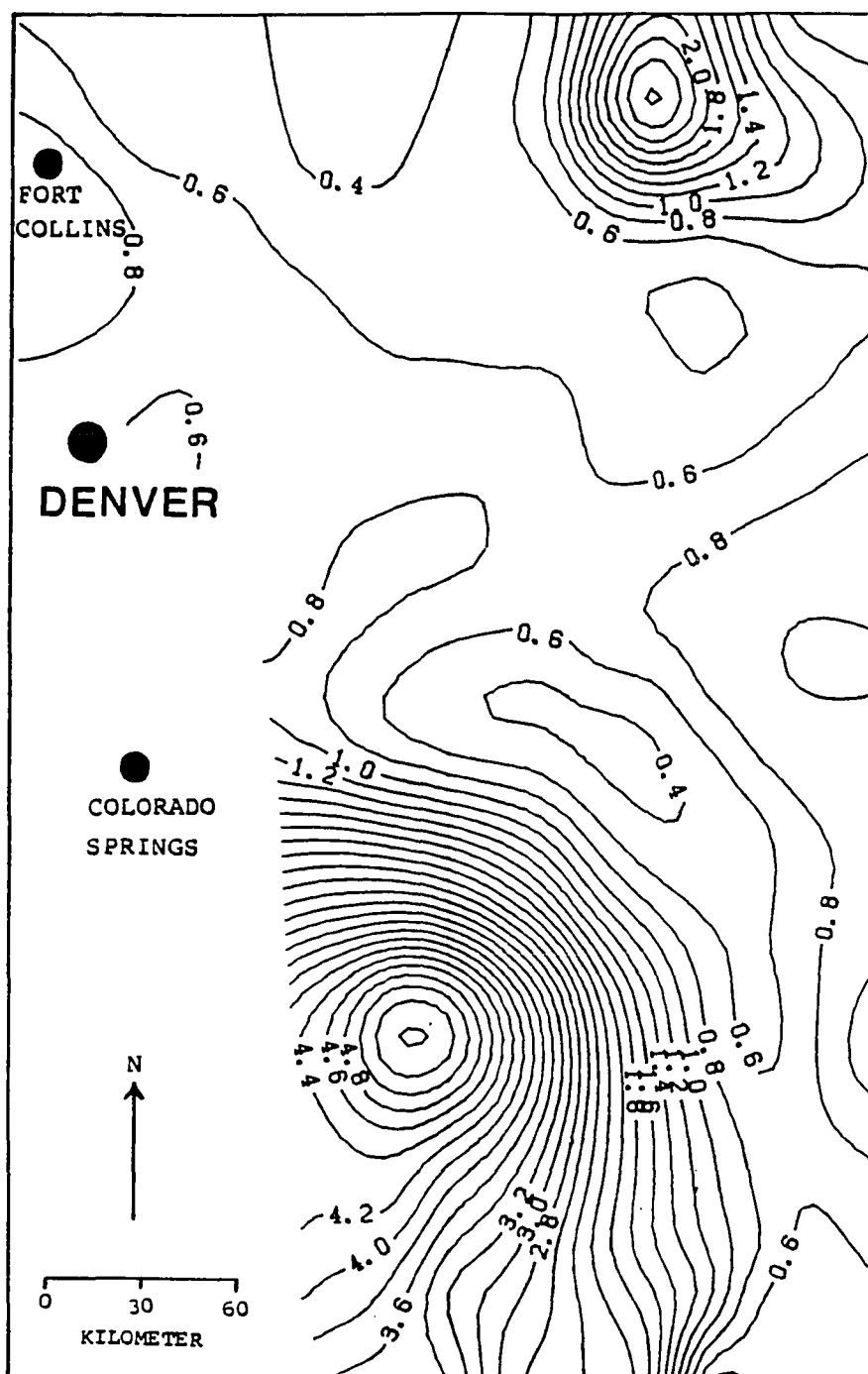
Fig. 80   Isarithm map of Zn (mg/kg) status of topsoils by
          isotropic block kriging, Colorado.
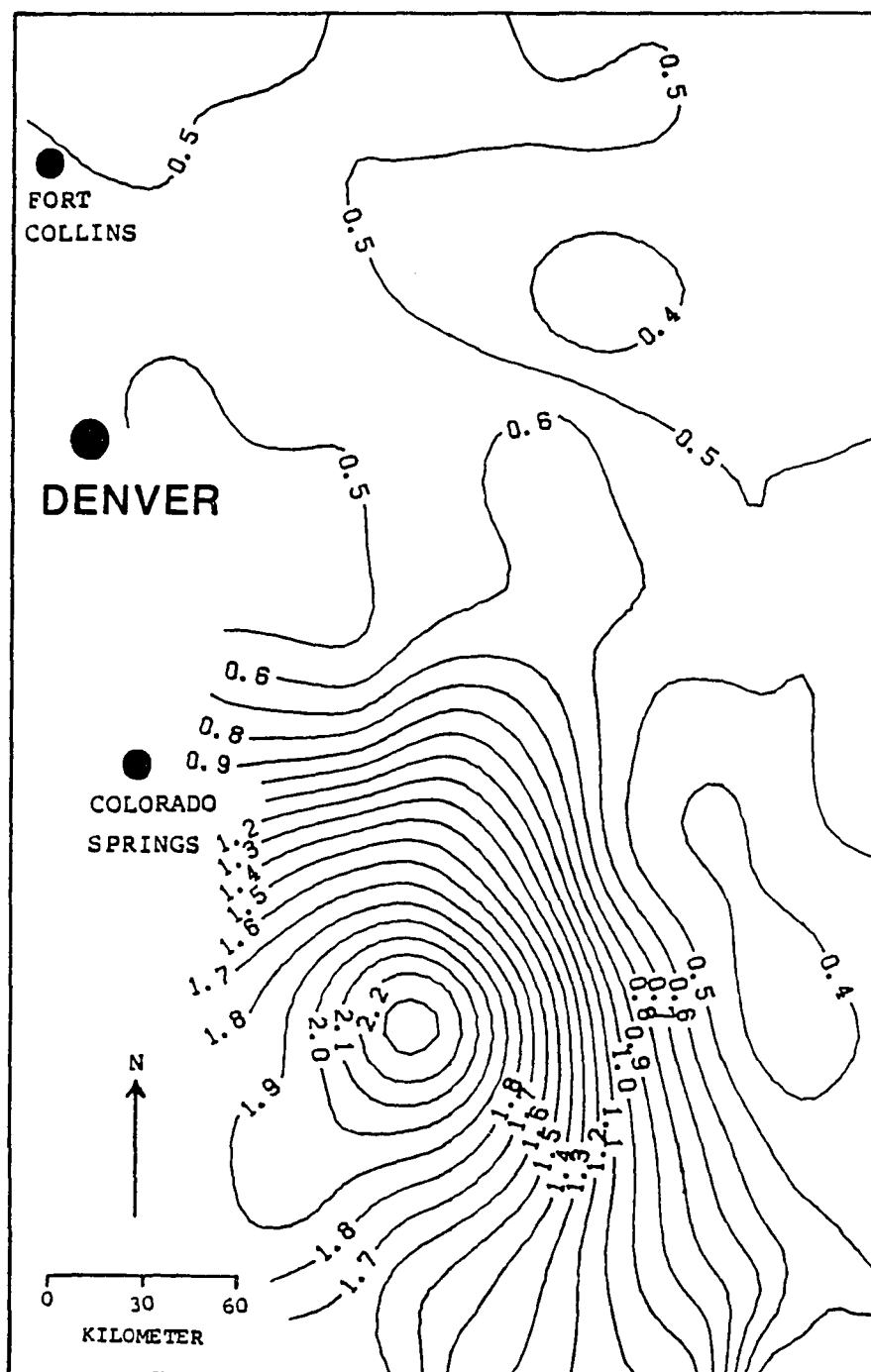
Fig. 81   Isarithm map of Zn (mg/kg) status of subsoils by
          isotropic block kriging, Colorado.
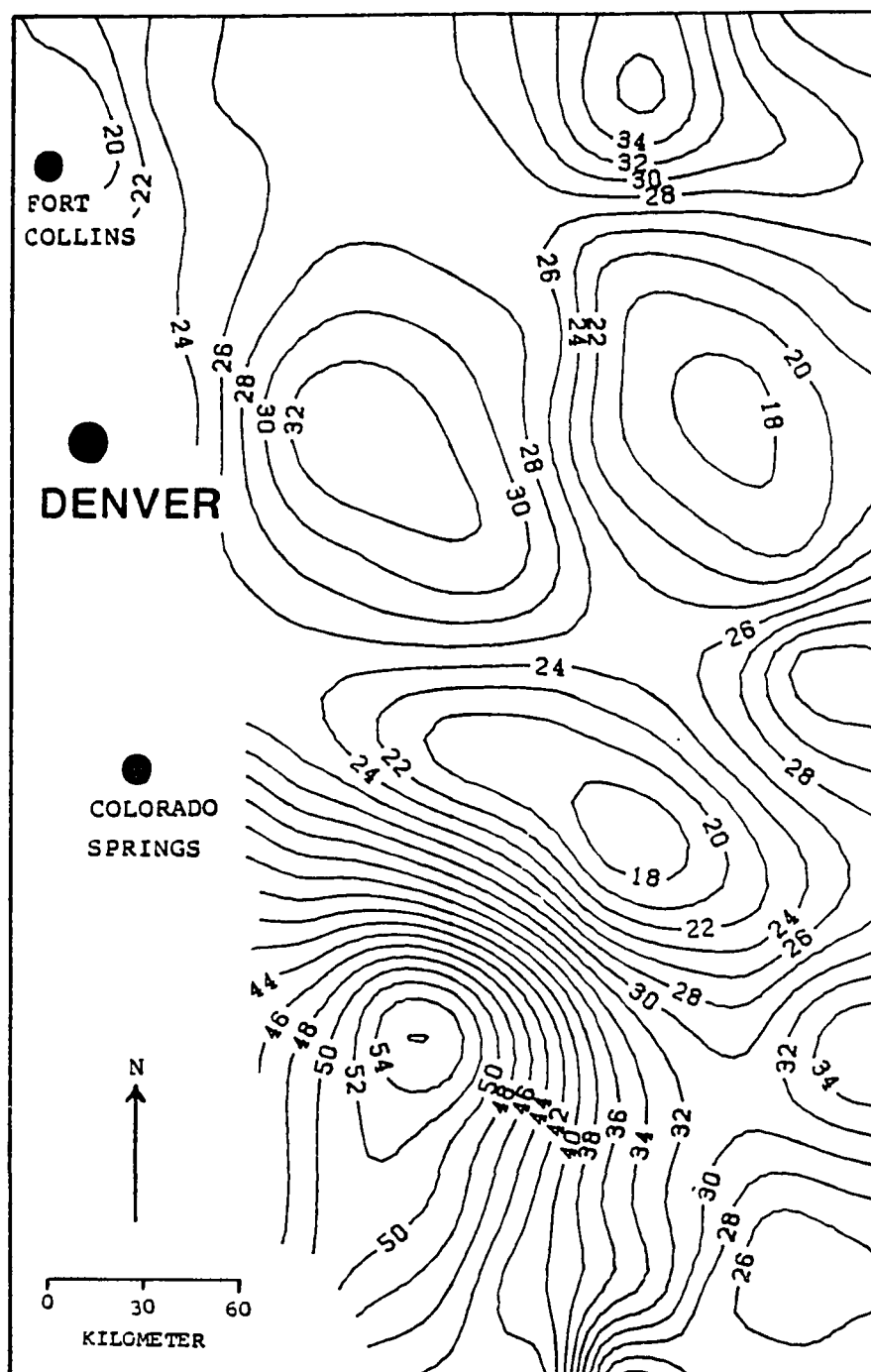
Fig. 82 Isarithm map of Zn (mg/kg) status of wheat seeds
by isotropic block kriging, Colorado.

high Zn levels (Fig. 80). Soil Zn status in other parts of the state varied from adequate to marginal or even deficient for sensitive crops (Soltanpour, 1985). For example, soil Zn in much of the north-east of the state appears to be deficient for sensitive crops like corn and soybeans. Another area of probable Zn deficiency is in the center of eastern Colorado (soil Zn < 0.6 mg Zn/kg soil; Fig. 80).

Levels of Zn in subsoils and in wheat grain generally coincided with topsoil Zn (Fig. 80-82). In the greenhouse studies, a level of Zn that was adequate for every crop produced wheat grain that contained 43 mg Zn/kg. Using this criterion, most parts of the mapped area in Colorado are deficient in Zn for the growth of sensitive crops. By the same grain Zn criterion, none of the soils are Zn deficient for wheat because wheat did not respond to Zn fertilizer even when grain Zn concentration was 14 mg Zn/kg.

The high-Zn area in the north-east corner of the state is based on several data points (Fig. 4) but the indication of a large high-Zn area in the south of the state is based entirely on one sample point. Incidentally, this particular sample location is Arkansas Valley Research Center, Rocky Ford. Zinc levels were high in topsoil, subsoil and wheat grains (Fig. 80-82). Therefore, the reliability of the data is not questioned. But agricultural experiment stations may not be ideal sites to represent the surrounding agricultural soils. More detailed sampling in this area, preferably from farmer fields, is required before statements can be made in confidence.

Maps of topsoil and subsoil pH, subsoil Fe, wheat seed Mn and Cu

are presented in Appendix 12-16.

2.   Hawaiian Commercial and Sugarcane Company, Maui, Hawaii

Soil pH and HCl-extractable Zn of HC&S plantation, both in surface

soils and subsoils, varied widely (Table 22). Although some soils were

both alkaline and calcareous, most pH values were less than 7.0.

Extractable Zn in most soils was greater than the critical level of

approximately 2 mg Zn/kg soil suggested by Kanehiro and Sherman (1967).

However, Zn status of some soils was marginal, or perhaps deficient,

for sensitive crops. Concentrations of leaf blade Zn varied widely

also. Plant tissue concentrations of nutrients, including N, P, K, Ca,

S, and Mn, also varied drastically (Table 22).

a.   Statistical analysis

A correlation analysis of soil and plant Zn with potential factors

is presented in Table 23. There was no correlation between soil pH and

HCl-extractable soil Zn. However, Zn contents of leaf blades were

negatively related to soil pH. Soil Zn and rainfall were positively

correlated. A positive correlation between rainfall and extractable Zn

could be attributed to the absence of $CaCO_3$ in soils of acid pH.

Rainfall and leaf blade Zn (dry-ashed) were related (r = 0.77).

Although Zn nutrition of plants is known to be adversely affected by

cool temperature (Lindsay, 1972), a significant negative correlation

between soil and plant Zn and air temperature was probably due to the

alkaline nature of the soils at low elevation and not due to variation

in temperature per se.

Table 22 Mean, range and standard deviation of properties of
soils, climate, and sugarcane leaf tissue, HC&S, Maui.

Variable	Mean/median[*]	Range	Standard deviation	Distribution
Topsoil pH	6.7	4.4-8.6	1.0	normal
Subsoil pH	6.8	4.1-8.5	1.0	normal
Topsoil Zn (mg/kg)	5.5	0.8-107	15.7	log
Subsoil Zn (mg/kg)	3.3	0.3-98	16.1	log
Topsoil P[b] (mg/kg) (mg/kg)	11.5	1.3-88.2	21.6	log
Subsoil P (mg/kg)	7.1	0.8-80.8	20.4	log
P req.[c] (mg/kg)				
Topsoil	251	-129-613	167	normal
Subsoil	381	-160-754	207	normal
Exch. K[d] (cmol/kg)	1.05	0.19-4.15	0.78	log
Elevation (m)	101	5-304	79	-[a]
Rainfall (mm)	612	348-1212	246	-
Maximum temperature (C)	28	26-30	1.7	-
Minimum temprature (C)	18	16-20	1.7	-
Pan evaporration (mm)	2294	1651-2515	183	-
Leaf sheaths				
P (%)	0.12	0.059-0.19	0.031	normal
K (%)	2.83	0.73-4.07	0.73	normal
Ca (%)	0.17	0.08-0.39	0.72	log
Mg (%)	0.17	0.035-0.421	0.07	-
Na (mg/kg)	54	20-255	36	log

Table 22   Mean, range and standard deviation of properties of
(cont.)   soils, climate, and sugarcane leaf tissue, HC&S, Maui.

Variable	Mean/ median *	Range	Standard deviation	Distribution
Leaf sheaths				
S (%)	0.27	0.037-0.68	0.15	normal
Mn (mg/kg)	98	16-487	97	-
SiO_2 (%)	2.4	1.1-4.0	0.7	normal
Moisture (%)	80	70-87	4.0	-
Growth index (g/20 sheaths)	325	216-513	62	log
Leaf blades				
Zn (mg/kg)				
dry-ashed	16.1	6.8-33.2	6.44	-
wet-digested	18.7	14.1-29.4	2.91	normal
N (%)	1.41	0.94-2.12	0.25	log
P (%)	0.24	0.14-3.0	0.34	-
K (%)	1.26	0.50-1.78	0.26	-
Ca (%)	0.23	0.12-0.53	0.095	log
Mg (%)	0.19	0.098-0.39	0.065	log
S (%)	0.17	0.09-0.30	0.045	log
Na (mg/kg)	172	59-560	94	-
Mn (mg/kg)	59	9-364	67	-
SiO_2 (%)	2.8	0.5-5.2	1.2	normal

* -- Median values are given for lognormally distributed data.
a -- Data did not fit to normal or log-normal distribution.
b -- $NaHCO_3$-extractable P.
c -- Fertilizer P requirements for 0.2 mg P/L.
d -- Ammonium acetate-extractable K.

Table 23 Correlation coefficients (r) and levels of significance
of some parameters related to Zn nutrition of plants,
HC&S, Maui, Hawaii.

	Topsoil Zn (mg/kg)	Subsoil Zn (mg/kg)	Leaf blade Zn (mg/kg) dry-ashed	wet-digested
Topsoil pH	0.029 (0.81)[a]	0.026 (0.83)	−0.56 (0.0001)	−0.28 (0.018)
Subsoil pH	−0.0021 (0.99)	−0.0099 (0.94)	−0.56 (0.0001)	−0.29 (0.015)
Topsoil Zn (mg/kg)	1	0.94 (0.0001)	0.32 (0.007)	0.14 (0.25)
Subsoil Zn (mg/kg)	0.94 (0.0001)	1	0.34 (0.005)	0.14 (0.24)
Elevation (m)	−0.11 (0.35)	−0.12 (0.32)	0.38 (0.0013)	0.031 (0.80)
Rainfall (mm)	0.46 (0.0001)	0.48 (0.0001)	0.77 (0.0001)	0.37 (0.0015)
Temperature (C)	−0.31 (0.0097)	−0.29 (0.014)	−0.39 (0.0008)	−0.16 (0.19)
Pan evaporation (mm)	−0.12 (0.31)	−0.24 (0.042)	−0.49 (0.0001)	−0.27 (0.025)

Leaf blades

Zn (mg/kg) dry-ashed	0.32 (0.007)	0.34 (0.0045)	1	0.56 (0.0001)
wet-digested	0.14 (0.25)	0.14 (0.24)	0.56 (0.0001)	1
P (%)	−0.0083 (0.95)	−0.022 (0.86)	−0.0804 (0.51)	−0.034 (0.78)
K (%)	−0.18 (0.14)	−0.21 (0.085)	−0.35 (0.0028)	−0.0870 (0.48)

Table 23 Correlation coefficients (r) and levels of significance
(cont.)   of some parameters related to Zn nutrition of plants,
          HC&S, Maui, Hawaii.

	Topsoil Zn (mg/kg)	Subsoil Zn (mg/kg)	Leaf blade Zn (mg/kg) dry-ashed	wet-digested
Leaf blades				
Na (mg/kg)	0.36 (0.0022)	0.39 (0.0008)	0.40 (0.0006)	0.27 (0.023)
Mn (mg/kg)	−0.11 (0.37)	−0.086 (0.48)	0.50 (0.0001)	0.35 (0.0026)
SiO$_2$ (%)	−0.088 (0.47)	−0.13 (0.30)	−0.62 (0.0001)	−0.089 (0.46)
Leaf sheaths				
P (%)	0.013 (0.91)	−0.015 (0.90)		
K (%)	−0.011 (0.93)	−0.029 (0.81)		
Na (mg/kg)	−0.00021 (1.00)	0.027 (0.82)		
Mn (mg/kg)	−0.11 (0.35)	−0.087 (0.48)		
SiO$_2$ (%)	−0.049 (0.69)	−0.081 (0.50)		

a -- The values in parentheses indicate the probability of a
     chance occurrence of the statistic.

Table 24 Parameter estimates of isotropic semi-variograms[a] of
soil, climate and sugarcane leaf tissue properties,
HC&S, Maui, Hawaii.

Variables	Range (km)	Nugget variance	Sill	% of sill	General variance	Model[b]	R^2 of model[c]
Topsoil pH	9.2	0.32	1.06	30	1.06	L	0.97
Subsoil pH	10.3	0.35	1.05	33	1.05	L	0.95
Topsoil Zn (mg/kg)	9.7	0.58	1.04	56	1.11	S	0.93
Subsoil Zn (mg/kg)	8.7	1.06	1.87	57	1.99	S	0.85
Topsoil P (mg/kg)	7.2	0.76	1.13	67	1.01	L	0.53
Subsoil P (mg/kg)	6.1	1.1	1.45	76	1.3	L	0.39
Topsoil P req. (mg/kg)	7.9	7227	27827	26	27827	L	0.98
Subsoil P req. (mg/kg)	7.9	15123	42118	36	42118	S	0.88
Exch. K (cmol/kg)	10.6	0.24	0.5	48	0.50	S	0.77
Maximum temperature (C)	8.0	0.55	2.96	19	2.96	L	0.77
Minimum temperature (C)	No structure						
Pan evaporation (mm)	7.3	9.96	44.0	23	51.2	M	0.50
Leaf sheaths P (%)	5.6	0.00067	0.00089	75	0.00097	S	0.60
K (%)	5.7	0.24	0.53	45	0.53	L	0.87
Ca (%)	5.3	0.061	0.15	41	0.16	S	0.85
Mn (mg/kg)	12.8	5010	8589	58	9473	S	0.81
SiO_2 (%)	7.0	0.11	0.46	24	0.49	S	0.92

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Table 24   Parameter estimates of isotropic semi-variograms[a] of
(cont.)   soil, climate and sugarcane leaf tissue properties,
            HC&S, Maui, Hawaii.

Variables	Range (km)	Nugget variance	Sill	% of sill	General Model variance	Model[b]	R^2 of model[c]
Leaf sheaths							
Mg (%)	No structure						
S (%)	No structure						
Na (mg/kg)	No structure						
Leaf blades							
Zn (mg/kg) dry-ashed	7.6	3.3	41.5	8	41.5	S	0.96
wet-digested	10.7	0.021	0.04	53	0.032	L	0.55
Ca (mg/kg)	8.2	0.015	0.14	11	0.14	M	0.74
SiO_2 (%)	5.7	0.59	1.35	44	1.35	L	0.88
N (%)	No structure						
P (mg/kg)	No structure						
K (mg/kg)	No structure						
Mg (mg/kg)	No structure						
S (mg/kg)	No structure						
Mn (mg/kg)	No structure						
Na (mg/kg)	No structure						

a -- Semi-variances for soil Zn, leaf sheath Ca, Na, growth
     index, leaf blade N, Ca, Mg, and S determined on log
     transformed values.

b -- L = Linear model, M = Mitscherlich (expontential) model,
     S = Spherical model.

c -- $R^2 = (SS_{corrected} - SS_{residual})/SS_{corrected}$.
     R^2 for model fitted up to range. All R^2 values
     significant at P<0.01 unless otherwise indicated.

$$\% \text{ of sill} = \frac{\text{nugget variance}}{\text{sill}} \times 100.$$

The correlation coefficient between Zn contents of leaf blades

recovered by dry-ashing and wet-digestion was only 0.56 (Table 23).

Silica contents of leaf blades were negatively correlated with Zn

contents of leaf blades (dry-ashed) (r = - 0.62). In the greenhouse

investigations, less Zn was detected in foliar tissues that had been

dry-ashed than tissues that were wet- digested. Foliar tissues were

rich in Si. Similar results were reported by other researchers

(Sedberry et al., 1971; Jones, 1972). Correlation coefficients less

than 1.00 are probably related to silica in leaf tissues.

Zinc contents of leaf blades (dry-ashed) were significantly

related to extractable Zn in both surface soil and subsoil samples

(Table 23). However, a low correlation value (r = 0.32) between

topsoil Zn and leaf blade Zn indicates that Zn nutrition of sugarcane

plants was affected by factors other than soil Zn. Leaf blade K was

negatively related with leaf blade Zn (dry-ashed) (r = -0.35). Leaf

blade Na and Mn, on the other hand, were positively correlated with Zn

contents of leaf blades (dry-ashed) (Table 23).

b. Spatial analysis

The properties listed in Table 24 were analyzed for spatial

dependence. Semi-variances, $\gamma(h) = \varepsilon[z(x)-z(x+h)]^2/2N$ were computed

and semi-variograms were used to determine the stucture of spatial

dependence of soil and plant tissue properties over the mapped area

(Matheron, 1963). Parameters associated with semi- variograms of

variables that varied isotropically are listed in Table 24 and the

Table 25 Mathematical models fitted to isotropic semi-variograms
of soil, climate and sugarcane leaf tissue properties,
HC&S, Maui, Hawaii.

Variable	Model	Equation
Topsoil pH	L	$\gamma(h) = 0.32 + 0.08\ h$
Subsoil pH	L	$\gamma(h) = 0.35 + 0.068\ h$
Topsoil Zn (mg/kg)	S	$\gamma(h) = 0.58 + 0.071 - 0.00026\ h^3$
Subsoil Zn (mg/kg)	S	$\gamma(h) = 1.06 + 0.14\ h - 0.00062\ h^3$
Olsen's P (mg/kg)		
Topsoil	L	$\gamma(h) = 0.76 + 0.055\ h$
Subsoil	L	$\gamma(h) = 1.1 + 0.05\ h$
P req. (mg/kg)		
Topsoil	L	$\gamma(h) = 7227 + 2526\ h$
Subsoil	S	$\gamma(h) = 15123 + 7524\ h - 0.00101\ h^3$
Topsoil exch. K (cmol/kg)	S	$\gamma(h) = 0.24 + 0.037 - 0.00042\ h^3$
Max. Temp. (C)	L	$\gamma(h) = 0.55 + 0.027\ h$
Pan Evaporation (mm)	M	$\gamma(h) = 43.95 - [33.99 \times \exp(-0.37\ h)]$

Leaf sheath

Variable	Model	Equation
P (%)	S	$\gamma(h) = 0.00067 + 0.0000061\ h - 0.0000006\ h^3$
K (%)	L	$\gamma(h) = 0.24 + 0.053\ h$
Ca (%)	S	$\gamma(h) = 0.061 + 0.03\ h - 0.00047\ h^3$
Mn (mg/kg)	S	$\gamma(h) = 5010 + 420\ h - 0.86\ h^3$
Si (%)	S	$\gamma(h) = 0.13 + 0.062\ h - 0.00013\ h^3$

Table 25   Mathematical models fitted to isotropic semi-variograms
(cont.)   of soil, climate and sugarcane leaf tissue properties,
           HC&S, Maui, Hawaii.

Variable	Model	Equation

Leaf blade

Zn (mg/kg)

dry-ashed	S	$\Upsilon(h) = 3.3 + 5.11\ h - 0.0068\ h^3$
wet-digested	L	$\Upsilon(h) = 0.021 + 0.0013\ h$
Ca (mg/kg)	M	$\Upsilon(h) = 0.14 - [0.13 \times \exp\ (-0.36\ h)]$
Silica (%)	L	$\Upsilon(h) = 0.59 + 0.13\ h$

L = Linear model   M = Mitscherlich (exponential) model
S = Spherical model

TOPSOIL pH

$R^2 = 0.97^{**}$
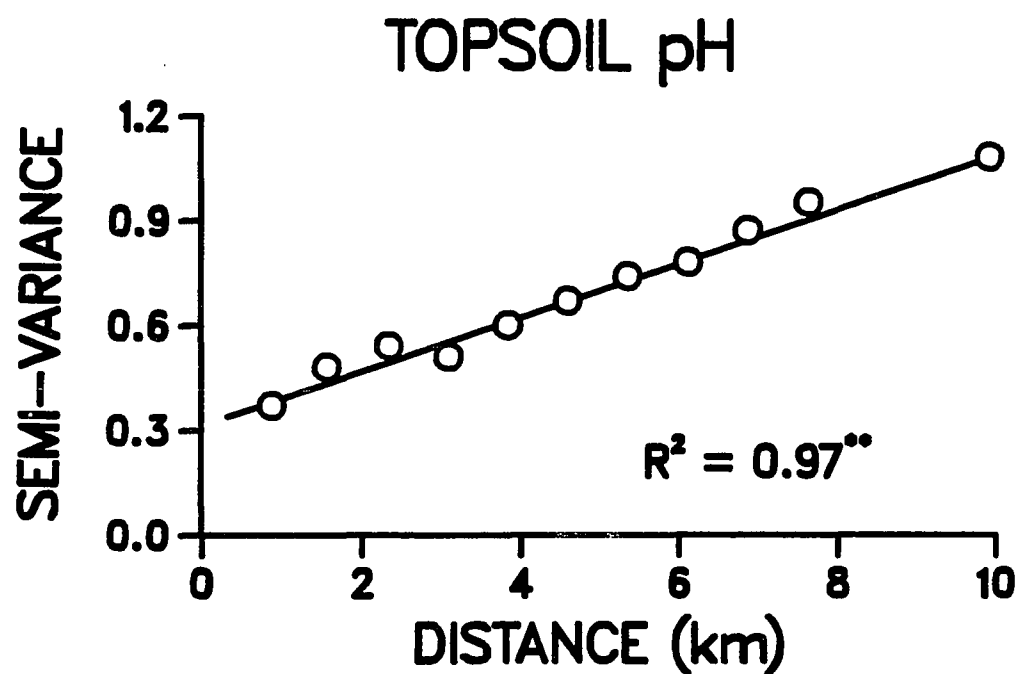
Fig. 83 Isotropic semi-variogram for pH of surface soils, HC&S, Maui.

TOPSOIL Zn

$R^2 = 0.93^{**}$
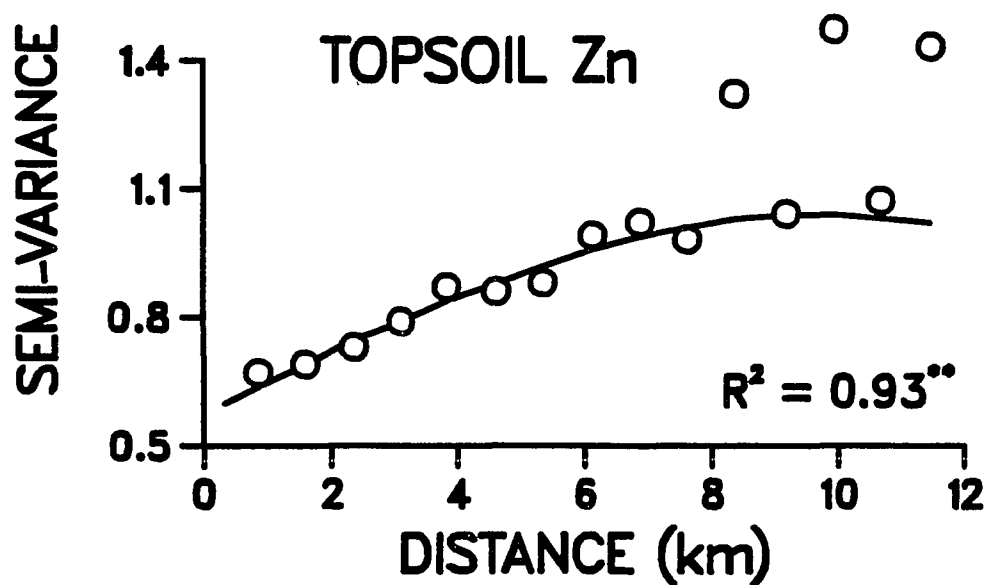
Fig. 84 Isotropic semi-variogram for log transformed values of
HCl-extractable Zn (mg/kg) in surface soils, HC&S, Maui.

mathematical models fitted to semi-variograms are listed in Table 25.

The semi-variogram of surface soil pH had linear structure (Fig. 83) implying that soil pH was nonstationary. Large intercepts were obtained for semi-variograms at both soil depths indicating large nugget variances which implies that there was considerable variation for distances smaller than sampling intervals. The range of spatial dependence for subsoil pH (10.3 km) was greater than topsoil pH (9.2 km). This agrees with Ahmad (1985).

Good structure was demonstrated in semi-variograms for HCl-extractable Zn in topsoils and subsoils. Spherical models were fitted to both semi-variograms (Table 24; Fig. 84). Intercepts of semi-variograms of extractable Zn were greater than intercepts for soil pH. Thus variation of soil Zn at distances smaller than the sampling distances was greater than for pH. The range for extractable Zn was greater for topsoils than subsoils (Table 24). For topsoils, the range of spatial dependence of extractable Zn (9.7 km) was approximately equal to the range for soil pH. However, the range of spatial dependence in subsoils was greater for soil pH (10.3 km) than extractable Zn (8.7 km).

The semi-variogram of P concentration of leaf sheaths was fit with an isotropic spherical model with an R^2 value of 0.60. The range (5.6 km) was smaller than the range of soil pH and soil Zn but approximately equal to the range of leaf sheath K and Ca (Table 24). A very large nugget variance (75% of sill) indicates much variation at distances smaller than the sampling intervals.

An isotropic linear model gave the best fit of the semi- variogram of leaf sheath K contents. The range of spatial dependence, 5.7 km, was approximately equal to the ranges of leaf sheath P and Ca.

A spherical model gave a better fit to the semi-variogram of Ca concentration in leaf sheaths than either linear or Mitscherlich models. The range was 5.3 km and nugget variance was 41 % of sill.

The semi-variogram of Mn concentration of leaf sheaths was fitted best by a spherical model with an R^2 value of 0.81. The range was 12.8 km, which was greater than the range value of all other variables associated with the leaf sheaths.

The semi-variogram of leaf sheath silica could be described by an isotropic spherical model (R^2 = 0.92). The range was 7.0 km, which was greater than for any of the other leaf sheath properties except Mn. Nugget variance was small.

Zinc, Ca and SiO_2 contents of leaf blades showed strong spatial dependence. A spherical model was fitted to the semi- variogram of Zn contents of leaf blades (dry-ashed) with an R^2 value of 0.96 (Fig. 85). The range of spatial dependence of dry- ashed Zn was 7.6 km, which was smaller than the range for extractable Zn in topsoils (9.7 km). A very small intercept of 6% of sill indicates negligible variation at distances smaller than the sampling distances. The semi-variogram of leaf blade Zn recovered by wet-digestion was fit by an isotropic linear model with an R^2 value of 0.55 (Fig. 86). The range of spatial dependence was 10.7 km, which is greater than the range for Zn contents of leaf tissue recovered by dry-ashing. However,
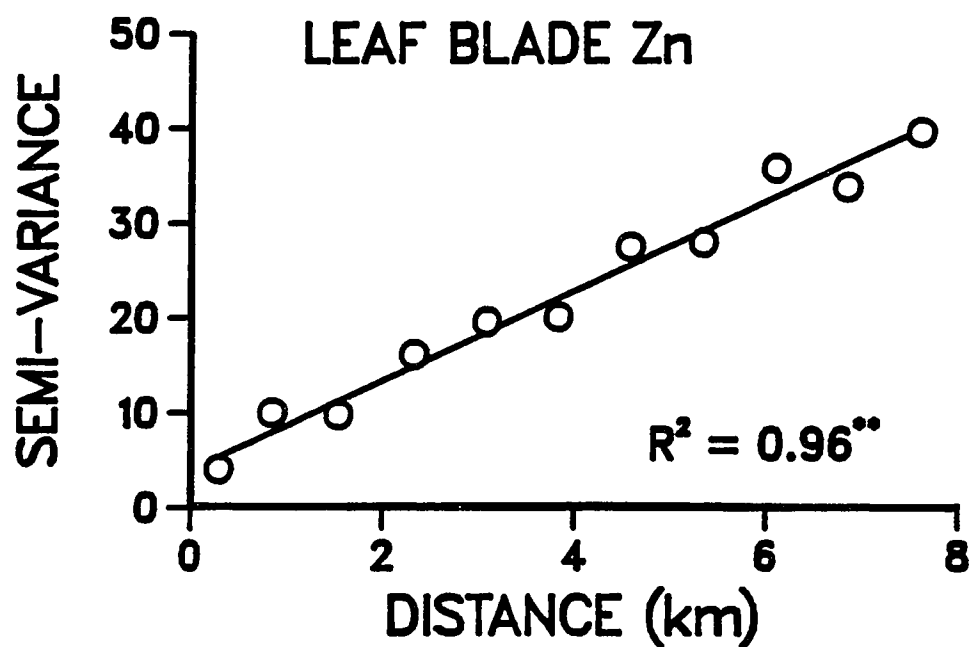
Fig. 85 Isotropic semi-variogram for Zn concentration (mg/kg) in sugarcane leaf blades (dry-ashed), HC&S, Maui.
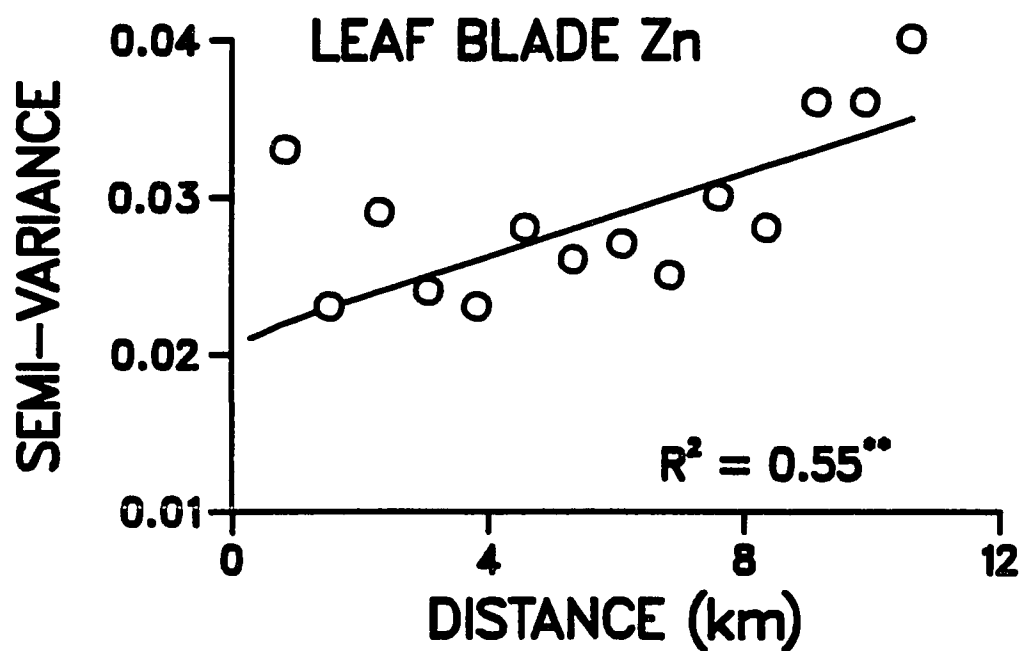
Fig. 86 Isotropic semi-variogram for Zn concentration (mg/kg) in sugarcane leaf blades (wet-digested), HC&S, Maui.
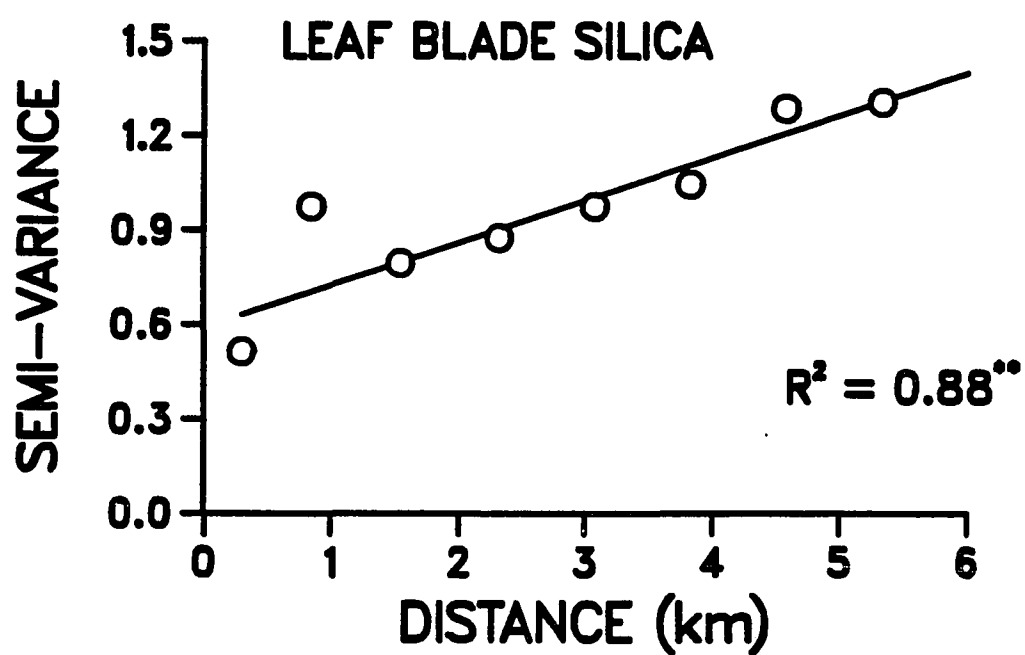
Fig. 87 Isotropic semi-variogram for silica concentration (%) in
sugarcane leaf blades, HC&S, Maui.

the nugget variance, 53% of sill, indicated much variation at distances smaller than the sampling intervals.

Mitscherlich model best fitted to the semi-variogram of Ca contents of leaf-blades (R^2 = 0.74). The range of spatial dependence was 8.2 km, which was greater than the range value for Ca contents of leaf sheaths (5.3 km). The nugget variance of the leaf blade was 11 % of sill, much smaller than the nugget value for leaf sheath Ca (41% of sill).

A linear model equation fitted to the semi-variogram of silica contents of leaf blades with an R^2 value of 0.88 (Fig. 87). The range for leaf blade SiO_2 was approximately equal to leaf sheath SiO_2 (Table 24).

The ranges of spatial dependence of P, K, Ca, and SiO_2 contents of leaf blades were similar, suggesting that their availability in soils resulted from similar processes or sets of reactions. The nugget variances of soil Zn, Olsen P, fertilizer P requirement, soil K, leaf sheath P, K, Ca, Mn, and leaf blade Zn (wet-digested) and silica were very high. This implies that the variation was great within the sampling intervals. Sampling at smaller intervals will hopefully minimize the nugget effects.

No structure or indication of spatial dependence could be detected in semi-variograms of Mg, S, Na, and moisture content of leaf sheaths or growth index. Similarly, semi-variograms of N, P, K, Mg, S, Mn, and Na contents of leaf blades did not show any stucture. This may be the result of insufficient sampling points.

c. Kriging

Isarithm maps of HCl-extractable Zn, Olsen P, fertilizer P requirement for 0.2 mg P/kg soil, and ammonium acetate extractable K were prepared by using block kriging and computer graphics procedures (Trangmar, 1984; Bridges and Becker, 1976). Similar maps were prepared for Zn, SiO_2, P, K, and Na contents of leaf blades and P contents of leaf sheaths. Because semi-variograms for P, K, and Na contents of leaf blades had no stucture, original (not kriged) data were used to prepare isarithm maps.

A comparison of these maps permits selecting areas of coincidence or contrast. Soil maps indicated coincident high soil pH and low extractable Zn (Fig. 88-91). Isarithmic map of Zn contents of leaf blades (dry-ashed) (Fig. 92) coincided closely with extractable soil Zn (Fig. 90, 91). Zinc in leaf blades (dry- ashed) was also plotted 3-dimensionally (Fig. 93). Zinc contents of leaf blades recovered by wet-digestion (Fig. 94) did not correspond with soil Zn (Fig. 90, 91) or leaf blade Zn recovered by dry-ashing (Fig. 92). This discrepancy between Zn contents of leaf blades appears to be related to silica contents of leaf tissue. Silica contents of leaf blades were much greater in areas which were low in soil Zn (Fig. 95, 90, 91). High-Zn leaf tissues produced on acid soils were low in silica. At least two factors may be responsible for differences in silica contents of leaf blades, namely: (a) higher availability of silica in geologically young alkaline calcareous soils (mostly Mollisols), in the west of the plantation, than in highly weathered acid soils (mostly Ultisols) in
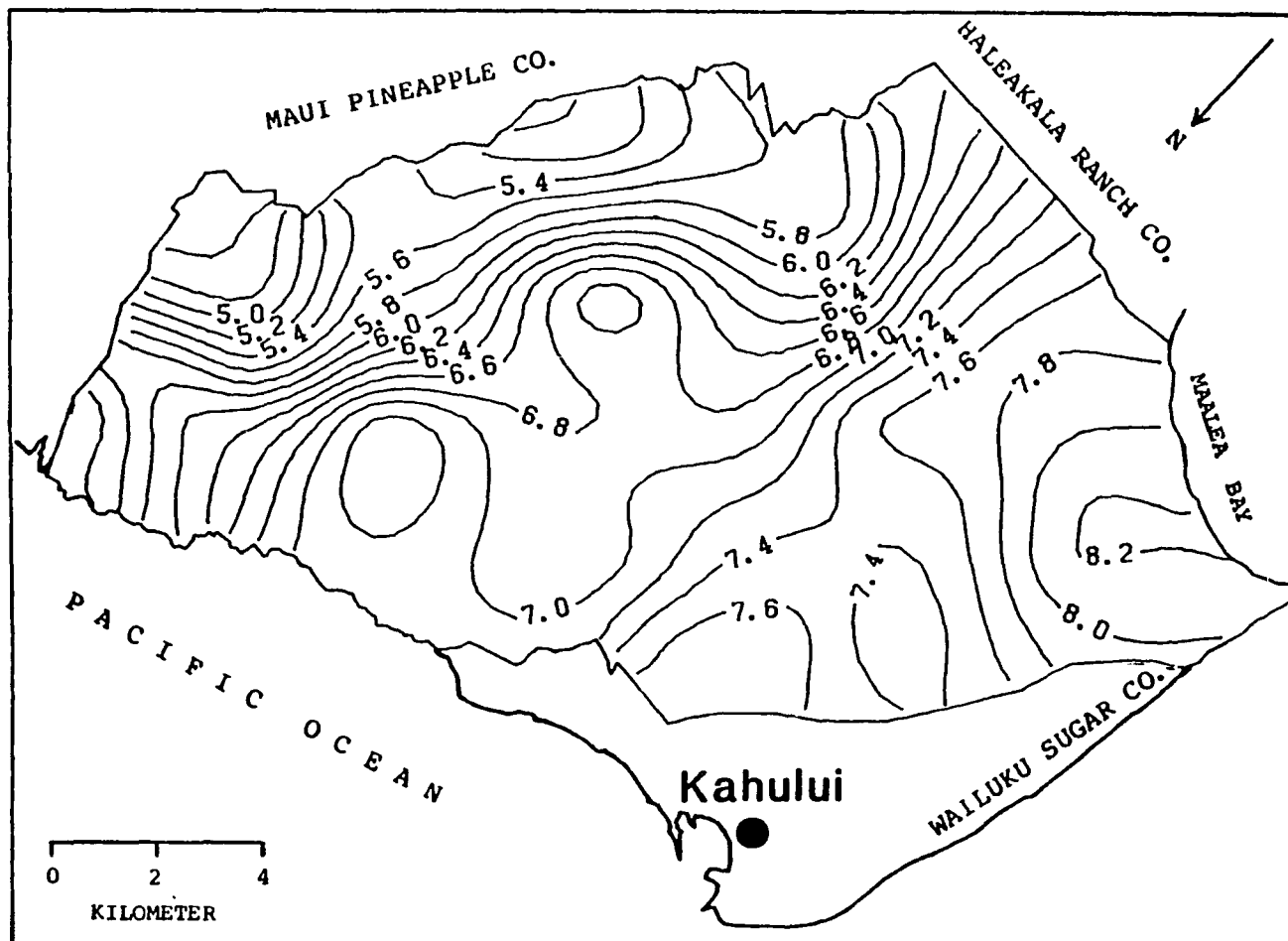
Fig. 88 Isarithm map of surface soil pH by isotropic block kriging, HC&S, Maui.
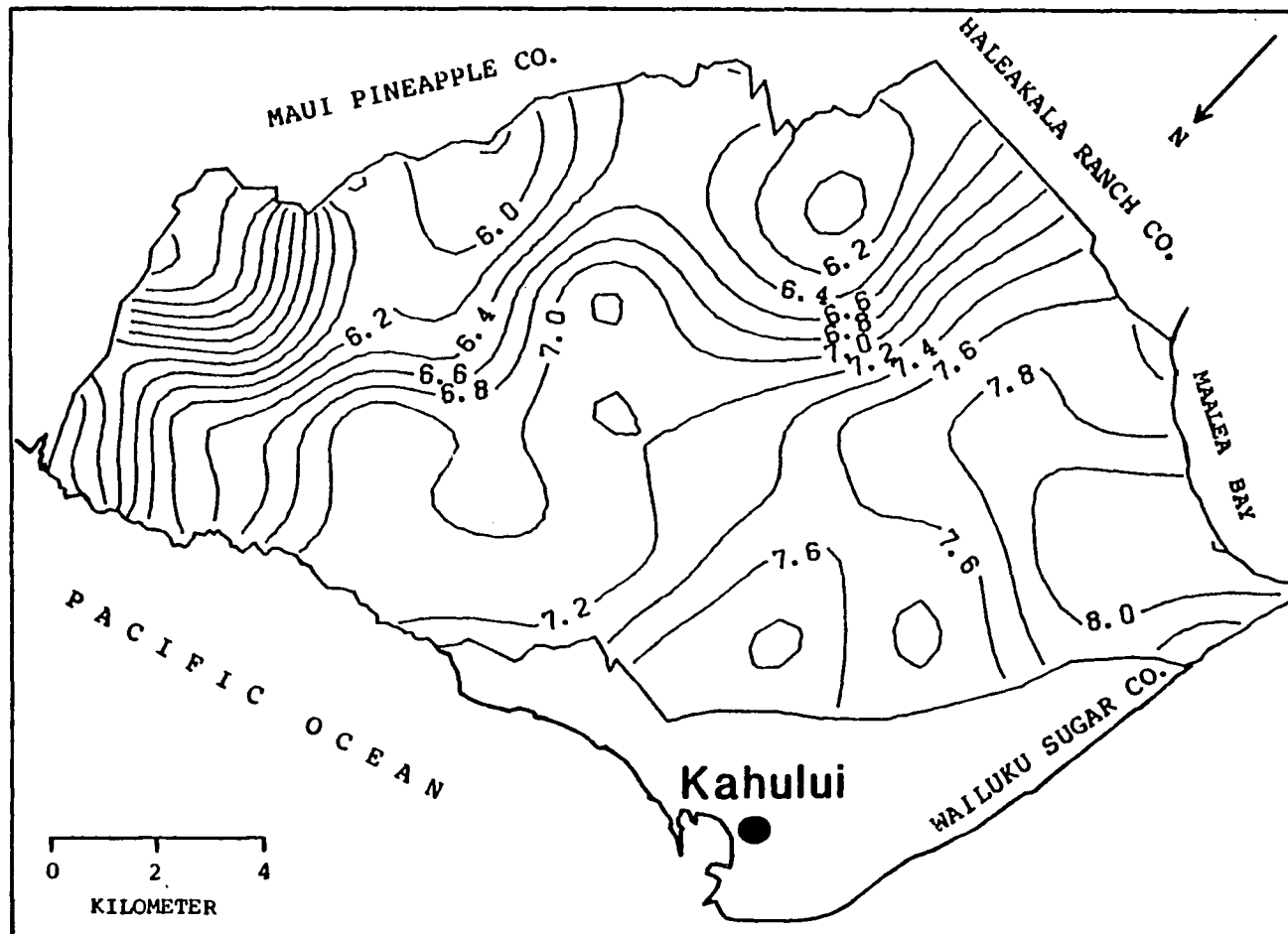
Fig. 89 Isarithm map of subsoil pH by isotropic block kriging, HC&S, Maui.
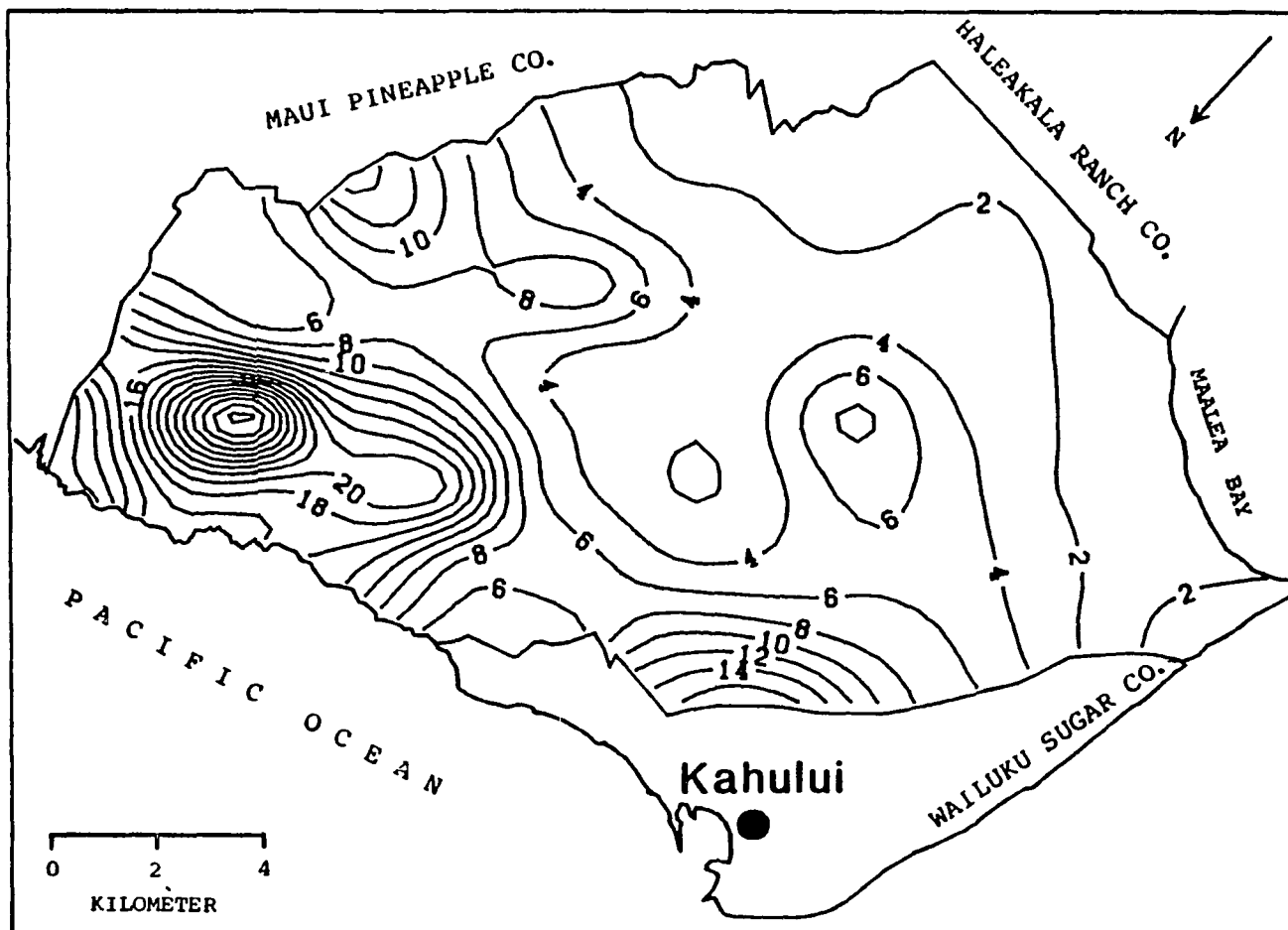
Fig. 90 Isarithm map of surface soil Zn (mg/kg) by isotropic block kriging, HC&S, Maui.
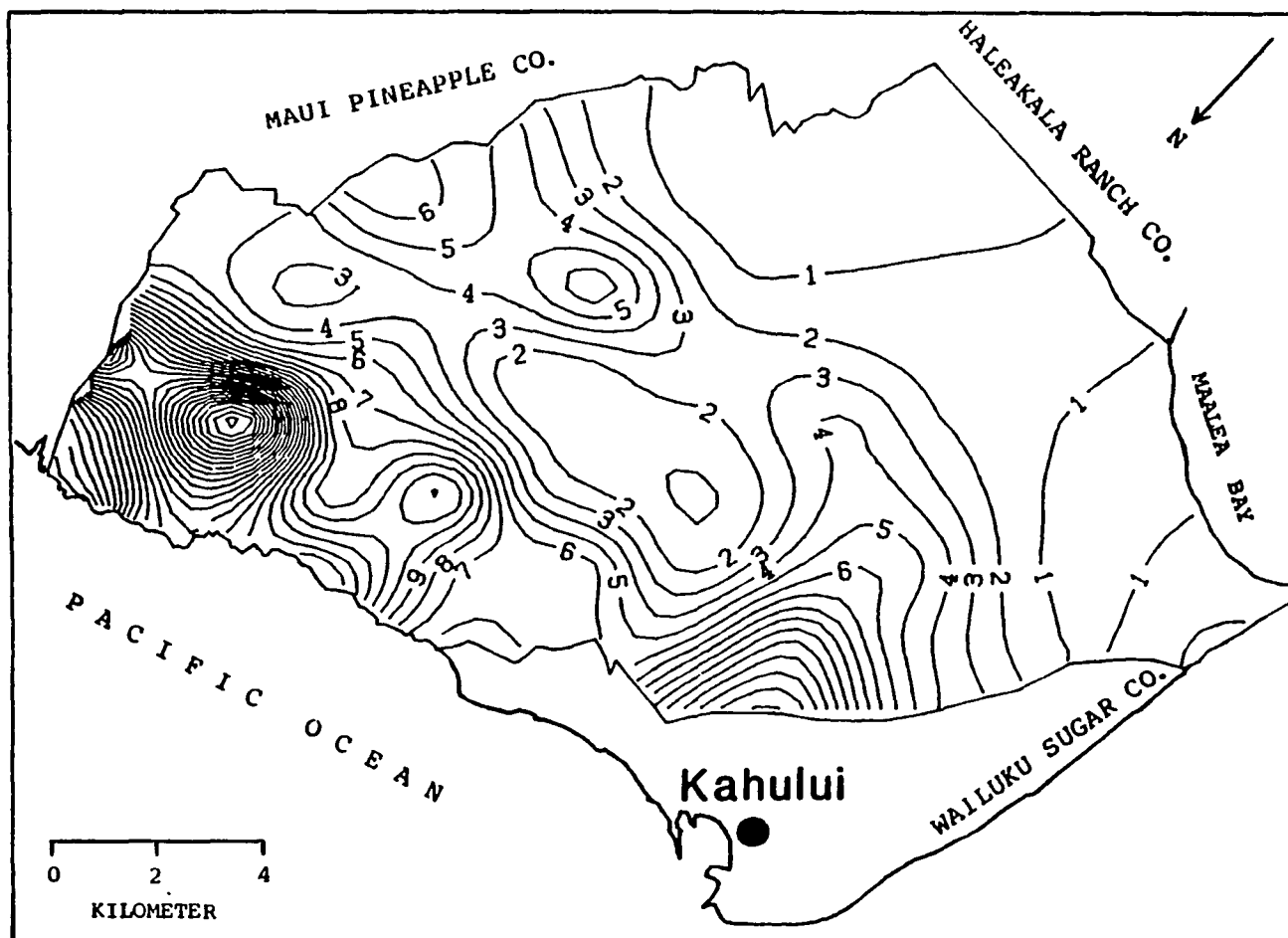
Fig. 91   Isarithm map of subsoil Zn (mg/kg) by isotropic block kriging, HC&S, Maui.
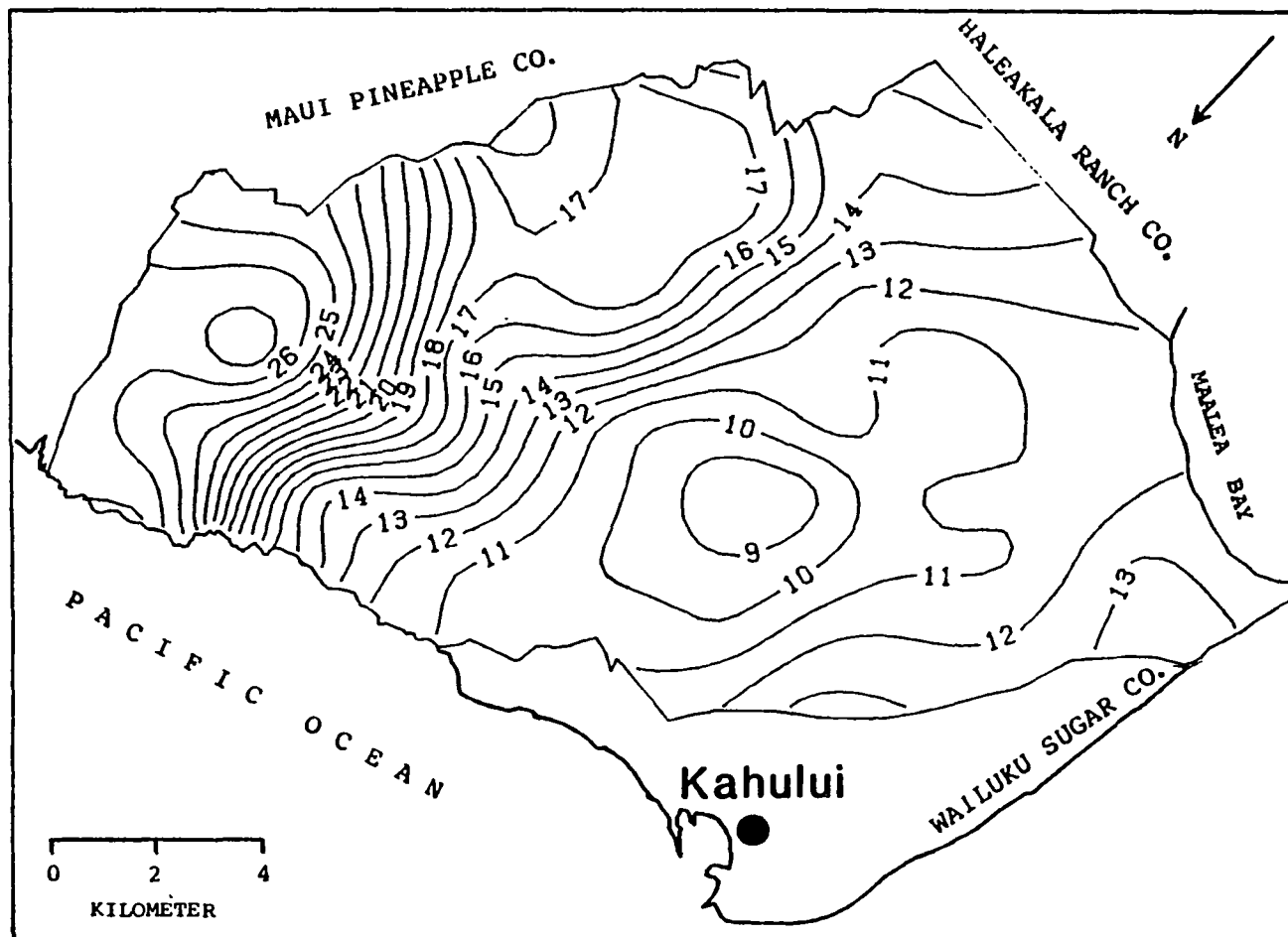
Fig. 92 Isarithm map of Zn status (mg/kg) of leaf blades (dry-ashed) by
isotropic block kriging, HC&S, Maui.
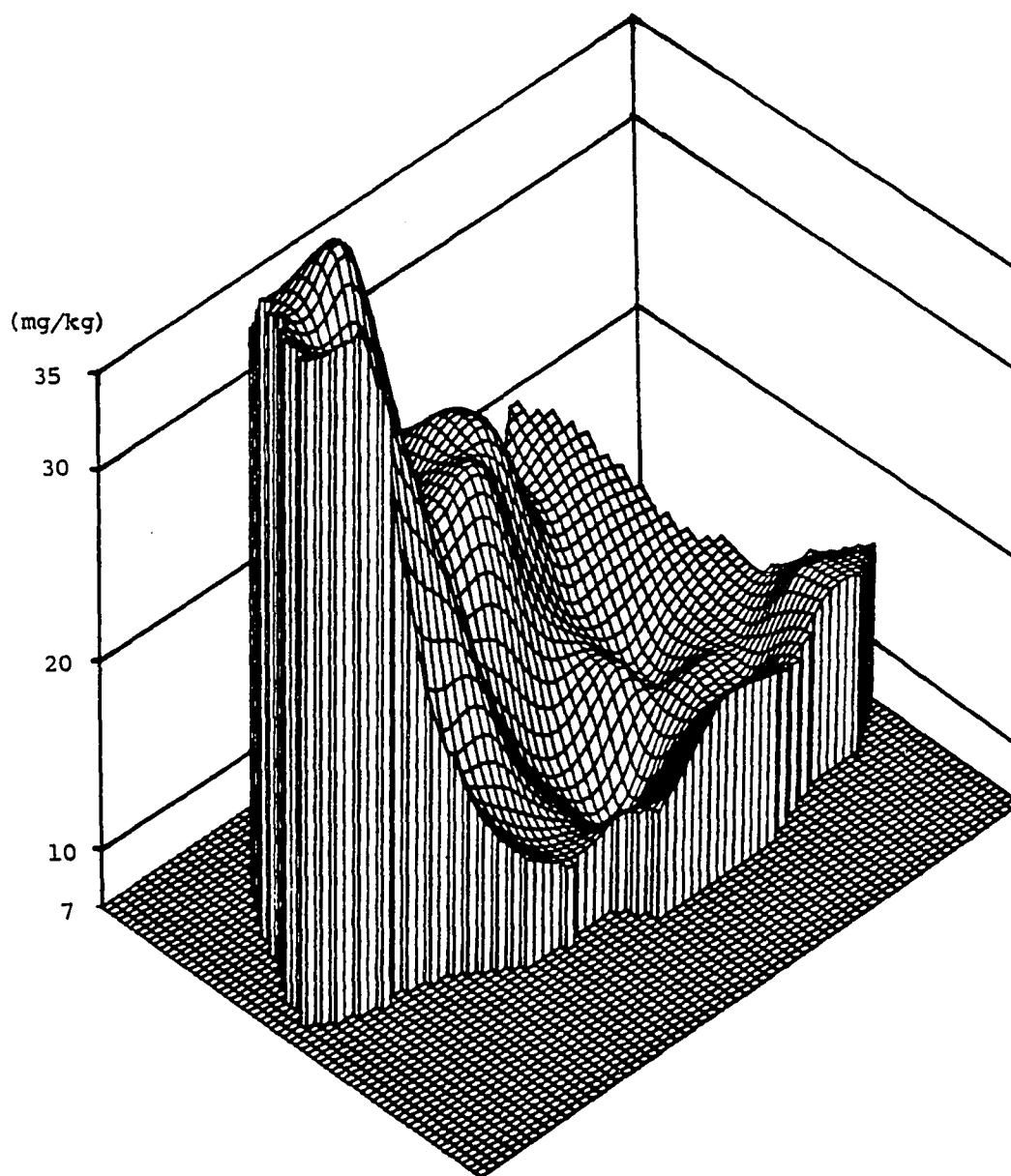
Fig. 93 Three-dimentional diagram of Zn status (mg/kg) of leaf blades
(dry-ashed), HC&S, Maui.
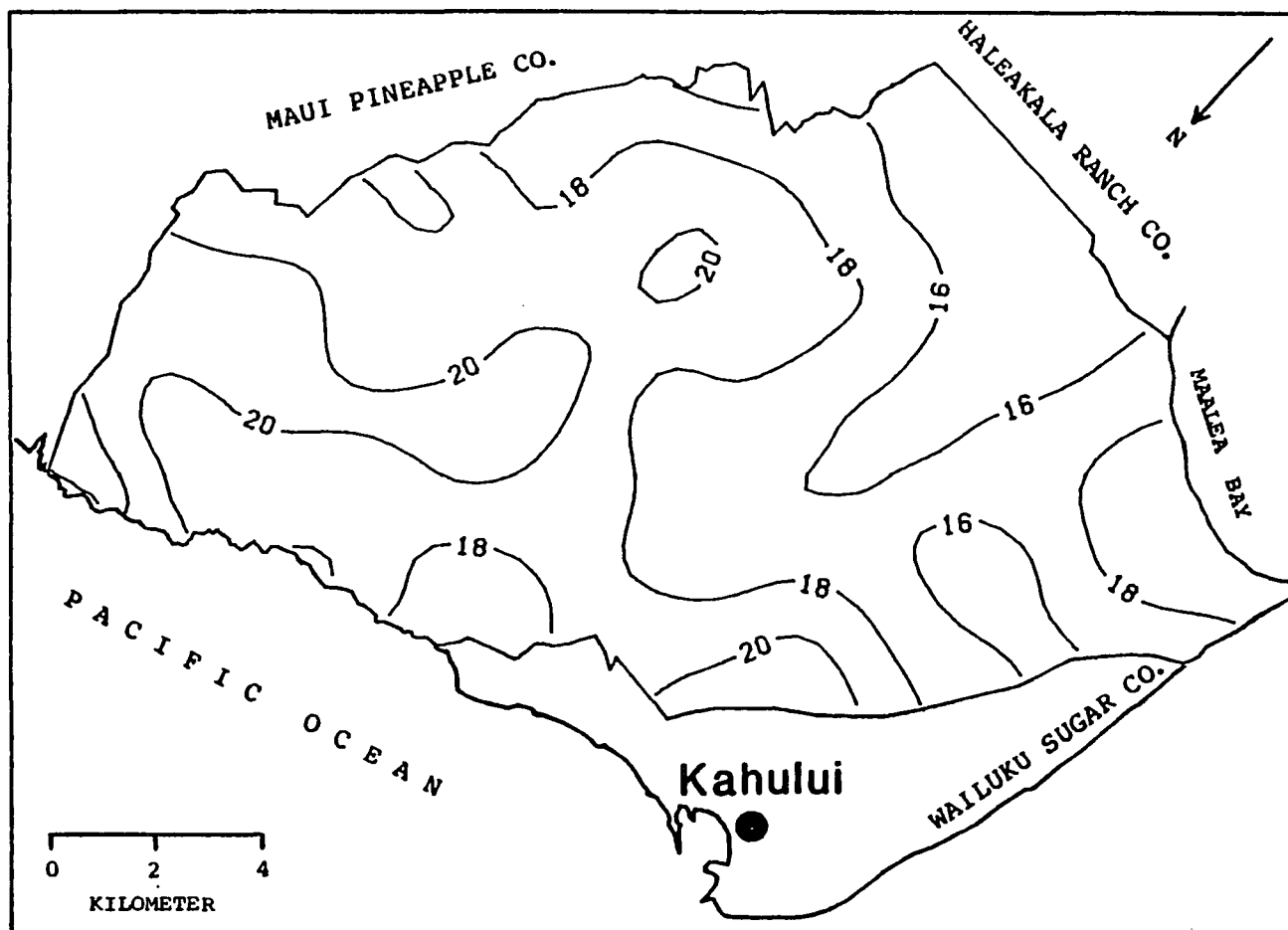
Fig. 94 Isarithm map of Zn status (mg/kg) of leaf blades (wet-digested) by
isotropic block kriging, HC&S, Maui.
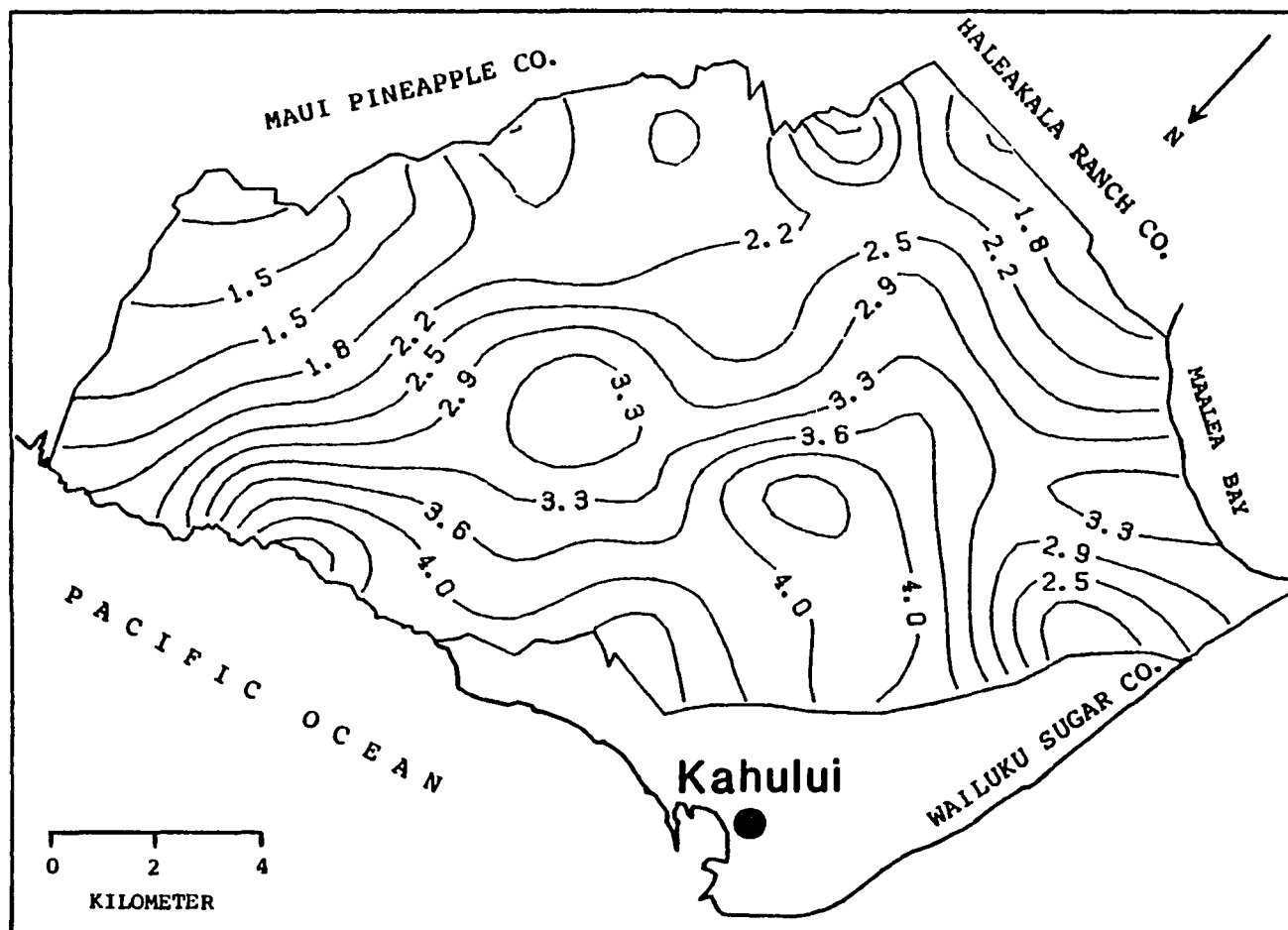
Fig. 95   Isarithm map of SiO_2 status (%) of leaf blades by isotropic block
kriging, HC&S, Maui.

the east of the plantation, and (b) slow plant growth in Zn-deficient soils resulting in more silica accumulation. Wet- digestion recovered relatively more Zn from plant tissues that were high in silica. This agrees with the greenhouse investigations discussed earlier in section A-4 of this chapter.

Higher recovery of Zn from leaf tissues with high silica contents, produced on low-Zn soils, narrowed the differences between Zn-deficient and Zn-adequate areas. These results suggest that dry-ashing of leaf-tissue is a better procedure to assess the status of 'functional' Zn in sugarcane plants. The low-Zn soils in the west of the plantation (towards Maalaea Bay), extending from north to south, were high in pH. Many of these soils were calcareous. The high-Zn soils in the east had low pH. According to Lindsay (1972), Zn activity decreases 100-fold for each unit increase in pH. In general, plant availability of soil Zn decreases as soil pH increases (Wear, 1956). An inverse relationship is attributed to precipitation of soil Zn as carbonates or hydroxides at higher soil pH levels (Jurinak and Thorne, 1955). This explanation, however, is not in accord with data showing that Zn deficiency of plants on calcareous soils can be corrected by fertilization with $ZnCO_3$ or $Zn(OH)_2$ (Boawn et al., 1957).

In the past, Maui growth failure has been observed in HC&S fields 808-813, 816,817, 820, 822, and 823 (Fig. 5a) (John Sakuma, personal communication). These fields lie within the low-Zn areas depicted in these maps. The possible role of Zn deficiency in Maui growth failure is discussed in section C of this chapter.

Sodium bicarbonate-extractable soil P is presented in Figure 96

and 97 and fertilizer P requirements to attain 0.2 mg P/kg soil in

Figure 98, 99. Phosphorus status of plant tissue corresponded with

soil P (Fig. 100, 101). Samuels et al. (1957) proposed a critical P

level of 0.2% in top-visible dewlap leaf of sugarcane. Phosphorus in

leaf blades was approximately 0.2 mg P/kg, except for extremely high

leaf P in a small area in the vicinity of Puunene sugar mill, near

Kahului, (Fig. 100, 5a). Although P status of leaf sheaths is also

high near Puunene sugar mill, it is not as high as in leaf blades.

Phosphorus contents of leaf sheaths was also high around Paia sugar

mill (north of plantation, Fig. 101, 5a). Presumably, these very high

P contents in soils and plant tissue are the result of application of

mill water, mill mud, and other byproducts of the mill to these fields.

Although P-induced Zn deficiency is well documented in many crops,

there was no apparent evidence of adverse effect of high P on Zn

nutrition in this instance -- probably because the factors that enhanced

P levels also enhanced Zn levels.

A map showing the K status of topsoils is presented in Figure 102.

Potassium contents of foliar tissue did not vary greatly in this

plantation (Fig. 103). In general, leaf blades contained

concentrations of K above the critical level of 1.1% proposed by

Samuels et al. (1957). Potassium contents of leaf blades were,

however, relatively low in a localized area in the south of the

plantation. These soils appear marginal to deficient in K.

Reliability of estimated values for Zn contents of soils and leaf
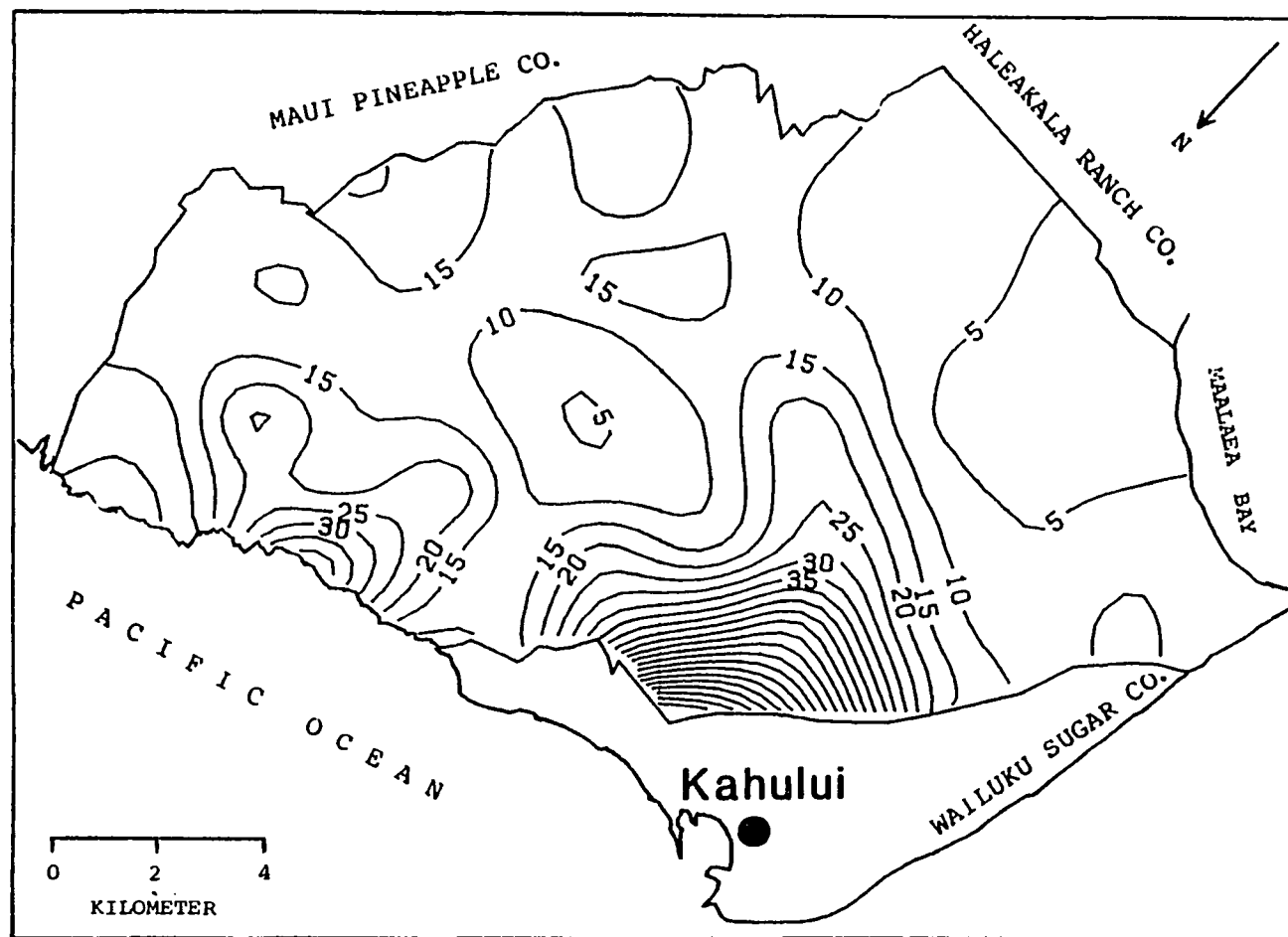
Fig. 96   Isarithm map of NaHCO$_3$-extractabel P (mg/kg) status of surface
soils by isotropic block kriging, HC&S, Maui.
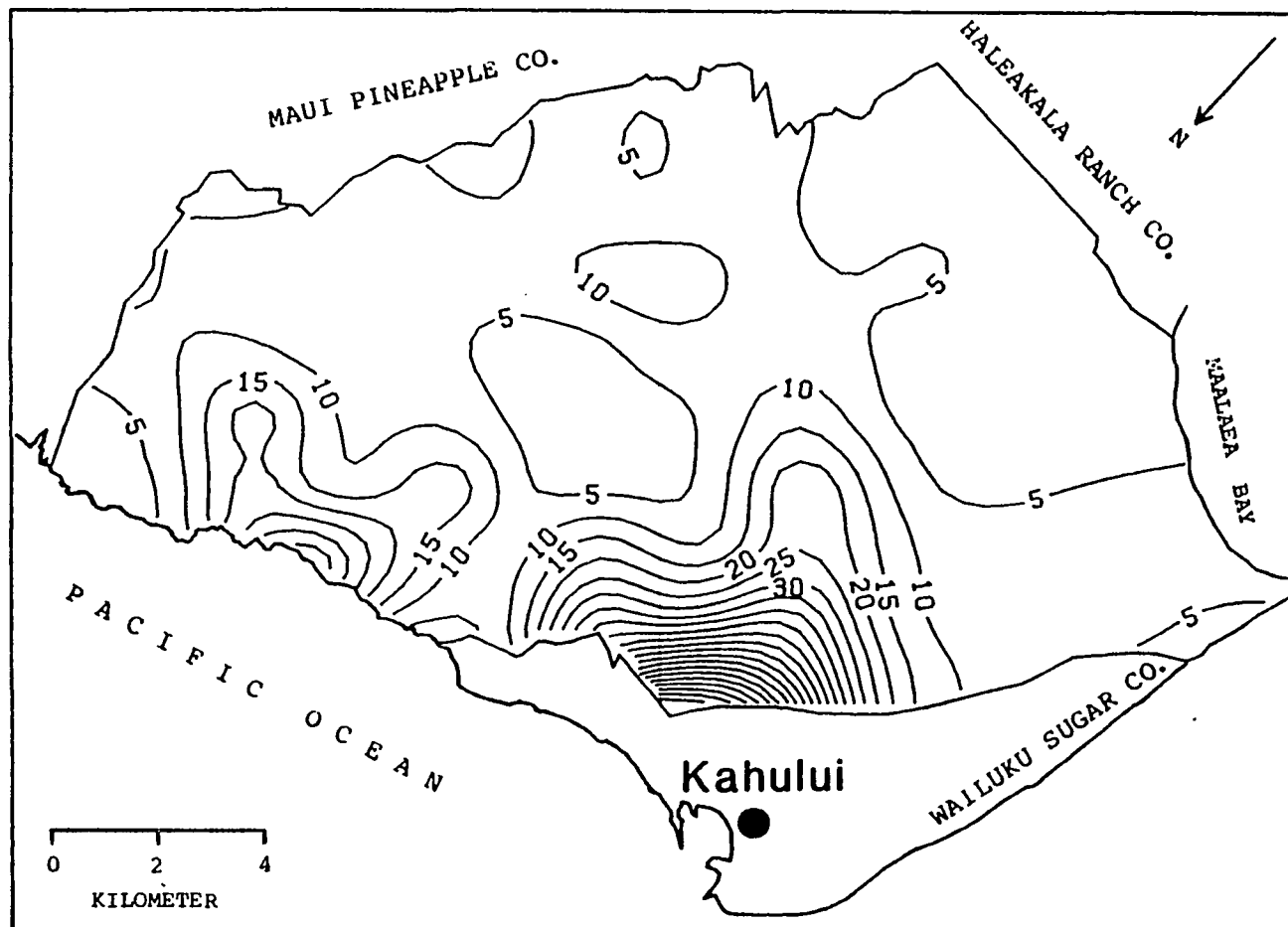
Fig. 97   Isarithm map of NaHCO₃-extractabel P (mg/kg) status of subsoils
          by isotropic block kriging, HC&S, Maui.
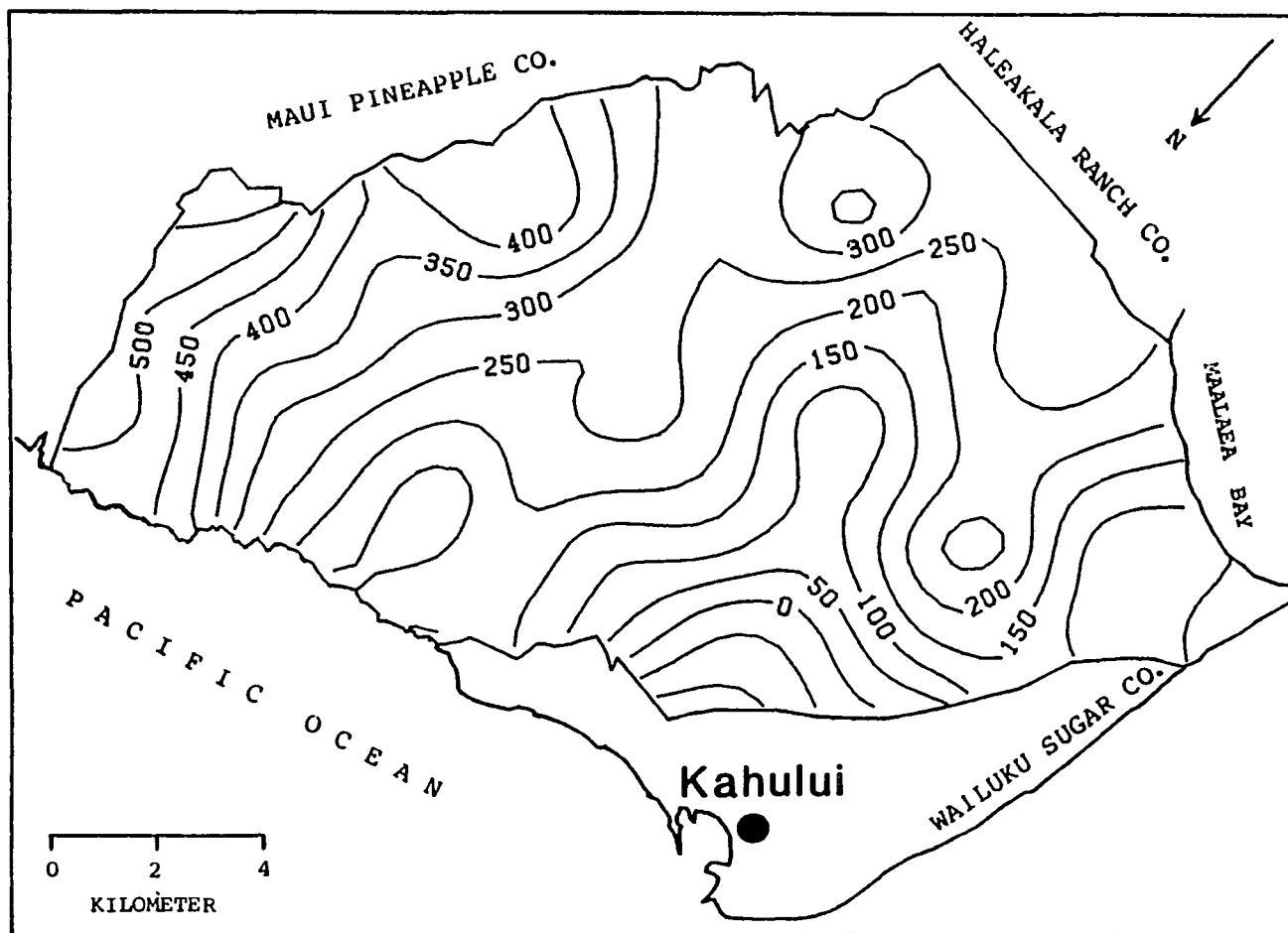
Fig. 98 Isarithm map of P requirements (mg/kg) of surface soils for 0.2
mg P/kg soil by isotropic block kriging, HC&S, Maui.
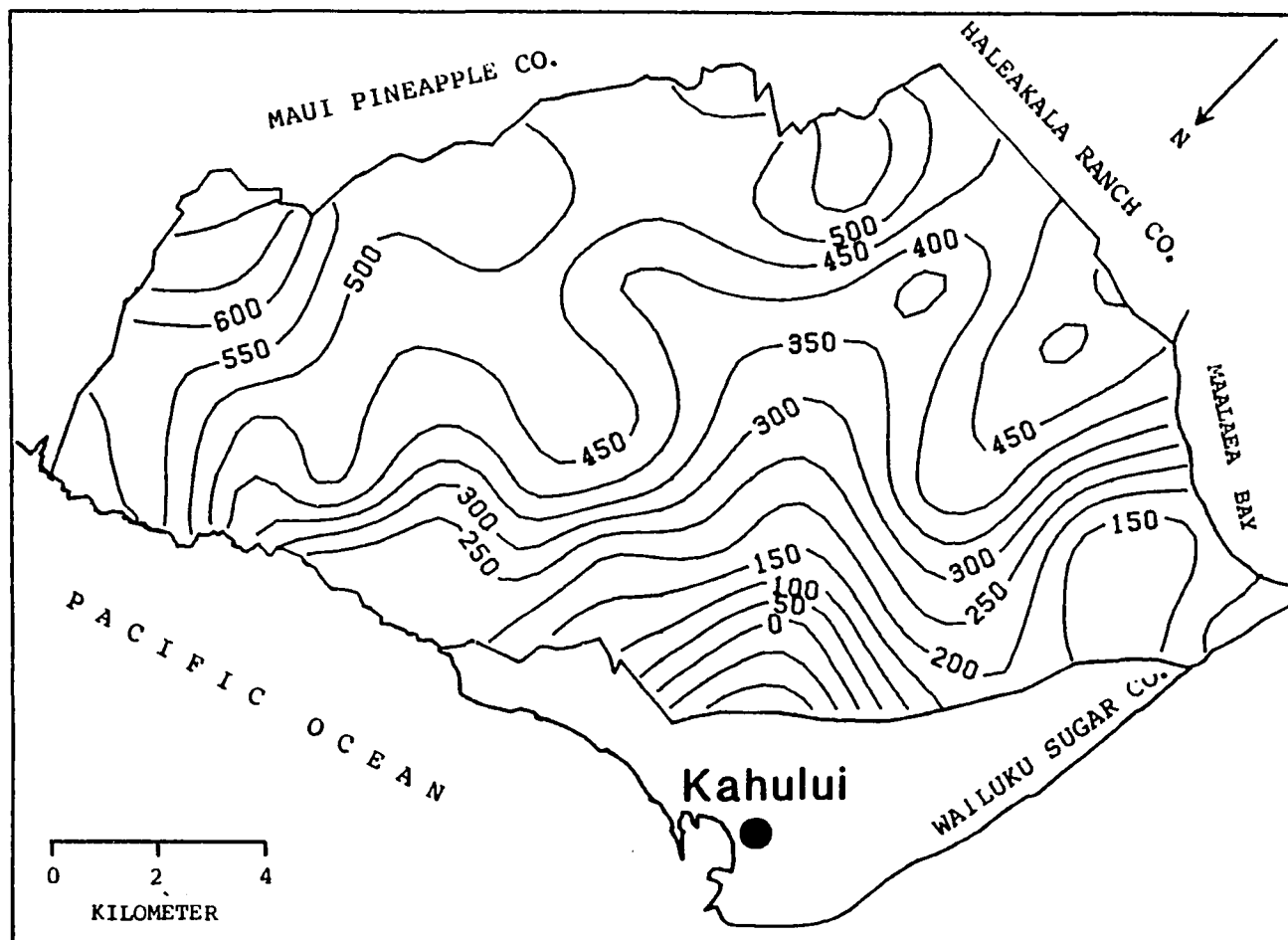
Fig. 99 Isarithm map of P requirements (mg/kg) of subsoils for 0.2 mg P/kg by isotropic block kriging, HC&S, Maui.
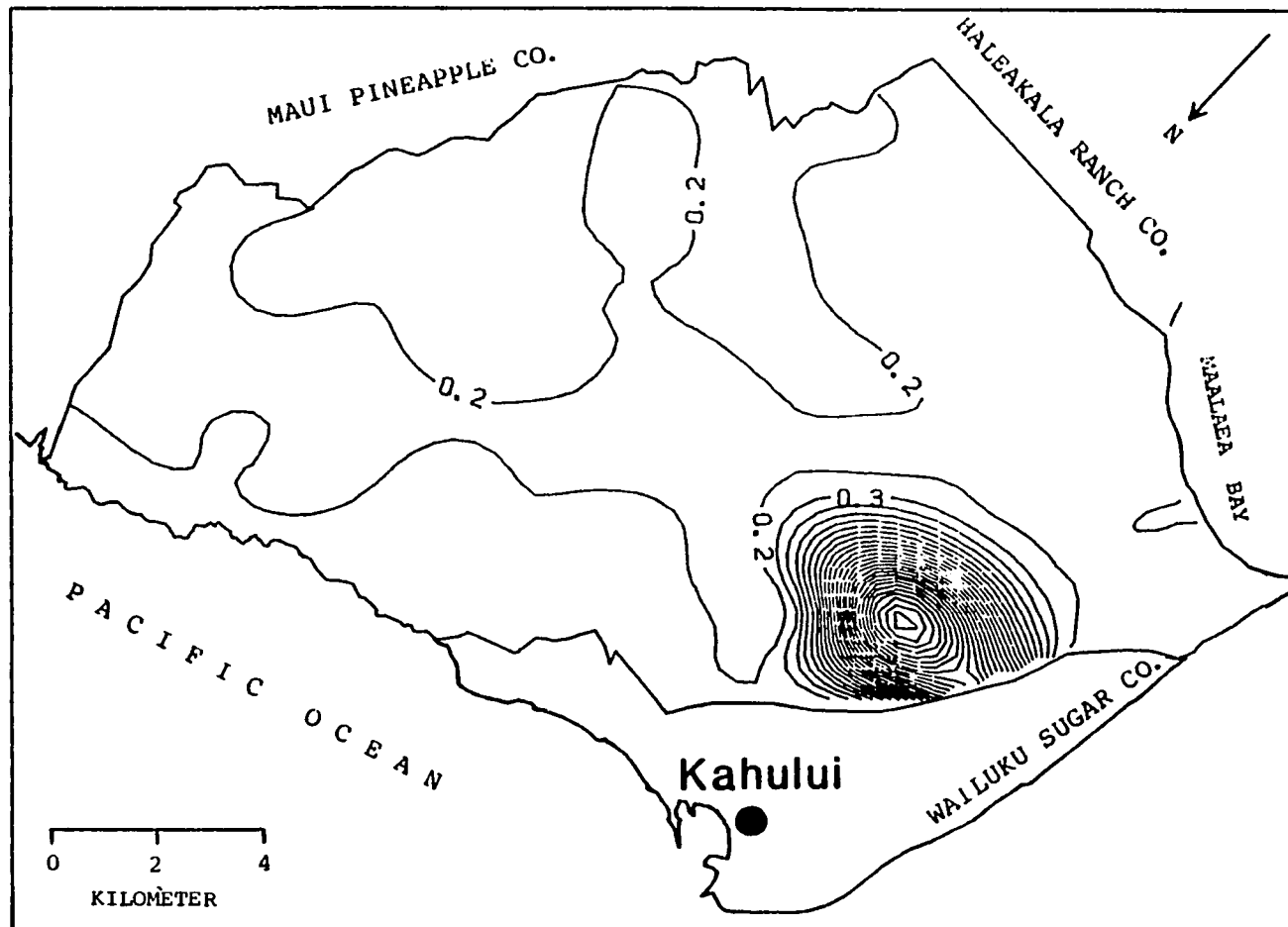
Fig. 100 Isarithm map of P status (%) of leaf blades from 70 observed values, HC&S, Maui.
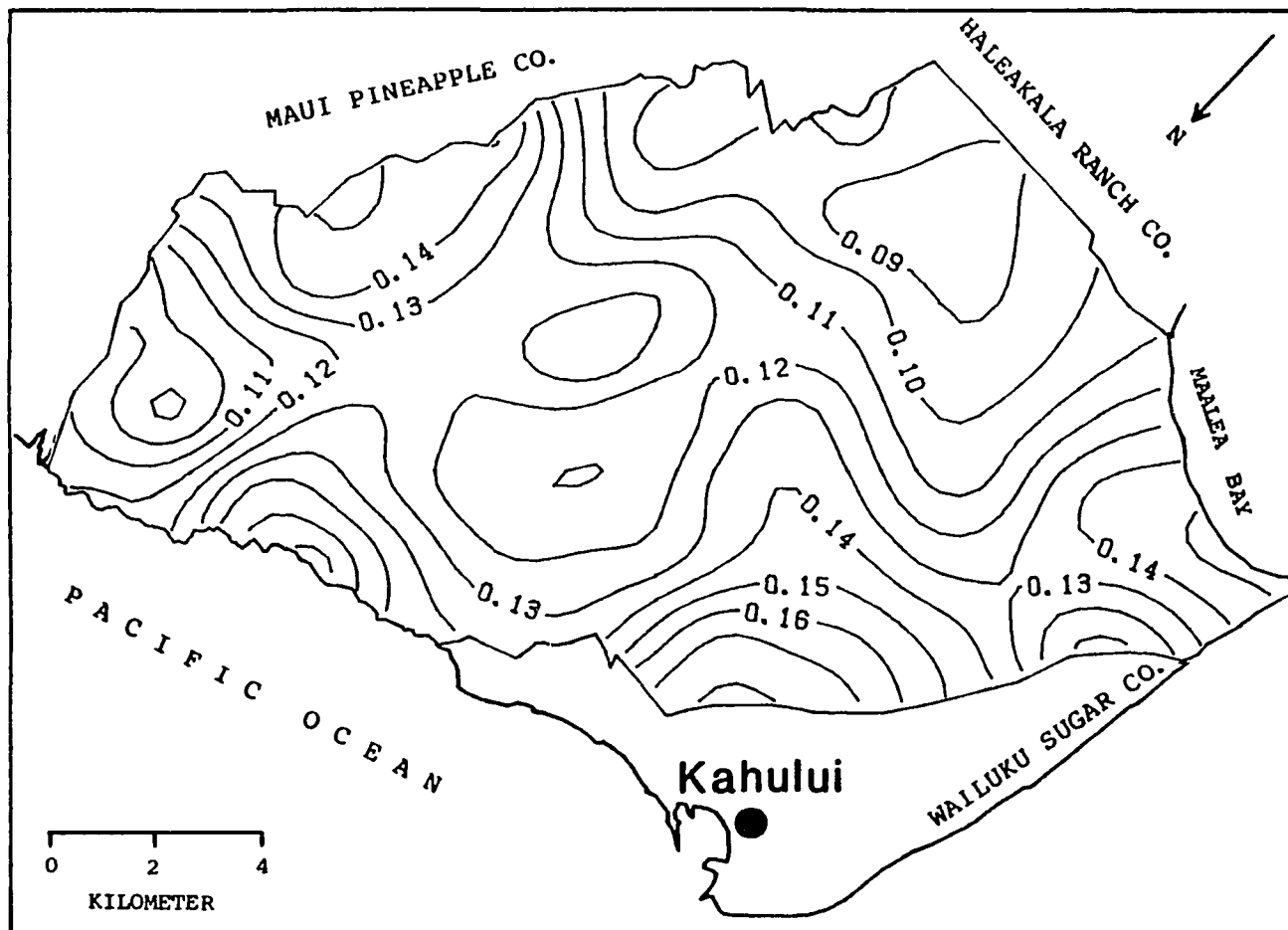
Fig. 101   Isarithm map of P status (%) of leaf sheaths by isotropic block
           kriging,HC&S, Maui.
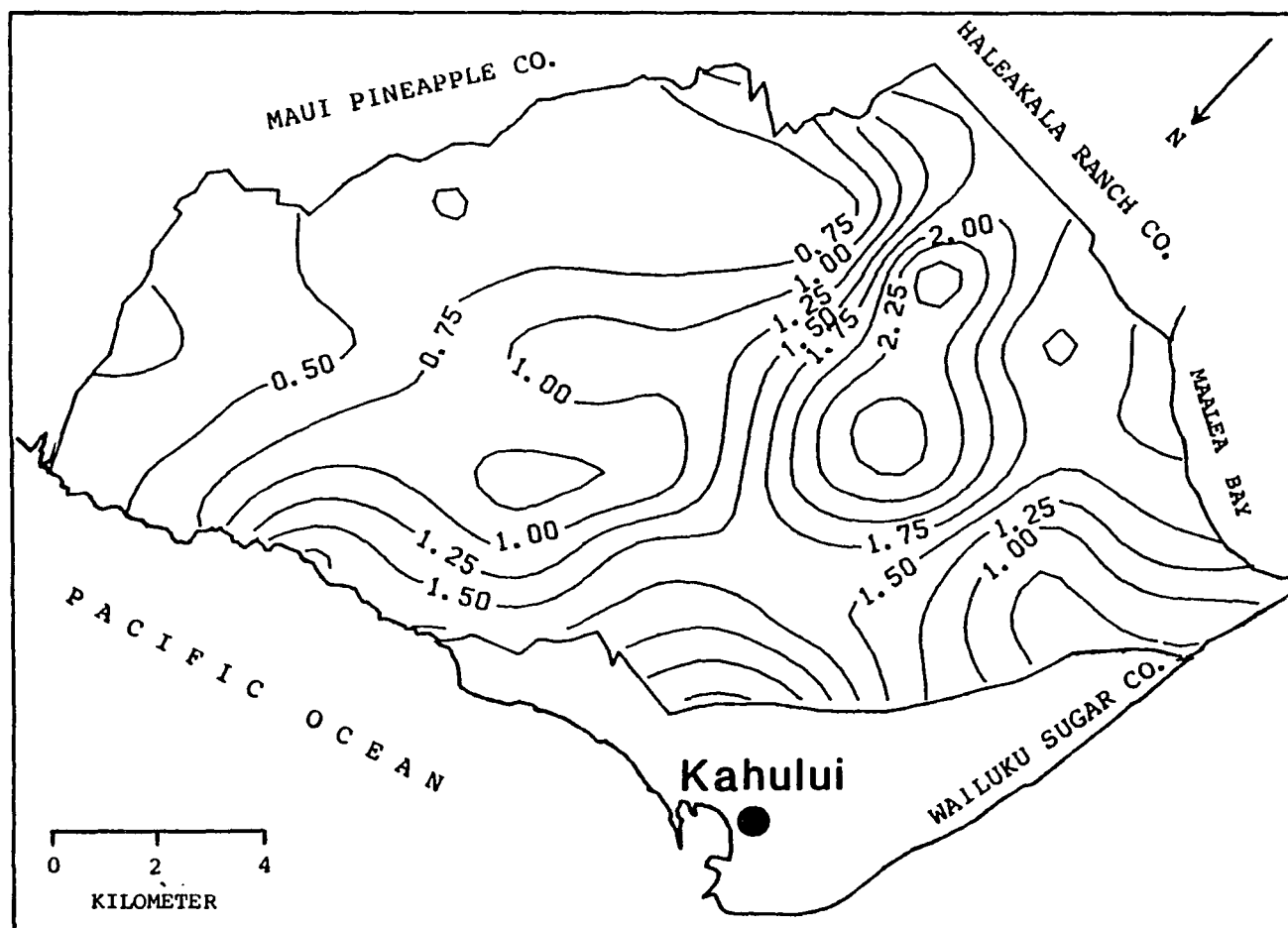
Fig. 102   Isarithm map of exchangeable K (mg/kg) status of surface soils by
isotropic block kriging, HC&S, Maui.
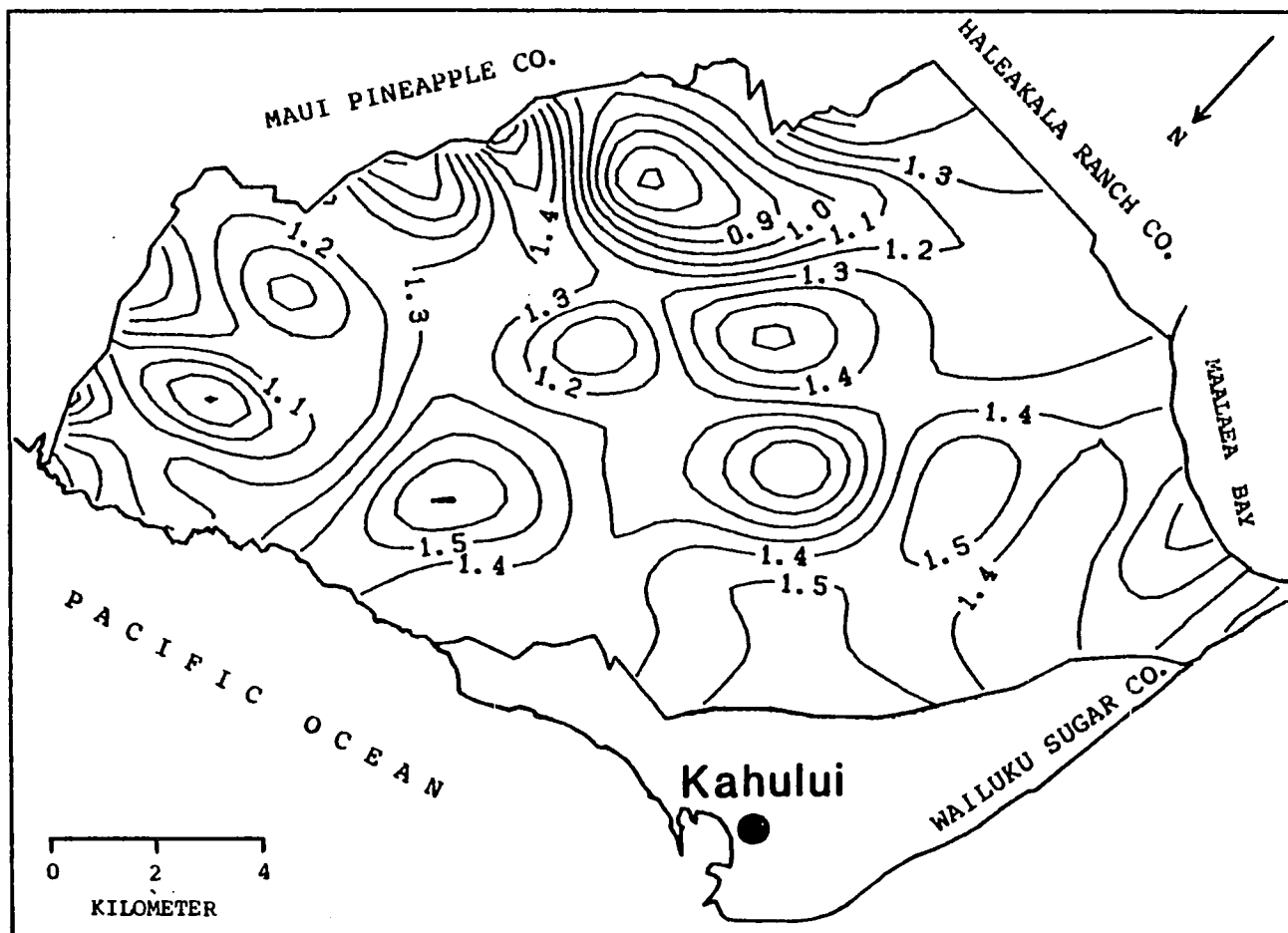
Fig. 103   Isarithm map of K status (%) of leaf blades from 70 observed values, HC&S, Maui.

blades decreased towards plantation boundaries, particularly the south and north boundaries (Appendix 17-19). This can be explained because there were fewer samples from these two areas and because fewer data points were available for calculating kriged values near area boundaries than in the interior.

Estimation-variances were much greater for topsoil Zn than for Zn contents of leaf blades (dry-ashed). In part, this resulted from a greater nugget variance for soil Zn (56% of sill). In contrast, nugget variance of leaf blade Zn was only 6% of sill. Kriging can be performed with minimal structure in the semi- variograms, however, this results in high estimation variances. High nugget variances result in high estimation variances. In contrast, low R^2 values or lack of fit are not propagated to high estimation variances.

Maps of leaf blade N, S, and Mn and leaf sheath K, Mn, S, Na, and Si are presented in Appendix 20-27.

3. Pioneer Mill Company, Maui, Hawaii

The total sugarcane area of Pioneer Mill Company is approximately 3300 hectares. A belt of sugarcane fields along the Pacific Ocean coastline have a wide range of elevation, 5 m to 385 m. The plantation is fragmented by gulches and rocky land areas extending from mountain slopes to the Pacific Ocean.

Field size varies from 0.8 to 100 hectares with an average of 16 hectares. There is a general trend of increasing rainfall from west coast of the island to east toward the West Maui mountain slopes. Mean annual temperature varies only from $22^{o}C$ to $25^{o}C$.

Some soils near the ocean coastline were alkaline but pH of most

soils was acid (Table 26). HCl-extractable topsoil Zn ranged from 1 to

20 mg Zn/kg soil. Zinc status of subsoils was generally less than

topsoils. This agrees with Kanehiro and Sherman (1967).

Zinc content of leaf sheaths and leaf blades (dry-ashed) varied

three-fold (Table 26). The ranges of Zn concentration are similar by

wet-digestion except that the values are greater than obtained by

dry-ashing. This agrees with the greenhouse results discussed earlier

in section A of this chapter. Plant tissue concentrations of P, K, Ca,

Mg, S, Na, Mn, and silica also varied greatly (Table 26).

a. Statistical analysis

Extractable soil Zn was not related to soil pH (Table 27). However,

Zn contents of leaf blades were negatively related to soil pH (r = -0.52).

Zinc contents of leaf sheaths and leaf blades were related to soil

Zn (Table 27). For leaf sheaths, the correlation coefficient between

dry-ashed and wet-digested Zn data was 0.85. A small r value of 0.56

was obtained for leaf blade Zn. Zinc recovery from leaf blades by

dry-ashing procedure was negatively related to silica contents of leaf

tissue (r = - 0.69). Sugarcane leaf blades contain more silica than

leaf sheaths (Table 15).

Phosphorus and Zn contents of leaf blades (dry-ashed) were

negatively related (r = -0.40). This agrees with earlier reports

(Olsen, 1972).

b. Spatial analysis

Soil, climate, and plant tissue properties were analyzed for

Table 26   Mean, range and standard deviation of properties of soils, climate, and sugarcane leaf tissues, Pioneer Mill Company, Maui, Hawaii.

Variable	Mean/ median*	Range	Standard deviation	Distribution
Topsoil pH	6.4	5.2-7.4	0.6	normal
Subsoil pH	6.5	5.5-7.3	0.47	normal
Topsoil Zn (mg/kg)	4.0	1.0-20.0	4.5	log
Subsoil Zn (mg/kg)	3.0	0.7-14.7	3.0	log
Elevation (m)	86	5-385	114	log
Rainfall (mm)	521	152-1194	277	normal
Maximum temperature (C)	28	27-29	1.9	-[a]
Minimum temeprature (C)	19	18-21	1.7	-
Pan evapo- ration (mm)	2111	1778-2591	197	-
Leaf sheaths				
Topsoil pH	6.4	5.2-7.4	0.6	normal
Zn (mg/kg)				
dry-ashed	7.9	5.5-16.9	2.7	log
wet- digested	10.8	5.8-20.2	3.5	normal
P (%)	0.088	0.057-0.14	0.025	-
K (%)	2.29	1.37-4.87	0.84	log
Ca (%)	0.11	0.05-0.18	0.034	normal
Mg (%)	0.15	0.025-0.23	0.050	normal
S (%)	0.21	0.044-0.47	0.12	normal

Table 26   Mean, range and standard deviation of properties of
(cont.)   soils, climate, and sugarcane leaf tissues, Pioneer
           Mill Company, Maui, Hawaii.

Variable	Mean/ median*	Range	Standard deviation	Distribution
Leaf sheaths				
Na (mg/kg)	71	34–163	30	log
Mn (mg/kg)	44	16–125	34	log
SiO$_2$ (%)	2.74	1.22–4.27	0.83	normal
Moisture (%)	79	69–86	3.9	normal
Growth index (g/20 sheaths)	335	269–432	51	–
Leaf blades				
Zn (mg/kg) dry-ashed	14.2	10.6–28.5	4.2	log
wet-digested	20.1	13.5–26.7	3.4	normal
N (%)	1.43	1.06–1.90	0.23	normal
P (%)	0.19	0.14–0.26	0.034	log
K (%)	1.35	0.90–1.93	0.26	normal
Ca (%)	0.18	0.11–0.30	0.054	normal
Mg (%)	0.18	0.10–0.28	0.050	normal
S (%)	0.13	0.085–0.30	0.055	log
Na (mg/kg)	151	109–240	34	log
Mn (mg/kg)	26	10–65	17	log
SiO$_2$ (%)	3.4	0.9–7.3	1.7	normal

* –– Median values are given for lognormally distributed data.
a –– Data did not fit to normal or log-normal distribution.

Table 27 Correlation coefficients (r) and leviels of significance
of some parameters related to Zn nutrition of plants,
Pioneer Mill Company, Maui, Hawaii.

	Topsoil Zn (mg/kg)	Subsoil Zn (mg/kg)	Dry-ashed Leaf blade Zn (mg/kg)	Leaf sheath Zn (mg/kg)
Topsoil pH	0.23 (0.21)[a]	0.20 (0.30)	-0.52 (0.0032)	0.18 (0.34)
Subsoil pH	0.15 (0.44)	0.14 (0.45)	-0.49 (0.0056)	0.064 (0.74)
Topsoil Zn	1	0.91 (0.0001)	-0.11 (0.55)	0.69 (0.0001)
Subsoil Zn	0.91 (0.0001)	1	-0.15 (0.42)	0.61 (0.0003)
Elevation (m)	-0.32 (0.086)	-0.31 (0.092)	0.64 (0.0001)	-0.28 (0.13)
Rainfall (mm)	-0.31 (0.099)	-0.31 (0.091)	0.52 (0.0034)	-0.45 (0.013)
Temperature (C)	0.26 (0.17)	0.26 (0.17)	-0.31 (0.098)	0.38 (0.040)
Pan evaporation (mm)	-0.074 (0.70)	-0.11 (0.56)	-0.43 (0.017)	-0.12 (0.52)
Leaf blades				
Zn (mg/kg) dry-ashed	-0.11 (0.55)	-0.15 (0.42)	1	0.078 (0.68)
wet-digested	0.52 (0.0031)	0.45 (0.012)	0.51 (0.0039)	0.58 (0.0009)
P (%)	0.41 (0.026)	0.36 (0.047)	-0.40 (0.030)	
K (%)	0.47 (0.0083)	0.42 (0.022)	0.33 (0.077)	

Table 27 Correlation coefficients (r) and levlels of significance
(cont.) of some parameters related to Zn nutrition of plants,
Pioneer Mill Company, Maui, Hawaii.

	Topsoil Zn (mg/kg)	Subsoil Zn (mg/kg)	Dry-ashed Leaf blade Zn (mg/kg)	Leaf sheath Zn (mg/kg)
Leaf blades				
Na (mg/kg)	-0.085 (0.66)	-0.00062 (0.97)	0.14 (0.45)	
Mn (mg/kg)	0.26 (0.16)	0.17 (0.36)	0.13 (0.50)	
SiO_2 (%)	0.56 (0.0014)	0.62 (0.0003)	-0.69 (0.0001)	0.49 (0.0063)
Leaf sheaths				
Zn (mg/kg)				
dry-ashed	0.69 (0.0001)	0.61 (0.0003)	0.078 (0.68)	1
wet-digested	0.70 (0.0001)	0.64 (0.0002)	-0.036 (0.85)	0.85 (0.0001)
P (%)	0.42 (0.020)	0.43 (0.018)		0.60 (0.0005)
K (%)	0.59 (0.0006)	0.58 (0.0008)		0.68 (0.0001)
Na (mg/kg)	0.37 (0.046)	0.34 (0.070)		0.59 (0.0006)
Mn (mg/kg)	0.035 (0.86)	-0.029 (0.88)		-0.027 (0.89)
SiO_2 (%)	0.52 (0.0035)	0.55 (0.0015)		0.46 (0.010)

a -- The values in parantheses indicate the probability of a
chance occurrence of the statistics.

Table 28 Parameter estimates of isotropic semi-variograms[a] of
properties of soil, climate, and sugarcane leaf
tissue, Pioneer Mill Company, Maui, Hawaii.

Variables	Range (km)	Nugget variance	Sill	% of sill	General variance	Model[b]	R^2 of model[c]
Topsoil pH	4.2	0.02	0.34	6	0.38	S	0.73
Subsoil pH	13.9	0.078	0.35	22	0.22	M	0.56
Topsoil Zn (mg/kg)	6.9	0.40	1.44	28	0.61	M	0.87
Subsoil Zn (mg/kg)	1.2	0.24	0.51	47	0.57	M	0.20*
Elevation (m)	4.9	0.078	1.06	7	1.48	S	0.78
Rainfall (mm)	7.3	28	119	23	119	L	0.54
Maximum temperature (C)	5.2	0.058	3.34	2	3.75	S	0.88
Minimum temperature (C)	No structure						
Pan evaporation (mm)	6.6	14.8	60.3	24	60.3	L	0.69

Leaf sheaths

Zn (mg/kg) dry-ashed	No structure						
wet-digested	No structure						
P (%)	16.0	0.00026	0.00079	33	0.00062	M	0.44
K (%)	6.6	0.058	0.113	51	0.091	L	0.65
S (%)	2.8	0.0043	0.011	39	0.013	S	0.55
Mn (mg/kg)	14.3	0.032	0.44	7	0.33	M	0.91
SiO_2 (%)	5.8	0.18	0.54	33	0.68	S	0.75
Ca (%)	No structure						
Mg (%)	No structure						
Na (mg/kg)	No structure						

Table 28   Parameter estimates of isotropic semi-variograms[a] of
(cont.)   properties of soil, climate, and sugarcane leaf
            tissue, Pioneer Mill Company, Maui, Hawaii.

Variables	Range (km)	Nugget variance	Sill	% of sill	General Model variance	Model[b]	R^2 of model[c]
Leaf blades							
Zn (mg/kg)							
dry-ashed	6.6	0.31	0.0803	39	0.061	L	0.41
wet-digested	No structure						
N (%)	No structure						
P (mg/kg)	5.3	0.022	0.033	67	0.033	L	0.19[*]
SiO_2 (%)	4.7	0.28	2.50	11	2.84	M	0.81
K (mg.kg)	No structure						
Ca (mg/kg)	No structure						
Mg (mg/kg)	No structure						
S (mg/kg)	No structure						
Mn (mg/kg)	No structure						
Na (mg/kg)	No structure						

a -- Semi-variances for soil Zn, elevation, leaf sheath K, Mn, Na, leaf blade Zn, P, S, Mn, and Na determined on log transformed values.

b -- L = Linear model, M = Mitscherlich (Spherical) model, S = Spherical model.

c -- $R^2 = (SS_{corrected} - SS_{residual})/SS_{corrected}$.

R^2 for model fitted up to range. All R^2 values significant at $P<0.01$ unless otherwise indicated.

* -- significant at $P < 0.05$.

$$\% \text{ of sill} = \frac{\text{nugget variance}}{\text{sill}} \times 100.$$

Table 29 Mathematical models fitted to isotropic semi-variograms
of soil, climate and sugarcane leaf tissue properties,
Pioneer Mill Company, Maui, Hawaii.

Variable	Model	Equation
Topsoil pH	S	$\gamma(h) = 0.02 + 0.11\ h - 0.0021\ h^3$
Subsoil pH	M	$\gamma(h) = 0.35 - 0.27\ [\exp\ (-0.20\ h)]$
Topsoil Zn (mg/kg)	M	$\gamma(h) = 1.44 - 1.04\ [\exp\ (-0.12h)]$
Subsoil Zn (mg/kg)	M	$\gamma(h) = 0.51 - 0.28\ [\exp\ (-2.02h)]$
Elevation (m)	S	$\gamma(h) = 0.078 + 0.30\ h - 0.0041\ h^3$
Rainfall (mm)	L	$\gamma(h) = 27.8 + 12.4\ h$
Max. temp. (C)	S	$\gamma(h) = 0.058 + 0.95\ h - 0.012\ h^3$
Pan Evap. (mm)	L	$\gamma(h) = 14.75 + 7.36\ h$

Leaf sheath

Variable	Model	Equation
P (%)	M	$\gamma(h) = 0.00079 - 0.00052\ [\exp\ (-0.17\ h)]$
K (%)	L	$\gamma(h) = 0.058 + 0.0113\ h$
S (%)	S	$\gamma(h) = 0.0043 + 0.0036\ h - 0.00015\ h^3$
Mn (mg/kg)	M	$\gamma(h) = 0.44 - 0.41\ [\exp\ (-0.21\ h)]$
Silica (%)	S	$\gamma(h) = 0.18 + 0.091\ h - 0.00091\ h^3$

Leaf blade

Variable	Model	Equation
Zn (mg/kg) dry-ashed	L	$\gamma(h) = 0.031 + 0.0083\ h$
P (%)	L	$\gamma(h) = 0.022 + 0.0013\ h$
Silica (%)	M	$\gamma(h) = 2.50 - 2.22\ [\exp\ (-0.49\ h)]$

L = Linear model
M = Mitscherlich (exponential) model
S = Spherical model

spatial dependence. Key parameters of isotropic semi-variograms are listed in Table 28 and the mathematical models fitted to semi-variograms are listed in Table 29.

Isotropic semi-variogram of surface soil pH had spherical structure (Fig. 104). Its sill was smaller than the general variance. The range of spatial dependence was 4.2 km. A nugget variance of 6% of sill indicates negligible variations within the sampling distances.

A Mitscherlich model fitted the semi-variogram of subsoil pH. Nugget variance for subsoil pH was greater than topsoil pH. Range of spatial dependence for subsoil pH (13.9) was much greater than topsoil pH. Soil management practices may be responsible for this big difference in the range of spatial dependence. Ahmad (1985) reported that the range of soil pH increased with soil depth.

Mitscherlich model equations fitted to the semi-variogram of extractable soil Zn in both soil layers (Table 29). The range of spatial dependence was 6.9 km for topsoil and 1.2 km for subsoil. For subsoil, R^2 values of fit and range of spatial dependence were very small and nugget variance was great (Table 28). Therefore, original data values of subsoil pH were used in constructing its isarithmic map.

A Mitscherlich model gave the best fit for isotropic semi-variogram of P concentration of leaf sheaths (Table 29). A spherical model was fitted to the semi-variogram of S contents of leaf sheaths. For leaf sheath S, the nugget variance was high and the range of spatial dependence was very small (2.8 km).
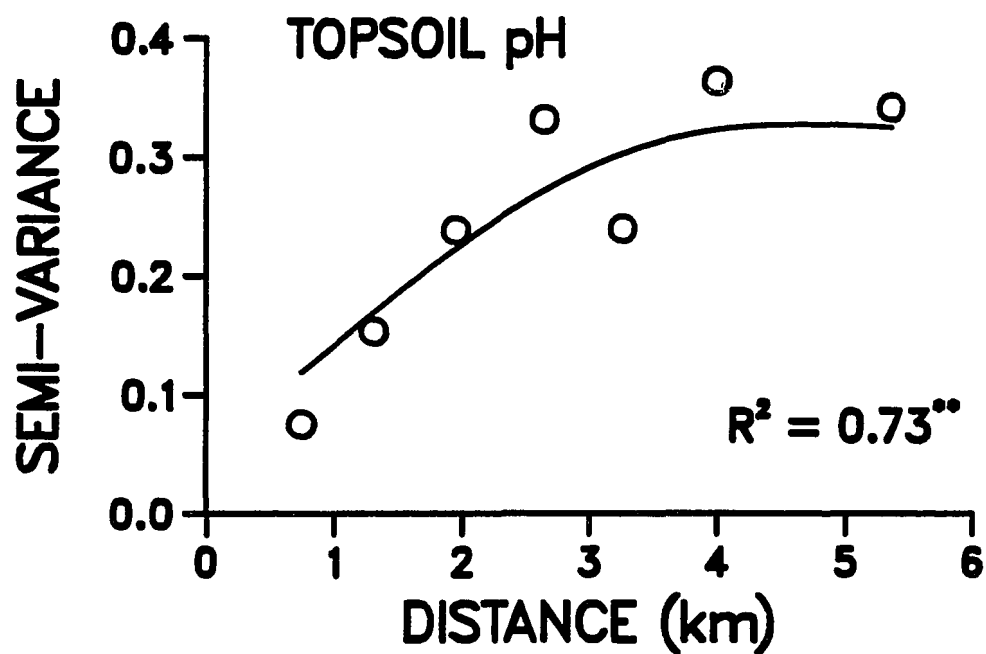
Fig. 104   Isotropic semi-variogram for pH of surface soils,
Pioneer Mill Comapany, Maui.
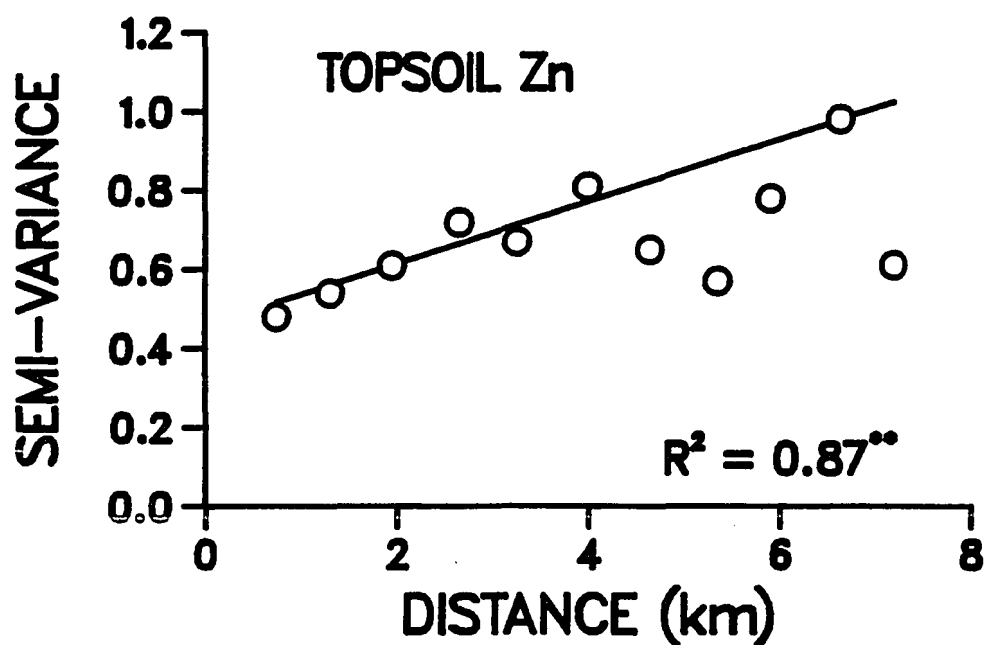
Fig. 105   Isotropic semi-variogram for log transformed values of
HCl-extractable Zn (mg/kg) in surface soils, Pioneer
Mill Comapany, Maui.
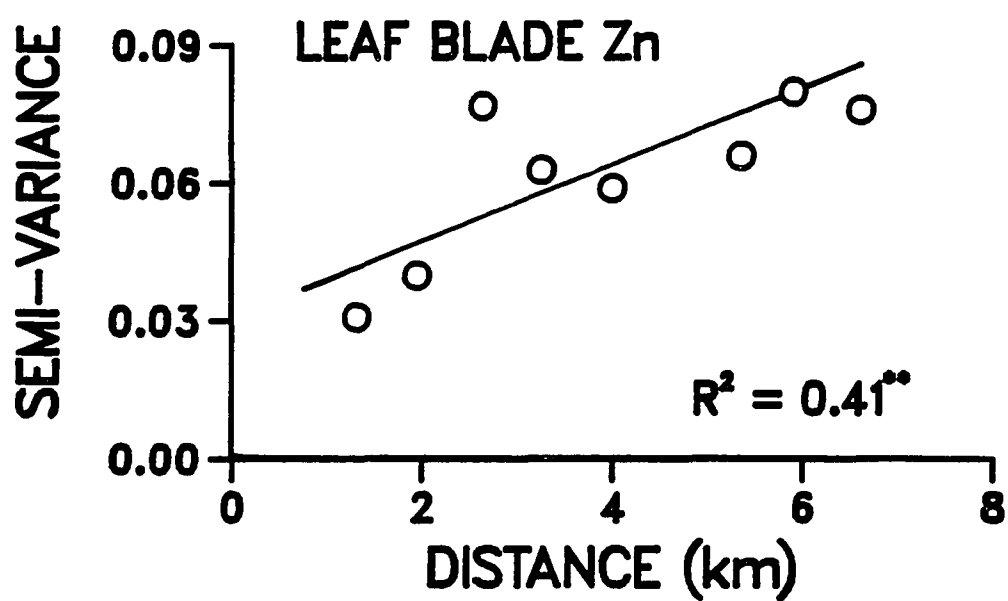
Fig. 106   Isotropic semi-variogram for log transformed values of
           Zn concentration (mg/kg) in leaf blades (dry-ashed),
           Pioneer Mill Comapany, Maui.

A Mitscherlich model fitted to the semi-variogram of Mn contents of leaf sheaths with R^2 value of 0.91. A low nugget variance (7% of sill) indicates very little variation within the sampling distances.

The range for spatial dependence of silica contents of leaf sheaths was 5.8 km. This is approximately equal to the range for Zn contents of leaf sheaths and leaf blades (dry-ashed).

Semi-variograms of Zn, Ca, Mg, and Na contents of leaf sheaths provided no structure or indication of spatial dependence.

For Zn contents of leaf blades, spatial dependence was obtained only for the data obtained by dry-ashing procedure. Zinc data obtained by wet-digesting indicated random variation or lack of spatial dependence. The semi-variogram of leaf blade Zn (dry-ashed) displayed linear structure (Table 28). A high nugget variance, 39% of sill, suggests closer sampling to get better structure of spatial dependence.

The semi-variogram of P contents of leaf blades indicated a weak linear trend with an R^2 value of 0.19 (significant at 0.05). The range of spatial dependence was 53 km. Because of low R^2 value and high nugget variance (67% of sill), the original data values were used in preparing isarithmic map.

A Mitscherlich model fitted to the semi-variogram of silica contents of leaf blades with an R^2 value of 0.81. The range of spatial dependence (4.7 km) was smaller than the range for leaf sheath silica (Table 28).

The semi-variograms for N, K, Ca, Mg, S, Mn, and Na did not have any structure. This may be the result of insufficient sampling points

and fragmented nature of the sugarcane area.

c. Kriging

HCl-extractable Zn contents at Pioneer Mill were especially high in a narrow belt along the Pacific Ocean coastline, between Lahaina and Olowalu, perhaps as a result of application of mill- mud and mill-water (Fig. 107-110). Some fields near Kaanapali shoreline and north of Olowalu, behind the high-Zn belt, were marginal or even deficient in Zn.

Zinc contents of leaf sheaths (dry-ashed) ranged from 5.5 to 16.9 mg Zn/kg (Fig. 111, 112). The coefficient of correlation between leaf sheath Zn and surface soil Zn was 0.69. Zinc contents in leaf blades (dry-ashed) ranged from 10.6 to 28.5 (Table 26). Concentrations of Zn in leaf blades did not correspond with soil Zn status. These anamolous results were probably caused by Zn contamination of the samples at some stage of production, sampling, or processing. If so, the results suggest that leaf sheaths are better indicator tissue than leaf blades because they are less likely to be contaminated.

The lower limits of Zn, both in the soils and the foliar tissues, indicate Zn deficiency at Pioneer Mill. Suspected problem areas are fields at higher elevations and some fields near the Kaanapali coastline (Fig. 107-112). Surface soil pH at Pioneer Mill ranged from 5.2 to 7.4. Although some fields near the coastline were alkaline, their pH was not very high. As the maps (Fig. 113, 114) indicate, soil pH tends to decrease with increasing elevation towards the mountains of West Maui. The high Zn status in soils of relatively high
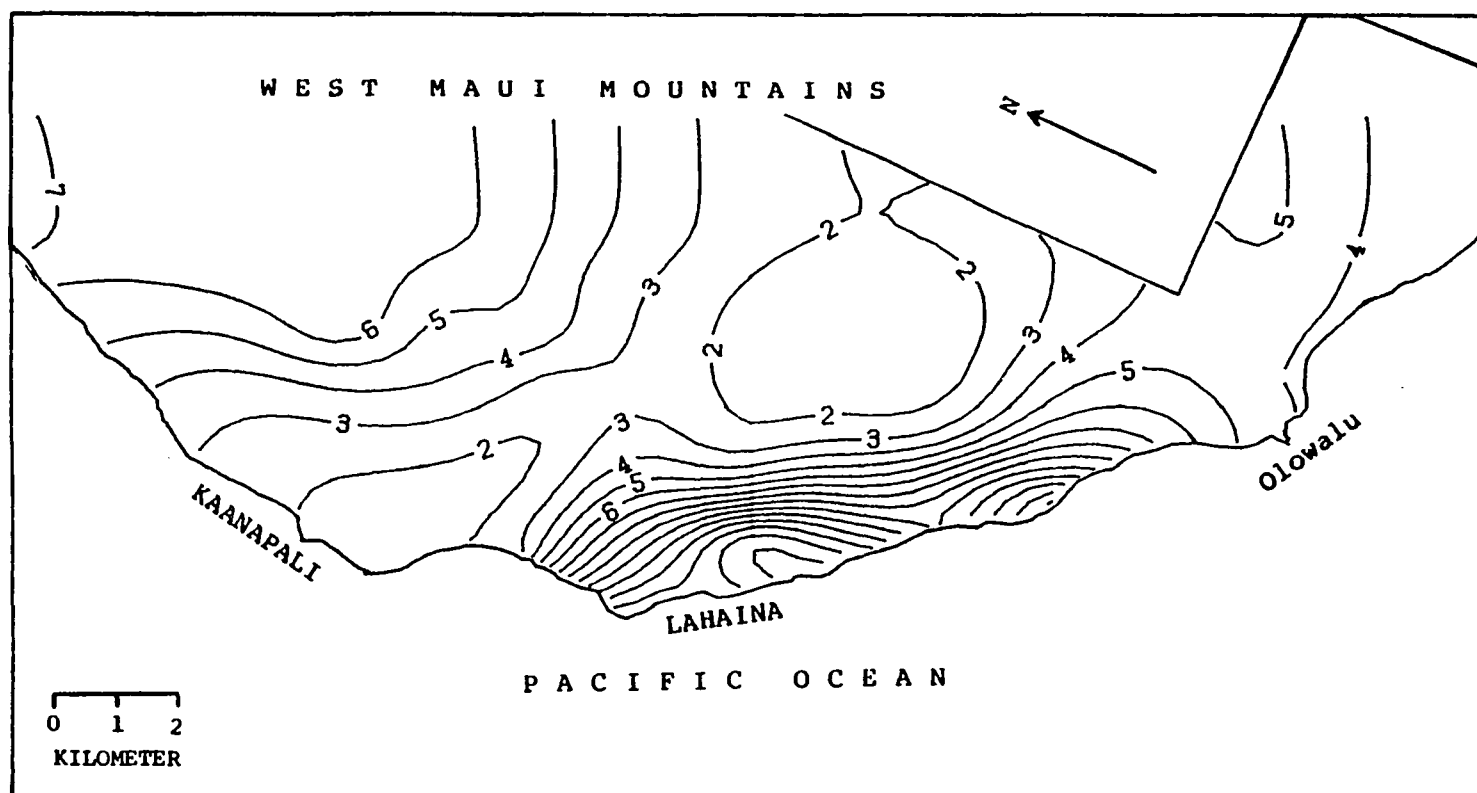
Fig. 107 Isarithm map of surface soil Zn (mg/kg) by isotropic block kriging,
Pioneer Mill Comapany, Maui.
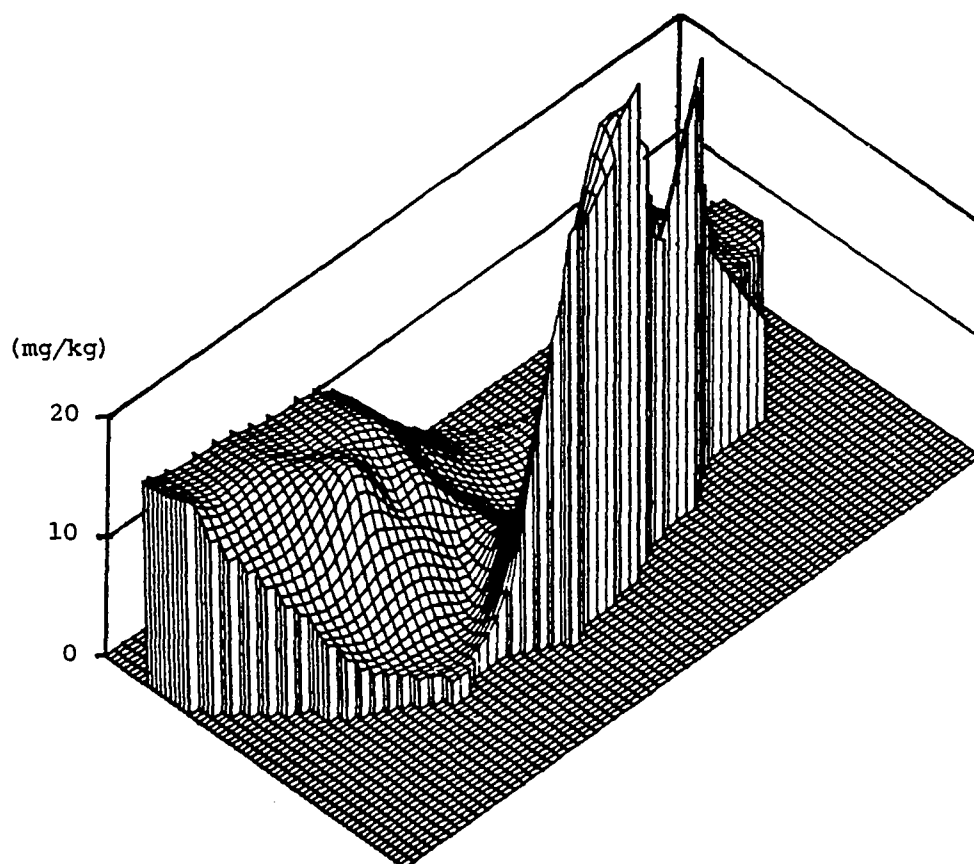
Fig. 108   Three-dimentional diagram of Zn status (mg/kg) of topsoils,
Pioneer Mill Comapany, Maui.
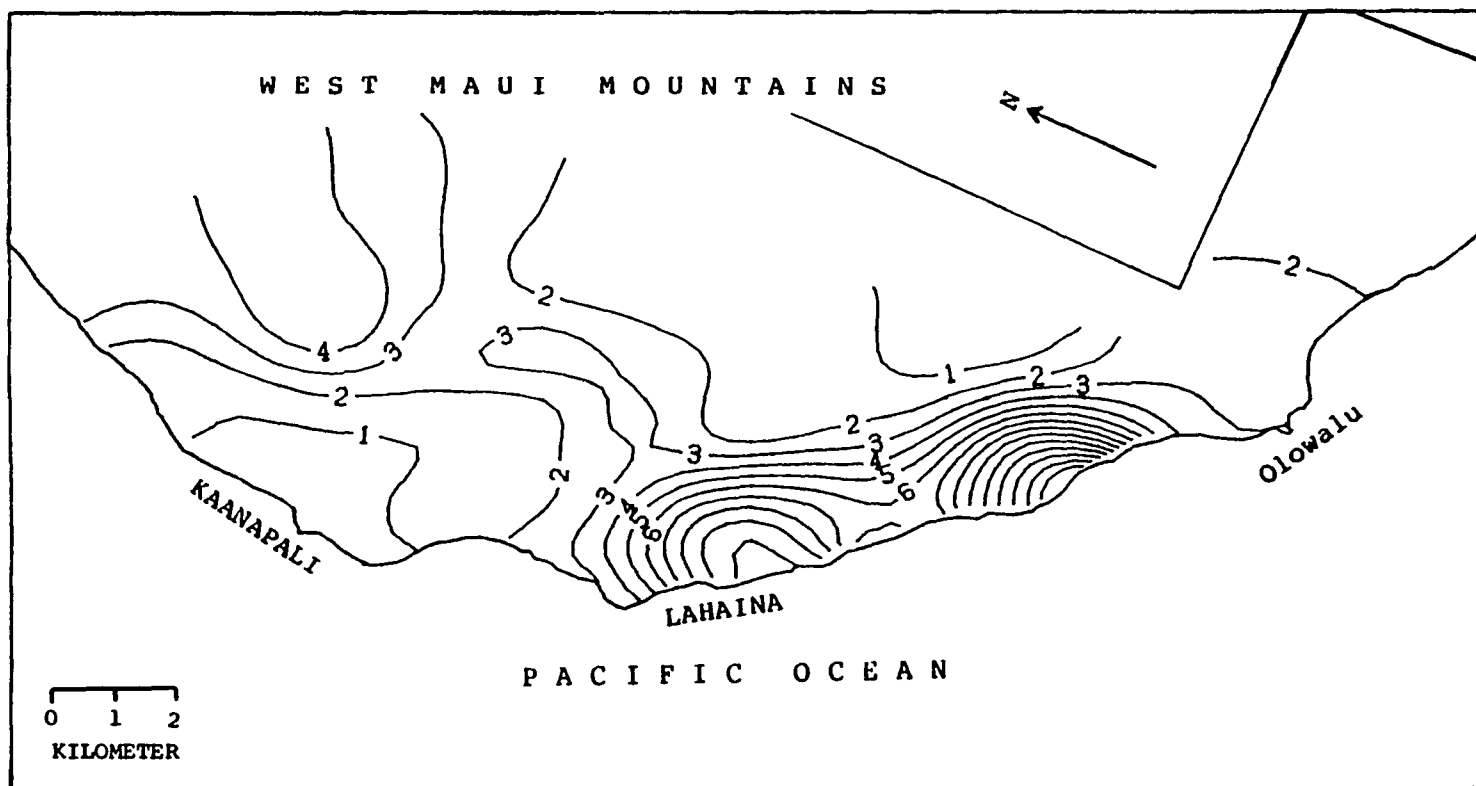
Fig. 109   Isarithm map of subsoil Zn (mg/kg) from 30 observed values, Pioneer
Mill Comapany, Maui.
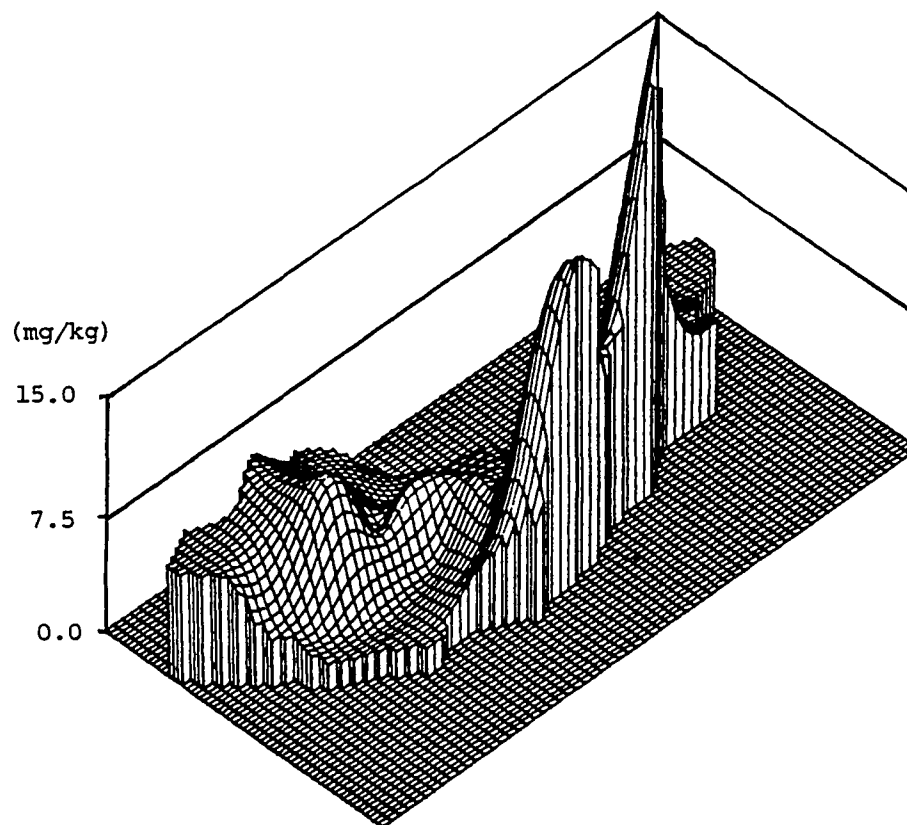
Fig. 110   Three-dimentional diagram of Zn status (mg/kg) of subsoils,
Pioneer Mill Comapany, Maui.
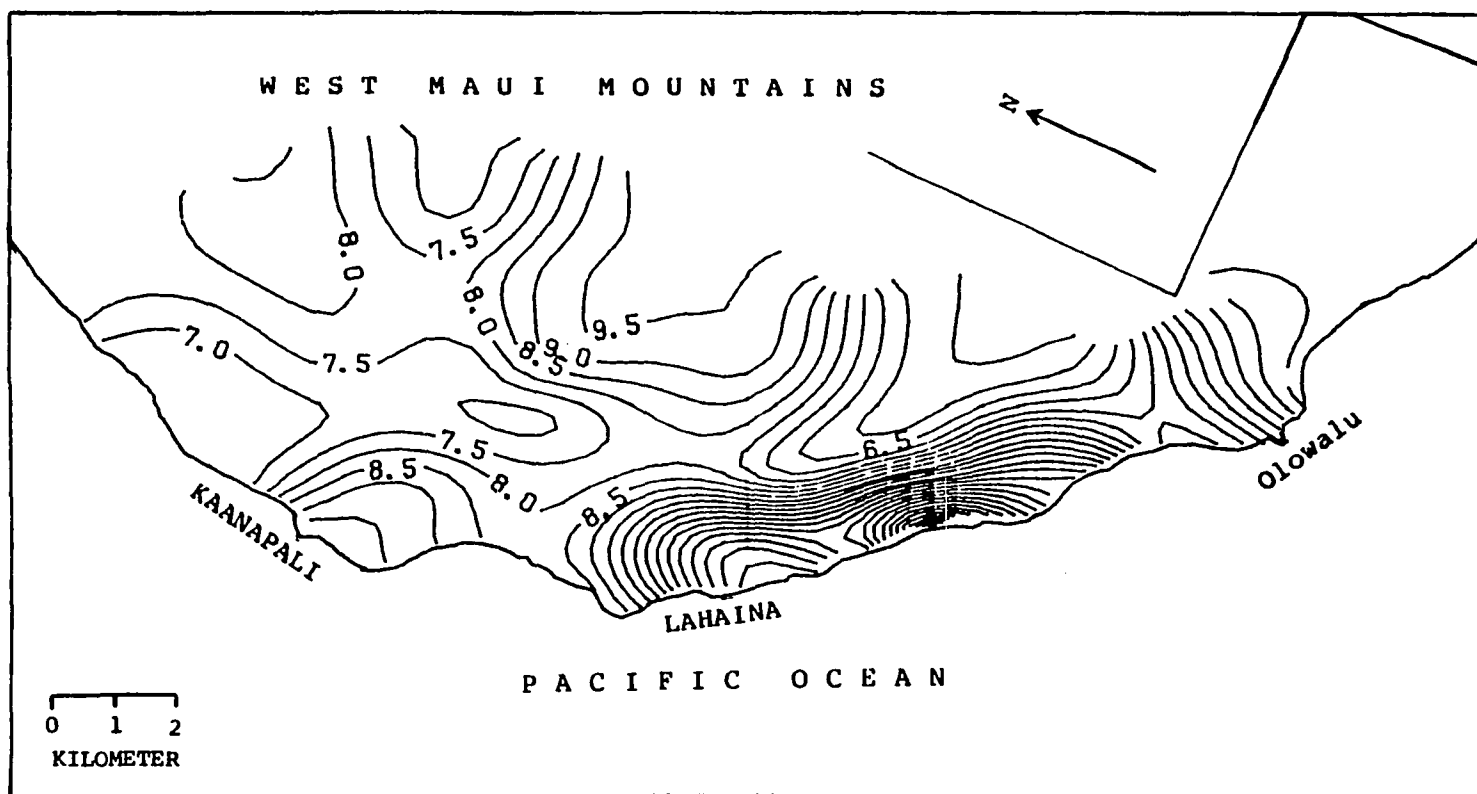
Fig. 111   Isarithm map of Zn status (mg/kg) of leaf sheaths (dry-ashed) from
30 observed values, Pioneer Mill Comapany, Maui.
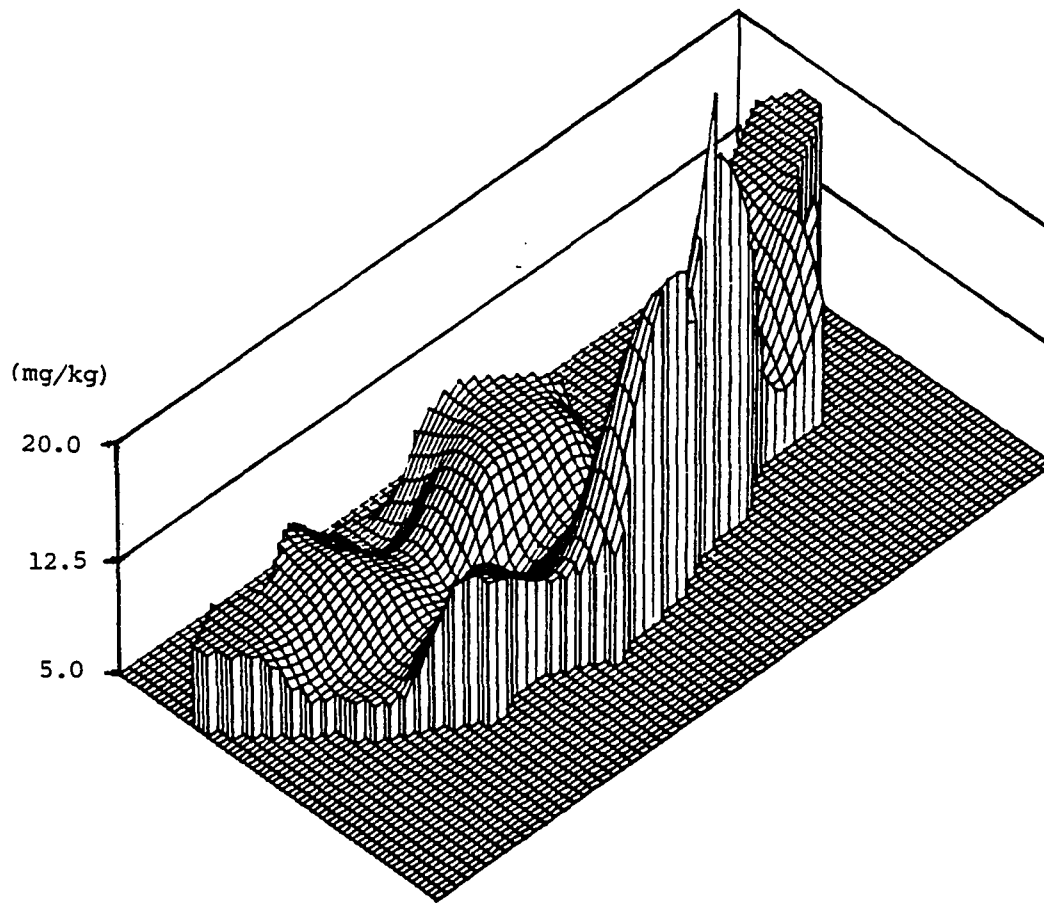
Fig. 112   Three-dimentional diagram of Zn status (mg/kg) of leaf sheaths
            (dry-ashed), Pioneer Mill Comapany, Maui.
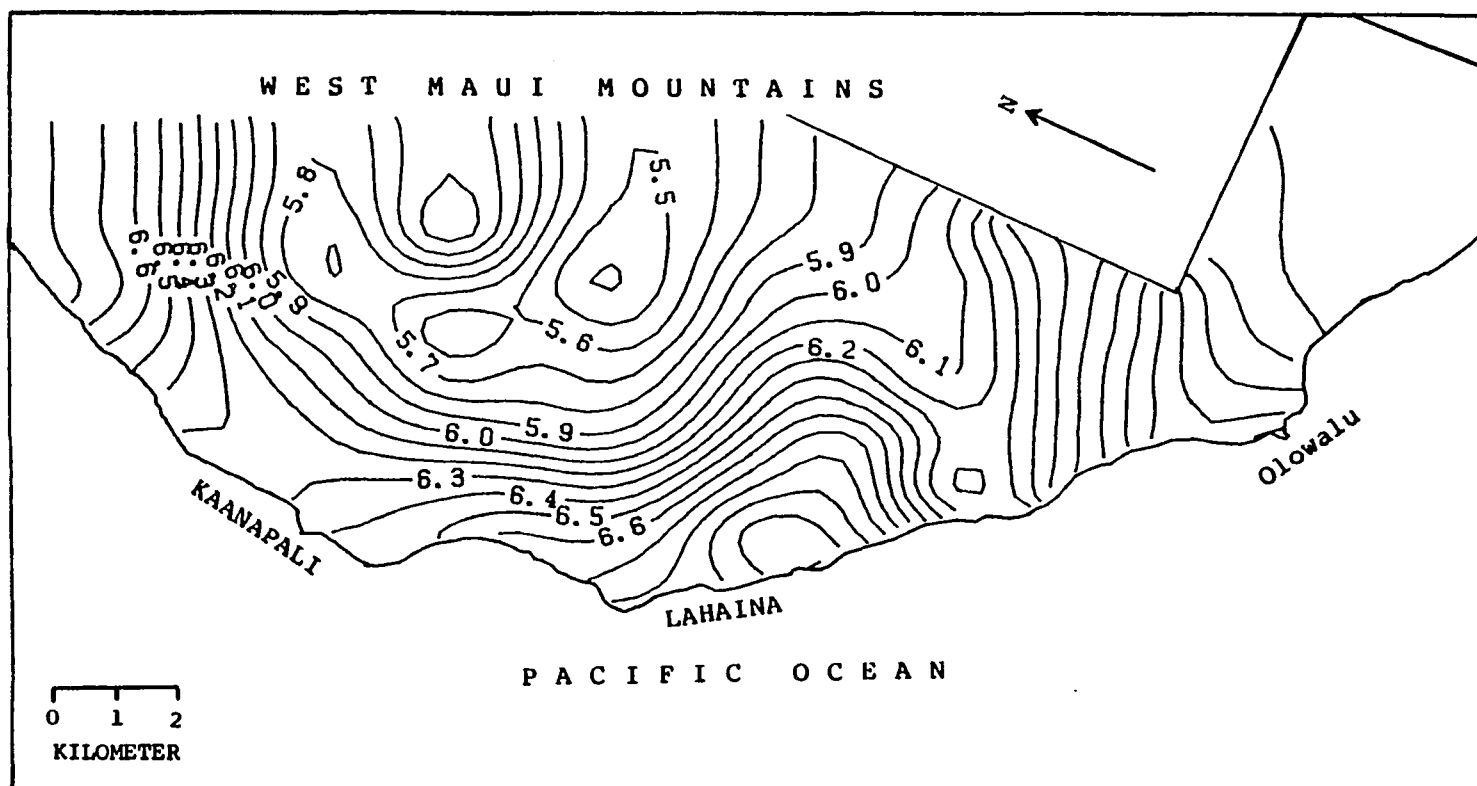
Fig. 113   Isarithm map of surface soil pH by isotropic block kriging, Pioneer
Mill Comapany, Maui.
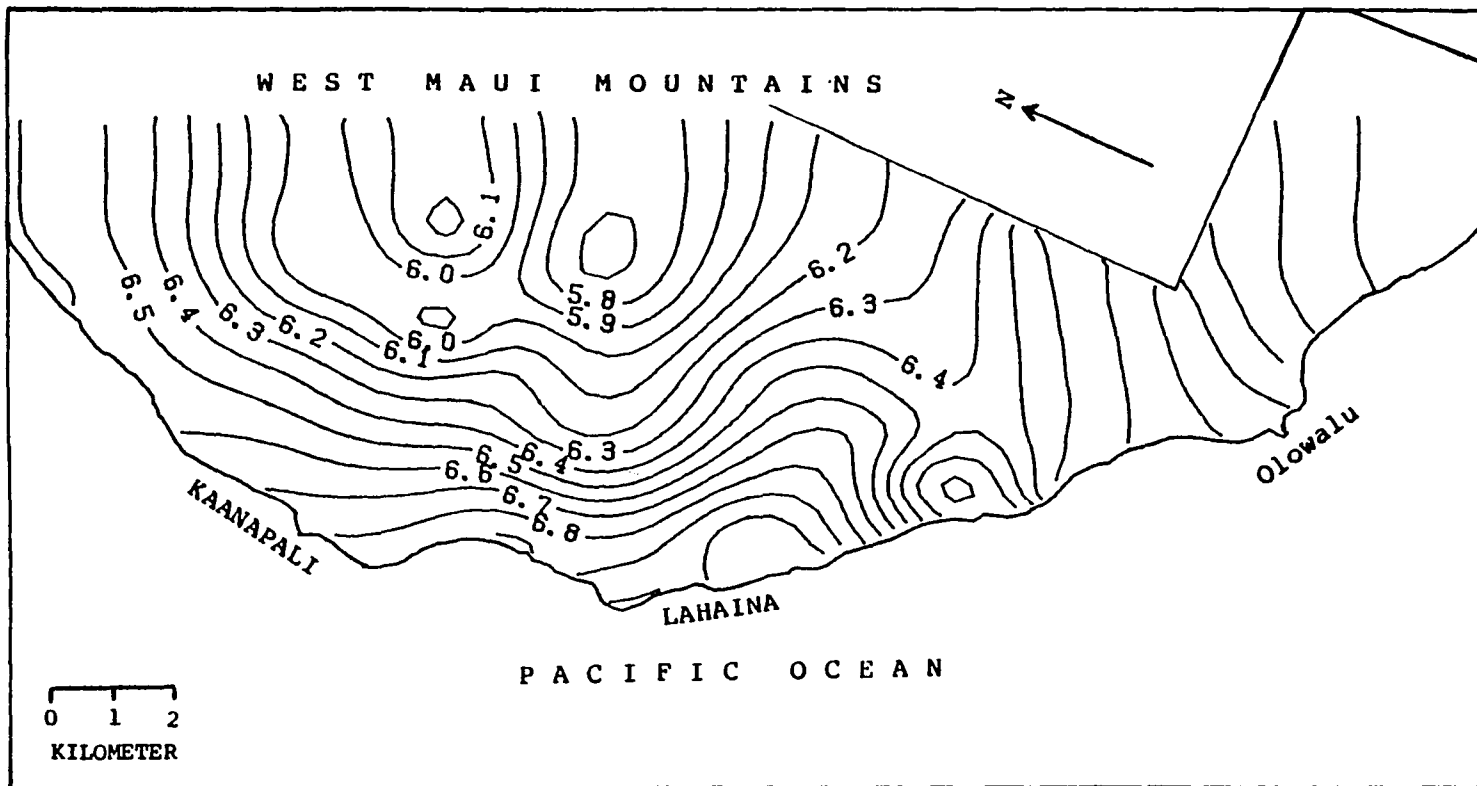
Fig. 114 Isarithm map of subsoil pH by isotropic block kriging, Pioneer Mill Comapany, Maui.

pH along the coastline between Lahaina and Olowalu (Fig. 107-110) demonstrates than soil pH is not inversely related to pH over the entire range of pH often encountered in soils. The correlation coefficient between surface soil pH and soil Zn was only 0.23. Correlation coefficient between sheath Zn and surface soil pH was also low, 0.18. Zinc contents in leaf blades were affected significantly by soil pH. Correlation coefficients of -0.52 between surface soil pH and leaf blade Zn indicate that Zn concentrations of this tissue were at least indirectly related to soil pH.

Because Zn contents of sheath tissues were more closely related to extractable soil Zn than leaf blade Zn contents were, greater confidence is placed in sheaths as index tissues for evaluating the Zn status of sugarcane. It is supposed that the problem with leaf blade analyses is related to contaminations from the ocean and from fly ash from the mill during growth but sanitation problems during sampling cannot be ruled out.

Phosphorus status of leaf blades ranged from 0.14 to 0.26%. The coefficient of correlation between leaf blade P and surface soil Zn was 0.41. Concentrations of P in leaf blades corresponded with soil Zn status (Fig. 115). Similar to Zn status of soils and plant tissue, P contents of leaf blades were especially high in a narrow belt along the Pacific Ocean coastline. In fields near the coastline, P contents of leaf blades were greater than the critical P concentration of 0.2 mg P/kg proposed by Samuels et al. (1957). The fields at high elevations behind the high-P belt were marginal to deficient in P.
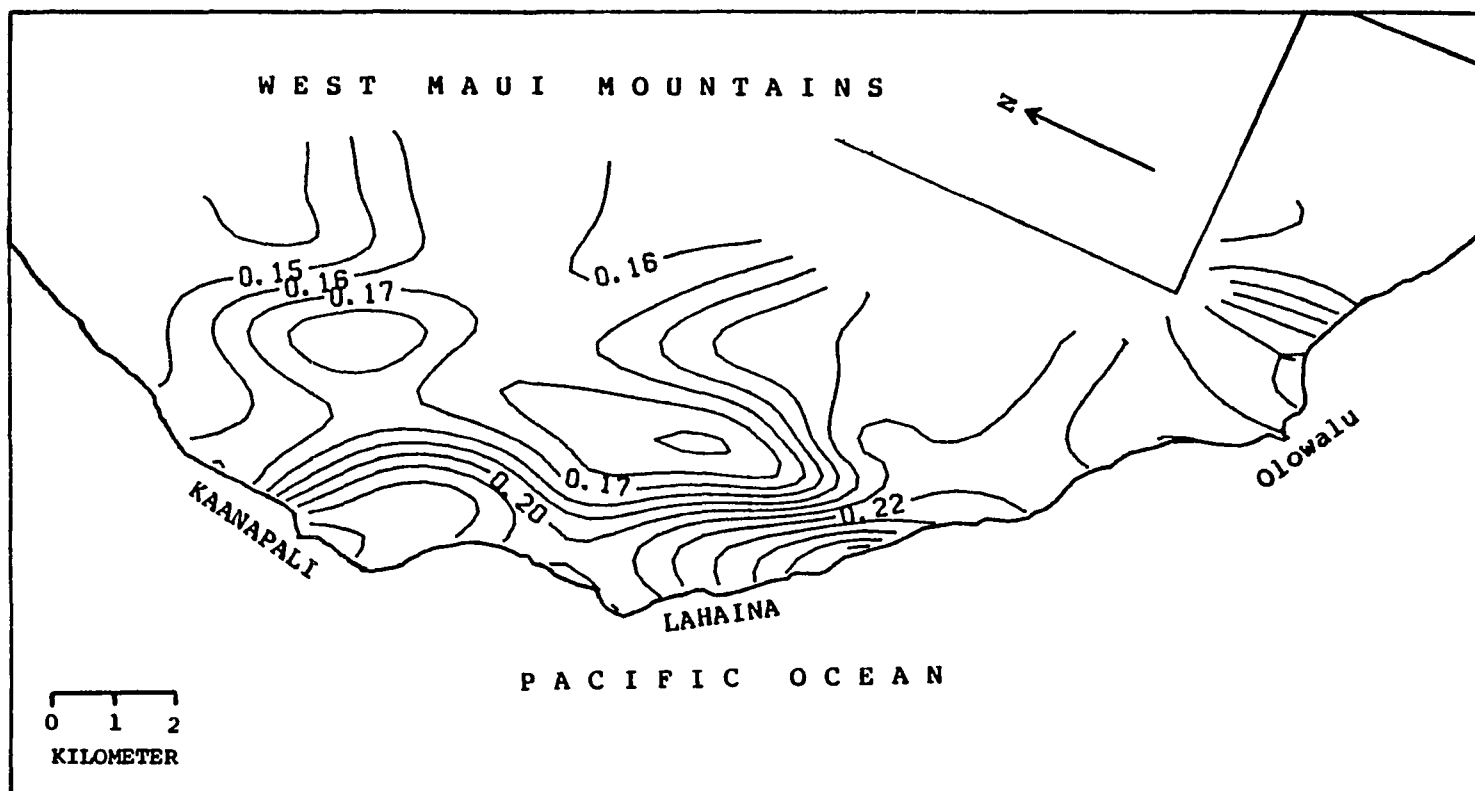
Fig. 115   Isarithm map of P status (%) of leaf blades (dry-ashed) from 30
           observed values, Pioneer Mil Comapany, Maui.
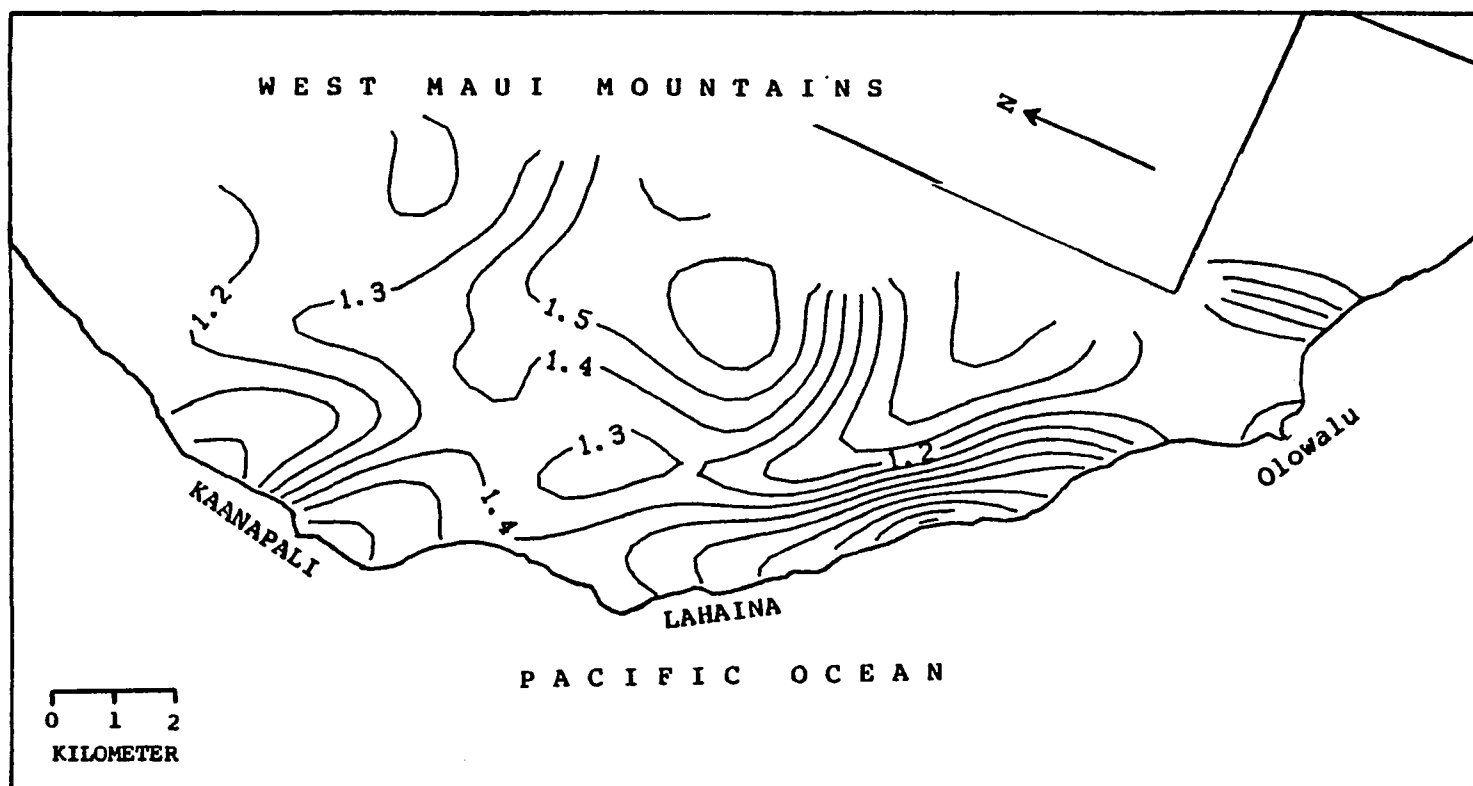
Fig. 116   Isarithm map of K status (%) of leaf blades (dry-ashed) from 30
observed values, Pioneer Mill Comapany, Maui.

Potassium contents of leaf blades ranged from 0.9 to 1.9%.

Samuels et al. (1957) proposed a critical level of 1.1% K in leaf

blade. Although K contents of leaf blades did not correspond closely

with Zn status of soils and foliar tissue, K status of leaf tissue was

highest along the Pacific Ocean Coastline (Fig. 116). Potassium

status of leaf blades was greater than the critical level proposed by

Samuels et al. (1957).

Maps of leaf blade N, S, Mn, Na, and Si and leaf sheath P, K, S,

Mn, and Si are presented in Appendix 28-37.

C. Zinc Status of Maui Soils and Sugarcane and its
Possible Role in Maui Growth Failure
1. Maui growth failure

Maui growth failure is an occasional disorder of sugarcane. It is

confined primarily to fields on the isthmus of Maui, although symptoms

have been noted on West Maui. It may adversely affect sugarcane growth

and reduce yields on as many as 8,000 hectares, though obvious symptoms

have been noted on only a few thousand hectares (Hagihara and Bosshart,

1984). The condition seems to be associated with saline basal ground

waters used for irrigation (Clements et al., 1974). Maui growth

failure occurs only with certain combinations of soils and sugarcane

varieties, and even then, it is usually associated with dry weather.

Maui growth failure has been a subject of discussion and research

for over 50 years. A number of factors such as variety, water quality,

temperature, season, nutrition, soil salinity, and other soil

properties may contribute to the development of Maui growth failure
(Hagihara and Bosshart, 1984). Maui growth failure has sometimes been
attributed to Zn deficiency (Clements et al., 1974), but a Zn
connection has never been proved.

2. Susceptibility of sugarcane to Zn deficiency

In greenhouse studies, Zn fertilization increased dry matter yield
of sugarcane 48% on Keahua subsoil and 28% on Paaloa subsoil (Fig. 23).

No growth response to Zn was observed when the Keahua surface
soil was used as growth media. Extractable Zn in this soil was
approximately half that thought by Juang et al. (1974) and Marzola and
Silva (1978) (2 to 3 mg Zn/kg) to be deficient.

Two months after planting, sugarcane growing in the two subsoils,
if they were without Zn fertilizer, exhibited stress symptoms which
resembled some of the symptoms of Maui growth failure, i.e. irregular
broad light-green to yellow bands of tissue on both sides of the midrib
(Martin, 1938; Hagihara and Bosshart, 1983). Symptoms were most severe
on the lower leaves of secondary shoots. Some lower leaves developed
an interveinal necrosis, which began as a chlorosis, turned into
bronzing, and finally resulted in necrotic tissue on both sides of the
midrib. Symptoms also resembled Zn deficiency as described by Juang
et al. (1974). Plants supplied with Zn grew vigorously and produced
broad, green leaves.

Without Zn fertilization, Zn concentration in leaf sheaths was
much less than the critical level of 10 mg Zn/kg reported for this
tissue (Clements, 1980; Bowen, 1983). Zinc concentrations in plant

tissues increased with Zn fertilization.

3. Accentuation of Zn deficiency by K and Na

Increasing levels of K application drastically depressed plant growth by accentuating Zn deficiency (Fig. 117). Without Zn application, relative dry matter yield of sugarcane was 52% at 0.012 mol K/kg soil, 43% at 0.035 mol K/kg soil, and 19% at 0.105 mol K/kg soil. Sodium was more detrimental than K. In the absence of Zn fertilization, when 0.07 mol Na/kg was superimposed on 0.035 mol K/kg soil, dry matter yield was only 10% of the maximum (Fig. 117). When the combination treatment of Na+K was used, plant growth was improved by the first increment of Zn fertilizer. Yields were maximum at the lowest level of K (0.012 mol K/kg soil) and decreased progressively with increased K levels. Although plant growth improved with Zn fertilization, the detrimental effect of Na was so severe that only 18% of the maximum yield was produced even with the highest level of Zn fertilizer (27 mg Zn/kg soil).

Symptoms of Zn deficiency were accentuated by applications of K and Na salts. At 0.012 mol K/kg soil and no Zn fertilizer, cane leaves developed broad bands of interveinal chlorosis confined to lower leaves of younger tillers. Plant growth was greater and deficiency symptoms were absent in Zn fertilized plants. With 0.105 mol K/kg soil, and combined applications of Na and K, plants produced fewer tillers (Table 30). These were very thin and bore short, narrow leaves which developed severe interveinal chloroses and yellowing and finally became necrotic. Leaf margins were dead from the leaf-tip downward (similar
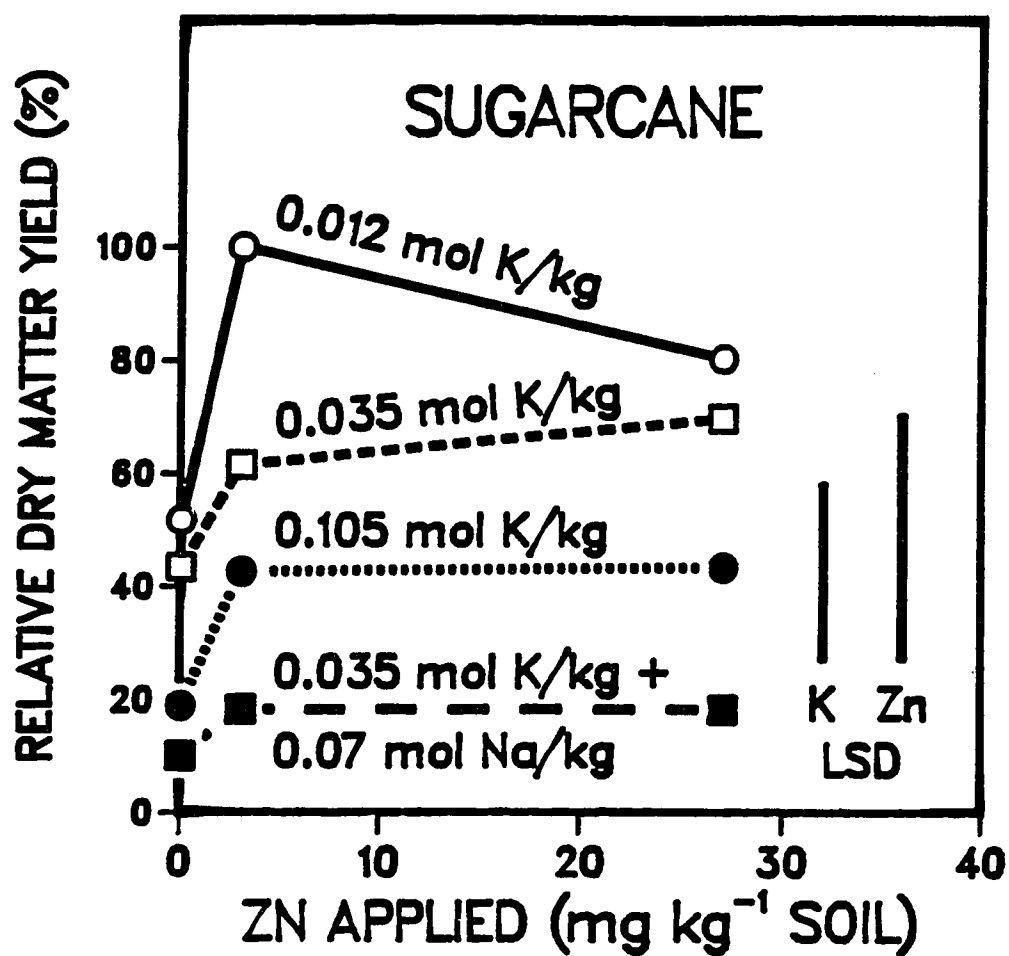
Fig. 117   Effect of K, Na, and Zn application to Keahua subsoil
on dry matter yield of sugarcane.

Table 30   Effect of Zn, K, and Na on sugarcane
           tillering.

K/Na applied (mol/kg soil)	Zn applied (mg/kg soil)	Tillers/plant
K, 0.012	0	9
	3	13
	27	11
K, 0.035	0	12
	3	16
	27	12
K, 0.105	0	5
	3	11
	27	12
K, 0.035 + Na, 0.07	0	7
	3	7
	27	10

Table 31   Effect of K and Na on Zn uptake by sugarcane.

K/Na applied (mol/kg soil)	Zn applied (mg/kg soil)	Zn conc (mg/kg) Leaf-sheaths	Leaf-blades
K, 0.012	0	11.5	14.5
	3	15.5	20.4
	27	22.2	30.3
K, 0.035	0	9.9	13.5
	3	15.5	19.8
	27	26.0	26.5
K, 0.105	0	8.3	14.0
	3	15.6	21.6
	27	29.4	27.3
K, 0.035 + Na, 0.07	0	6.0	13.8
	3	23.0	18.3
	27	34.2	25.5

to tip withering). Lower leaves were dead and upper leaves were yellowish-green, drooping downward. A few older secondary tillers in the +Na, -Zn treatment died. Symptoms were less severe on lower leaves in the +Na +Zn treatment. Even 27 mg Zn/kg soil did not correct all of the symptoms induced by excess K and Na.

Clements et al. (1974) noted that when the soil was thoroughly leached to decrease Na in the soil solution from 116 mg/kg to 15 mg/kg, Zn deficiency disappeared without adding Zn, but Mn and Cu deficiencies developed. Alkali earth cations, including K and Na, are known to depress Zn absorption by plant roots. For example, in the presence of 250 umol calcium nitrate and 1 umol $ZnCl_2$, additional nitrates of K and Na (750 umol) depressed Zn absorption by wheat seedlings (Chaudhry and Loneragan, 1972).

Zinc contents of plant tissues increased with increased quantities of Zn fertilizer at all levels of K. Zinc concentration in sugarcane leaf sheaths and leaf blades were depressed only slightly with increasing levels of K (Table 31). Leaf sheath Zn was decreased most by Na (Table 31) which in turn resulted in poorest plant growth. Although Zn fertilization resulted in Zn concentrations higher than the critical level, plant yields did not increase accordingly. The internal Zn requirement of sugarcane was constant regardless of the concentrations of monovalent cations. These conclusions suggest that monovalent cations especially Na^+ antagonized Zn uptake.

4. Zinc status of Maui growth failure affected areas

a. Hawaiian Commercial & Sugar Company, Maui, Hawaii

The Zn status of soils and sugarcane was mapped on two sugarcane

plantations, HC&S in Central Maui and Pioneer Mill in West Maui. In HC&S fields, HCl-extractable Zn in surface soils (0-15 cm) ranged from 0.8 to 107 mg/kg with a mean of 8.8 mg/kg. HCl-extractable Zn in 30 to 45 cm soil layers ranged from 0.3 to 98.0 mg/kg with a mean of 6.4 mg/kg. Zinc contents of subsoil samples were generally lower than surface soil samples. According to the criteria of Kanehiro and Sherman (1967), Juang et al. (1974) and Marzola and Silva (1978), many fields at HC&S were deficient in Zn for sensitive crops. However critical values for soil Zn in pot experiments are higher than in the field.

Zinc concentration (dry ash) of sugarcane leaf blades (first visible dew-lap leaf) ranged from 6.8 to 33.2 mg/kg with a mean of 16.1 mg/kg. Many samples contained less Zn than the critical level, 18 mg Zn/kg, as had been estimated in the greenhouse studies. The maps of Zn status in soil and leaf-blades are presented in Figure 90-93. The area lowest in leaf tissue Zn was not necessarily associated with lowest soil Zn. The correlation coefficient between leaf-blade Zn and surface soil Zn was 0.32. Obviously other factors must be affecting the Zn nutrition of plants. These other factors may include soil pH, alkali earth cations, and other micronutrient cations.

Fields with lowest Zn status are in the west (towards Maalaea Bay), extending from north to south (Fig. 90-93). In past years, Maui growth failure has been observed in fields 808-813, 816, 817, 820, 822, and 823 (Fig. 5a; John Sakuma, personal communication), fields which

lie within the low-Zn areas depicted in these maps. The ground water

used for irrigation at HC&S is saline with electrical conductivity

ranging from 0.13 S/m (Pump 3, Reservoir 82) to 0.17 S/m (Pump 1,

Reservoir 83). Its total cation concentration ranges from 0.012 mol

(+)/L to 0.017 mol (+)/L and 70% of the total cations is Na (R.

Roberts, unpublished data). During dry years, water levels in wells

falls down and salts get concentrated. Irrigation with such ground

water can adversely affect Zn uptake by sugarcane due to the

antagonsitic effect of Na and K. This is especially expected on soils

having marginal supplies of Zn.

Maui growth failure is especially prevalent during dry years when

roots of plants are most active in deeper soil layers. Low Zn

availability in subsoils may thus induce Zn deficiency in plants of

susceptible varieties of sugarcane. Use of high salt irrigation water

(Clements et al., 1974) aggravates the problem.

b. Pioneer Mill Company, Maui, Hawaii

HCl-extractable Zn in surface soils of Pioneer Mill ranged from

1.0 to 20.0 mg/kg (mean 5.5 mg/kg) and in subsoils ranged from 0.7 to

14.7 mg/kg (mean 3.5 mg/kg) (Fig. 107-110). Zinc contents were

especially high in a narrow belt along the Pacific Ocean coastline,

between Lahaina and Olowalu, perhapes as a result of application of

mill-mud and mill-water (Fig. 107-112). Some fields near Kaanapali

shoreline and north of Olowalu, behind the high-Zn belt, were marginal

or even deficient in Zn.

The lower limits of Zn, both in the soils and the foliar tissues,

indicate Zn deficiency at Pioneer Mill. Suspected problem areas are fields at higher elevations and some fields near the Kaanapali coastline (Fig. 107-112). At Pioneer Mill, ground water is applied to the fields at lower to medium elevations. This water is saline with electrical conductivities ranging from 0.1 to 0.35 S/m, Na contents ranging from 0.6 to 24 mmol/L and K contents ranging from 0.03 to 0.6 mmol/L (Derrick Nishimura, personal communication). The high Na contents of ground water may be responsible for occasional occurrence of induced deficiencies of Zn in susceptible varieties of sugarcane.

V. SUMMARY AND CONCLUSIONS

The major objectives of this study were to:

1. Investigate the possibility of using plant tissue (grain and leaf) analyses to map the Zn fertility of soils.

2. Calibrate tissue composition with plant response to soil Zn status.

3. Determine the comparative Zn requirement of crop species.

4. Verify the applicability and sensitivity of Zn maps using a specific problem - Maui growth failure.

Internal Zn requirement of eight crops, corn, wheat, rice, sorghum, millet, sugarcane, soybean, and cowpea, were estimated in pot experiments. Grains of cereal and legume crops were evaluated for use as a diagnostic tissue. To verify the greenhouse results, the relationship between Zn content of wheat grains and soil Zn was determined in farmers' fields of eastern Colorado.

Semi-variograms were constructed for soil and plant tissue properties to determine the degree and nature of spatial dependence in these properties. The structural information contained in the semi-variograms was used to krige (estimate) these properties in a grid over the entire mapped area. Contour (isarithm) maps were produced from the kriged points, unless the variable did not indicate spatial dependence.

Zinc status of soils and associated wheat grains was mapped in eastern Colorado. Similar maps were prepared for soil Zn, sugarcane tissue Zn and some other parameters in two sugarcane plantations on the island of Maui. Relationships between soil Zn, leaf tissue Zn, and some potentially related parameters were determined to identify the role of Zn deficiency in Maui growth failure of sugarcane, which is a syndrome of an old disease of sugarcane on the island of Maui.

The findings of this study can be summarized as follows:

1. Crop species differed in sensitivity of Zn deficiency. The order of sensitivity was: wheat $<$ sugarcane $<$ sorghum $<$ rice $<$ millet $<$ soybean $<$ cowpea $<$ corn.

2. The critical Zn concentration in leaf tissue of eight crop species ranged from 14 to 24 mg Zn/kg leaf tissue. The Zn requirements (mg Zn/kg) for individual crops were: ear leaf of corn at early silking, 24; flag leaf of sorghum and millet at head emergence, 19 and 24; ear leaf of rice and wheat at early heading, 19 and 17; leaf sheath nos. 3, 4, 5, and 6 and leaf blade of first visible dewlap leaf of sugarcane, 14 and 18; most recent fully expanded leaf of soybean and cowpea, 22 and 21.

3. In greenhouse experiments, Zn content of all grains, especially wheat, was sensitive to soil Zn levels. The ranges (mg Zn/kg) in grains were: corn, 17 to 45; sorghum 6 to 28; millet 13 to 51; rice 12 to 44; wheat 14 to 71; soybean 23 to 68; and cowpea 16 to 54.

Zinc content of wheat grains from farmers' fields of Colorado ranged from 12 to 60 mg Zn/kg.

4. The critical levels of Zn mg Zn/kg) in grains were: corn, 18; sorghum, 10; millet, 15; rice, 15; wheat, 15; soybean, 43; and cowpea, 36. These critical levels are tentative.

5. The greenhouse and field data suggest that grain and foliar analyses provide a valid basis for evaluating and mapping the Zn fertility of soils.

6. Semi-variograms of soil and wheat grain Zn show long range spatial dependence of these properties in Colorado soils. The distance of spatial dependence (range) varies from 117 km for wheat grain Zn to 142 km for subsoil Zn.

7. The maps of soil and wheat grain Zn, eastern Colorado, coincided with each other.

8. Semi-variograms of soil and sugarcane leaf tissue properties demonstrated a range of spatial dependence of these properties in soils of two sugarcane plantations on the island of Maui, Hawaii. At HC&S, the range varied from 5.3 km for leaf sheath Ca to 10.7 km for Zn content of leaf blades (wet-digested). At Pioneer Mill Company, the range varies from 1.2 km for subsoil Zn to 13.9 km for subsoil pH.

9. The Zn and P status of leaf tissue coincided with their status in soils.

10. The greenhouse and field investigations suggest a role of Zn deficiency in Maui sugarcane growth failure.

Appendix 1   Classification of soils sampled from Colorado.

Site no.	Symbol	Mapping unit	Soil family
1	1	Rocky Ford silty clay loam, 1 to 3 percent slopes	Fine-silty, mixed, calcareous, mesic Ustic Torriorthents
2	2	Richfield silt loam, 0 to 1 percent slopes	Fine, montmorillonitic, mesic Aridic Argiustolls
3	3	Wiley silt loam, 0 to 3 percent slopes	Fine-silty, mixed, mesic Ustollic Haplargids
4	4	Colby silt loam, 0 to 3 percent slopes	Fine-silty mixed, (calcareous), mesic Ustic Torriorthents
5	5	Wiley loam	Fine-silty, mixed, mesic Ustollic Haplargids
6	6	Baca^1- Wiley^2 complex, 0 to 2 percent slopes	1) Fine, montmorillonitic, mesic Ustollic Haplargids 2) Fine-silty, mixed, mesic Ustollic Haplargids
7	7	Ascalon^1- Platner^2 - Stoneham^3	1) Fine-loamy, mixed, mesic Aridic Argiustolls 2) Fine, montmorillonitic, mesic Aridic Paleustolls 3) Fine-loamy, mixed, mesic Ustollic Haplargids
8	8	Platner^1- Ascalon^2 - Haxtun^3	1) Fine, montmorillonitic, mesic Aridic Paleustolls 2) Fine-loamy, mixed, mesic Pachic Argiustolls 3) Fine-loamy, mixed, mesic Pachic Argiustolls
9	9	Platner loam	Fine, montmorillonitic, mesic Aridic Paleustolls
10	10	Colby^1- Norka^2 loams, 5 to 9 percent slopes	1) Fine-silty, mixed (calcareous), mesic Ustic Torriorthents 2) Fine-silty, mixed, mesic Aridic Argiustolls

Appendix 1 (cont.) Classification of soils sampled from Colorado.

Site no.	Symbol	Mapping unit	Soil family
11	11	Rago silt loam	Fine, montmorillonitic, mesic Cumulic Argiustolls
12	12	Keith$^1_3$- Richfield^2 - Colby^3	1) Fine-silty, mixed, mesic Aridic Argiustolls 2) Fine, montmorillonitic, mesic Aridic Argiustolls 3) Fine-silty, mixed (calcareous), mesic Ustic Torriorthents
13	13	Keith^1- Kuma^2- Richfield^3 silt loams complex, 0 to 2 percent slopes	1) Fine-silty, mixed, mesic Aridic Argiustolls 2) Fine-silty, mixed, mesic, Pachic Argiustolls 3) Fine, montmorillonitic, mesic Aridic Argiustolls
14	14	Weld$^1_3$ Adena^2- Colby^3	1) Fine, montmorillonitic, mesic Aridic paleustolls 2) Fine-loamy, mixed, mesic Ustollic Paleargids 3) Fine-silty, mixed (calcareous), mesic Ustic Torriorthents
15	15	Bresser$^1_3$Truckton^2- Blakeland^3 complex, 3 to 9 percent slopes	1) Fine-loamy, mixed, mesic Aridic Argiustolls 2) Coarse-loamy, mixed, mesic Aridic Argiustolls 3) Sandy, mixed, mesic Torriorthentic Haplustolls
16	16	Weld loam, 1 to 3 percent slopes	Fine, montmorillonitic, mesic Abruptic Paleustolls
17	9	Platner loam	Fine, montmorillonitic, mesic Aridic Paleustolls
18	16	Weld loam, 1 to 3 percent slopes	Fine, montmorillonitic, mesic Aridic Paleustolls
19	17	Ascalon fine sandy loam, 3 to 5 percent slopes	Fine-loamy, mixed, mesic Aridic Argiustolls

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Appendix 1 (cont.) Classification of soils sampled from Colorado.

Site no.	Symbol	Mapping unit	Soil family
20	18	Julesburg loam sand, 0 to 3 percent slopes	Coarse-loamy, mixed, mesic Aridic Argiustolls
21	19	Platner[1]- Rago[2]- Dacono[3] loams	1) Fine, montmorillonitic, mesic Aridic Paleustolls 2) Fine, montmorillonitic, mesic Pachic Argiustolls 3) Clayey over sandy or sandy-skeletal, montmorillonitic, mesic Aridic Argiustolls
22	20	Rago[1] and Kuma[2] loams, 0 to 3 percent slopes	1) Fine, montmorillonitic, mesic Aridic Argiustolls 2) Fine-silty, mixed, mesic Pachic Argiustolls
23	20	Rago[1]- Kuma[2] loams	1) Fine, montmorillonitic, mesic Aridic Argiustolls 2) Fine-silty, mixed, mesic Pachic Argiustolls
24	21	Rago[1]- Kuma[2]- silt loams, 0 to 3 percent slopes	1) Fine, montmorillonitic, mesic Aridic Argiustolls 2) Fine-silty, mixed, mesic Pachic Argiustolls
25	9a	Platner loam, 0 to 3 slopes	Fine, montmorillonitic, mesic Aridic Paleustolls
26	16	Weld loam, 1 to 3 percent slopes	Fine, montmorillonitic, mesic Aridic Paleustolls
27	16	Weld loam, 1 to 3 percent slopes	Fine, montmorillonitic, mesic Abruptic Paleustolls
28	22	Nunn clay loam, 0 to 1 percent slopes	Fine, montmorillonitic, mesic Aridic Argiustolls
29	22	Nunn clay loam, 0 to 1 percent slopes	Fine, montmorillonitic, mesic Aridic Argiustolls
30	23	Kim loam, 1 to 3 percent slopes	Fine-loamy, mixed (calcareous), mesic Ustic Torriorthents

Appendix 1 (cont.) Classification of soils sampled from Colorado.

Site no.	Symbol	Mapping unit	Soil family
31	13	Keith[1]- Kuma[2]- Richfield[3] silt loams complex, 0 to 2 percent slopes	1) Fine-silty, mixed, mesic Aridic Argiustolls 2) Fine-silty, mixed, mesic, Pachic Argiustolls 3) Fine, montmorillonitic, mesic Aridic Argiustolls
32	9a	Platner loam, 0 to 3 percent slopes	Fine, montmorillonitic, mesic Aridic Paleustolls
33	24	Norka silt loam, 0 to 2 percent slopes	Fine-silty, mixed,mesic Aridic Argiustolls
34	7	Ascalon[1]-[3]Platner[2] - Stoneham[3]	1) Fine-loamy, mixed, mesic Aridic Argiustolls 2) Fine, montmorillonitic, mesic Aridic Paleustolls 3) Fine-loamy, mixed, mesic Ustollic Haplargids
35	14	Weld[1]-[3]Adena[2]- Colby[3]	1) Fine, montmorillonitic, mesic Aridic paleustolls 2) Fine-loamy, mixed, mesic Ustollic Paleargids 3) Fine-silty, mixed (calcareous), mesic Ustic Torriorthents
36	15	Bresser[1]-[3]Truckton[2]- Blakeland[3] complex	1) Fine-loamy, mixed, mesic Aridic Argiustolls 2) Coarse-loamy, mixed, mesic Aridic Argiustolls 3) Sandy, mixed, mesic Torriorthentic Haplustolls
37	9	Platner loam	Fine, montmorillonitic, mesic Aridic Paleustolls

Appendix 1 (cont.) Classification of soils sampled from Colorado.

Site no.	Symbol	Mapping unit	Soil family
38	25	Weld[1]_ Rago[2]- Norka[3] complex	1) Fine, montmorillonitic, mesic Aridic Paleustolls 2) Fine, montmirillonitic, mesic Pachic Argiustolls 3) Fine-silty, mixed, mesic Aridic Argiustolls
39	8	Platner[1]_ Ascalon[2] – Haxtun[3]	1) Fine, montmorillonitic, mesic Aridic Paleustolls 2) Fine-loamy, mixed, mesic Pachic Argiustolls 3) Fine-loamy, mixed, mesic Pachic Argiustolls
40	16	Weld loam, 1 to 3 percent slopes	Fine, montmorillonitic, mesic Abruptic Paleustolls
41	20	Rago[1]- Kuma[2] loams	1) Fine, montmorillonitic, mesic Aridic Argiustolls 2) Fine-silty, mixed, mesic Pachic Argiustolls

Appendix 2 Classification of soils sampled from HC&S, Maui, Hawaii.

Field no.	Symbol	Mapping unit	Soil family
100	PcB	Paia silty clay, 3 to 7 percent slopes	Fine, kaolinitic, isohyperthermic Typic Haplustolls
103	IaB	Iao silty clay, 3 to 7 percent slopes	Fine, kaolinitic, isohyperthermic Typic Haplustolls
105	PcB	Paia silty clay, 3 to 7 percent slopes	Fine, kaolinitic, isohyperthermic Typic Haplustolls
106	PcB	Paia silty clay, 3 to 7 percent slopes	Fine, kaolinitic, isohyperthermic Typic Haplustolls
108	HhC	Haliimaile silty clay, 7 to 15 percent slopes	Fine, kaolinitic, isothermic Ustoxic Humitropepts
109	HaB	Haiku silty clay, 3 to 7 percent slopes	Clayey, ferritic, isothermic Humuoxic Tropohumults
112	HhB	Haliimaile silty clay, 3 to 3 percent slopes	Fine, kaolinitic, isothermic Ustoxic Humitropepts
113	HlB	Hamakuapoko silty clay, 3 to 7 percent slopes	Clayey, oxidic, isothermic Orthoxic Tropohumults
114	PcB	Paia silty clay, 3 to 7 percent slopes	Fine, kaolinitic, isohyperthermic Typic Haplustolls
115	PcB	Paia silty clay, 3 to 7 percent slopes	Fine, kaolinitic, isohyperthermic Typic Haplustolls
118	HlB	Hamakuapoko silty clay, 3 to 7 percent slopes	Clayey, oxidic, isothermic Orthoxic Tropohumults
200	HhC	Haliimaile silty clay, 7 to 15 percent slopes	Fine, kaolinitic, isothermic Ustoxic Humitropepts
201	PcB	Paia silty clay, 3 to 7 percent slopes	Fine, kaolinitic, isohyperthermic Typic Haplustolls
202	PcC2	Paia silty clay, 7 to 15 percent slopes, eroded	Fine, kaolinitic, isohyperthermic Typic Haplustolls

Appendix 2 (cont.) Classification of soils sampled from HC&S, Maui.

Field no.	Symbol	Mapping unit	Soil family
203	PcB	Paia silty clay, 3 to 7 percent slopes	Fine, kaolinitic, isohyperthermic Typic Haplustolls
204	PcB	Paia silty clay, 3 to 7 percent slopes	Fine, kaolinitic, isohyperthermic Typic Haplustolls
205	PcB	Paia silty clay, 3 to 7 percent slopes	Fine, kaolinitic, isohyperthermic Typic Haplustolls
206	PcB	Paia silty clay, 3 to 7 percent slopes	Fine, kaolinitic, isohyperthermic Typic Haplustolls
210	IaB	Iao silty clay, 3 to 7 percent slopes	Fine, kaolinitic, isohyperthermic Typic Haplustolls
212	PpA	Pulehu silt loam, 0 to 3 percent slopes	Fine-loamy, mixed, isohyperthermic Cumulic Haplustolls
213	PcB	Paia silty clay, 3 to 7 percent slopes	Fine, kaolinitic, isohyperthermic Typic Haplustolls
300	PcB	Paia silty clay, 3 to 7 percent slopes	Fine, kaolinitic, isohyperthermic Typic Haplustolls
302	KnB	Keahua silty clay loam, 3 to 7 percent slopes	Fine, kaolinitic, isohyperthermic Torroxic Haplustolls
304	KnB	Keahua silty clay loam, 3 to 7 percent slopes	Fine, kaolinitic, isohyperthermic Torroxic Haplustolls
306	PcB	Paia silty clay, 3 to 7 percent slopes	Fine, kaolinitic, isohyperthermic Typic Haplustolls
309	KnC	Keahua silty clay loam, 7 to 15 percent slopes	Fine, kaolinitic, isohyperthermic Typic Haplustolls
310	KnB	Keahua silty clay loam, 7 to 15 percent slopes	Fine, kaolinitic, isohyperthermic Typic Haplustolls
311	KnaB	Keahua cobbly silty clay loam, 3 to 7 percent slopes	Fine, kaolinitic, isohyperthermic Torroxic Haplustolls

Appendix 2 (cont.) Classification of soils sampled from HC&S, Maui.

Field no.	Symbol	Mapping unit	Soil family
404	KnB	Keahua silty clay loam, 3 to 7 percent slopes	Fine, kaolinitic, isohyperthermic Torroxic Haplustolls
407	KnB	Keahua silty clay loam, 3 to 7 percent slopes	Fine, kaolinitic, isohyperthermic Torroxic Haplustolls
410	KnB	Keahua silty clay loam, 3 to 7 percent slopes	Fine, kaolinitic, isohyperthermic Torroxic Haplustolls
411	KnaB	Keahua cobbly silty clay loam, 3 to 7 percent slopes	Fine, kaolinitic, isohyperthermic Torroxic Haplustolls
413	KnB	Keahua silty clay loam, 3 to 7 percent slopes	Fine, kaolinitic, isohyperthermic Torroxic Haplustolls
414	WID2	Waiakoa extremely stony silty clay loam, 3 to 25 percent slopes, eroded	Fine, kaolinitic, isohyperthermic Aridic Haplustolls
415	WID2	Waiakoa extremely stony silty clay loam, 3 to 25 percent slopes, eroded	Fine, kaolinitic, isohyperthermic Aridic Haplustolls
417	KnbD	Keahua very stony silty clay loam, 7 to 25 percent slopes	Fine, kaolinitic, isohyperthermic Torroxic Haplustolls
503	KnB	Keahua silty clay loam, 3 to 7 percent slopes	Fine, kaolinitic, isohyperthermic Torroxic Haplustolls
504	MuB	Molokai silty clay loam, 3 to 7 percent slopes	Clayey, kaolinitic, isohyperthermic Typic Torrox
505	WfB	Waikoa cobbly silty clay loam, 3 to 7 percent slopes,	Fine, kaolinitic, isohyperthermic Aridic Haplustolls
509	MuB	Molokai silty clay loam, 3 to 7 percent slopes	Clayey, kaolinitic, isohyperthermic Typic Torrox

Appendix 2 (cont.) Classification of soils sampled from HC&S, Maui.

Field no.	Symbol	Mapping unit	Soil family
511	WfB	Waikoa cobbly silty clay loam, 3 to 7 percent slopes,	Fine, kaolinitic, isohyperthermic Aridic Haplustolls
601	IaA	Iao silty clay, 0 to 3 percent slopes	Fine, kaolinitic, isohyperthermic Typic Haplustolls
603	MuB	Molokai silty clay loam, 3 to 7 percent slopes	Clayey, kaolinitic, isohyperthermic Typic Torrox
605	PrB	Pulehu cobbly silt loam, 3 to 7 percent slopes	Fine-loamy, mixed, isohyperthermic Cumulic Haplustolls
606	WeB	Waiakoa silty clay loam, 3 to 7 percent slopes	Fine, kaolinitic, isohyperthermic Aridic Haplustolls
607	MuA	Molokai silty clay loam, 0 to 3 percent slopes	Clayey, kaolinitic, isohyperthermic Typic Torrox
610	PsA	Pulehu clay loam, 3 to 7 percent slopes	Fine-loamy, mixed, isohyperthermic Cumulic Haplustolls
700	WeB	Waiakoa silty clay loam, 3 to 7 percent slopes	Fine, Kaolinitic, isohyperthermic Aridic Haplustolls
702	WeB	Waiakoa silty clay loam, 3 to 7 percent slopes	Fine, kaolinitic, isohyperthermic Aridic Haplustolls
710	MuB	Molokai silty clay loam, 3 to 7 percent	Clayey, kaolinitic, isohyperthermic Typic Torrox
712	EaA	Ewa silty clay loam, 0 to 3 percent slopes	Fine, kaolinitic, isohyperthermic Aridic Haplustolls
714	EaA	Ewa silty clay loam, 0 to 3 percent slopes	Fine, kaolinitic, isohyperthermic Aridic Haplustolls
717	PpA	Pulehu cobbly silt loam, 0 to 3 percent slopes	Fine-loamy, mixed, isohyperthermic Cumulic Haplustolls

Appendix 2 (cont.) Classification of soils sampled from HC&S, Maui.

Field no.	Symbol	Mapping unit	Soil family
718	PsA	Pulehu cobbly silt loam, 3 to 7 percent slopes	Fine-loamy, mixed, isohyperthermic Cumulic Haplustolls
801	AcA	Alae cobbly sandy loam, 0 to 3 percent slopes	Medial, isohyperthermic Mollic Vitrandepts
805	PtA	Pulehu cobbly silt loam, 0 to 3 percent slopes	Fine-loamy, mixed, isohyperthermic Cumulic Haplustolls
806	WeB	Waiakoa silty clay loam, 3 to 7 percent slopes	Fine, kaolinitic, isohyperthermic Aridic Haplustolls
809	PrA	Pulehu cobbly silt loam, 0 to 3 percent slopes	Fine-loamy, mixed, isohyperthermic Cumulic Haplustolls
813	PtA	Pulehu cobbly silt loam, 0 to 3 percent slopes	Fine-loamy, mixed, isohyperthermic Cumulic Haplustolls
818	AcA	Alae cobbly sandy loam, 0 to 3 percent slopes	Medial, isohyperthermic Mollic Vitrandepts
821	WID2	Waiakoa extremely stony silty clay loam, 3 to 25 percent slopes, eroded	Fine, kaolinitic, isohyperthermic Aridic Haplustolls
904	PpA	Pulehu silt loam, 0 to 3 percent slopes	Fine-loamy, mixed, isohyperthermic Cumulic Haplustolls
905	PrA	Pulehu cobbly silt loam, 0 to 3 percent slopes	Fine-loamy, mixed, isohyperthermic Cumulic Haplustolls
907	PtA	Pulehu cobbly clay loam, 0 to 3 percent slopes	Fine-loamy, mixed, isohyperthermic Cumulic Haplustolls
909	JaC	Jaucas sand, 0 to 15 percent slopes	Carbonatic, isohyperthermic Typic Ustipsamments
910	PpB	Pulehu silt loam, 3 to 7 percent slopes	Fine-loamy, mixed, isohyperthermic Cumulic Haplustolls
911	EcB	Ewa cobbly silty clay loam 3 to 7 percent slopes	Fine, kaolinitic, isohyperthermic Aridic Haplustolls

Appendix 2 (cont.) Classification of soils sampled from HC&S, Maui.

Field Symbol no.		Mapping unit	Soil family
913	PtB	Pulehu cobbly clay loam, 3 to 7 percent slopes	Fine-loamy, mixed, isohyperthermic Cumulic Haplustolls
914	EaA	Ewa silty clay loam, 0 to 3 percent slopes	Fine, kaolinitic, isohyperthermic Aridic Haplustolls
916	EaA	Ewa silty clay loam, 0 to 3 percent slopes	Fine, kaolinitic, isohyperthermic Aridic Haplustolls
918	KMW	Kealia silt loam	Coarse-loamy, mixed, isohyperthermic Aridic Haplustolls
605 EaA S1-T2		Ewa silty clay loam, 0 to 3 percent slopes	Fine, kaolinitic, isohyperthermic Aridic Haplustolls
603 EaA S2-T2		Ewa silty clay loam, 0 to 3 percent slopes	Fine, kaolinitic, isohyperthermic Aridic Haplustolls
603 MuB S3-T2		Molokai silty clay loam 3 to 7 percent slopes	Clayey, kaolinitic, isohyperthermic Typic Torrox
500 MuB S4-T2		Molokai silty clay loam, 3 to 7 percent slopes	Clayey, kaolinitic, isohyperthermic Typic Torrox
304	KnB	Keahua silty clay loam, 3 to 7 percent slopes	Fine, kaolinitic, isohyperthermic Torroxic Haplustolls
301 HhB S6-T2		Haliimaile silty clay, 3 to 7 percent slopes	Fine, kaolinitic, isohyperthermic Ustoxic Humitropepts
300 PcB S7-T2		Paia silty clay, 3 to 7 percent slopes	Fine, kaolinitic, isohyperthermic Typic Haplustolls
901 PpA S1-T4		Pulehu silt loam, 0 to 3 percent slopes	Fine-loamy, mixed, isohyperthermic Cumulic Haplustolls
200 PcB S3-T5		Paia silty clay, 3 to 7 percent slopes	Fine, kaolinitic, isohyperthermic Typic Haplustolls
403	KnaB	Keahua cobbly silty clay loam, 3 to 7 percent slopes	Fine, kaolinitic, isohyperthermic Torroxic Haplustolls

Appendix 3   Classification of soils sampled from Pioneer Mill Company, Maui, Hawaii.

Field no.	Symbol	Mapping unit	Soil family
150	LaC	Lahaina silty clay, 7 to 15 percent slopes	Clayey, kaolinitic, isohyperthermic Typic Torrox
160	LaB	Lahaina silty Clay, 3 to 7 percent slopes	Clayey, kaolinitic, isohyperthermic Typic Torrox
200	AeC	Alaeloa silty clay, 7 to 15 percent slopes	Clayey, oxidic, isohyperthermic Orthoxic Tropohumults
220	LaC	Lahaina silty clay, 7 to 15 percent slopes	Clayey, kaolinitic, isohyperthermic Typic Torrox
225	KbC	Kahana silty clay, 7 to 15 percent slopes	Clayey, kaolinitic, isothermic Tropeptic Haplustox
260	LaB	Lahaina silty Clay, 3 to 7 percent slopes	Clayey, kaolinitic, isohyperthermic Typic Torrox
295	LaC	Lahaina silty clay, 7 to 15 percent slopes	Clayey, kaolinitic, isohyperthermic Typic Torrox
320	MuB	Molokai silty clay loam, 3 to 7 percent slopes	Clayey, kaolinitic, isohyperthermic Typic Torrox
345	WcB	Wahikuli stony silty clay 3 to 7 percent slopes	Clayey, kaolinitic, isohyperthermic Typic Torrox
405	AeE	Alaeloa silty clay, 15 to 35 percent slopes	Clayey, oxidic, isohyperthermic Orthoxic Tropohumults
425	LaC	Lahaina silty clay, 7 to 15 percent slopes	Clayey, kaolinitic, isohyperthermic Typic Torrox
445	WcC	Wahikuli stony silty clay 7 to 15 percent slopes	Clayey, kaolinitic, isohyperthermic Typic Torrox
460	WcC	Wahikuli stony silty clay 7 to 15 percent slopes	Clayey, kaolinitic, isohyperthermic Typic Torrox
540	WdB	Wahikuli very stony silty clay, 3 to 7 percent slopes	Clayey, kaolinitic, isohyperthermic Typic Torrox

Appendix 3(cont.) Classification of soils sampled from Pioneer Mill, Maui.

Field no.	Symbol	Mapping unit	Soil family
550	WcB	Wahikuli stony silty clay 3 to 7 percent slopes	Clayey, kaolinitic, isohyperthermic Typic Torrox
565	WcC	Wahikuli stony silty clay 7 to 15 percent slopes	Clayey, kaolinitic, isohyperthermic Typic Torrox
600	WxC	Wainee very stony silty clay, 7 to 15 percent slopes	Clayey-skeletal, kaolinitic, Isohyperthermic Aridic Haplustolls
650	WyC	Wainee extremely stony silty clay, 7 to 15 percent slopes	Clayey-skeletal, kaolinitic, Isohyperthermic Aridic Haplustolls
710	WxC	Wainee very stony silty clay, 7 to 15 percent slopes	Clayey-skeletal, kaolinitic, Isohyperthermic Aridic Haplustolls
720	WyC	Wainee extremely stony silty clay, 7 to 15 percent slopes	Clayey-skeletal, kaolinitic, Isohyperthermic Aridic Haplustolls
730	WyC	Wainee extremely stony silty clay, 7 to 15 percent slopes	Clayey-skeletal, kaolinitic, Isohyperthermic Aridic Haplustolls
770	WyB	Wainee extremely stony silty clay, 3 to 7 percent slopes	Clayey-skeletal, kaolinitic, Isohyperthermic Aridic Haplustolls
810	EaA	Ewa silty clay loam, 0 to 3 percent slopes	Fine, kaolinitic, isohyperthermic Aridic Haplustolls
825	PtB	Pulehu cobbly clay loam, 3 to 7 percent slopes	Fine-loamy, mixed,isohyperthermic Cumulic Haplustolls
835	WxB	Wainee very stony silty clay, 3 to 7 percent slopes	Clayey-skeletal, kaolinitic, Isohyperthermic Aridic Haplustolls
850	rSM	Stony alluvial land	

Appendix 3(cont.) Classification of soils sampled from Pioneer Mill Maui.

Field no.	Symbol	Mapping unit	Soil family
910	PsA	Pulehu clay loam, 0 to 3 percent slopes	Fine-loamy, mixed, isohyperthermic Cumulic Haplustolls
935	PpA	Pulehu silt loam, 0 to 3 percent slopes	Fine-loamy, mixed, isohyperthermic Cumulic Haplustolls
945	PsA	Pulehu clay loam, 0 to 3 percent slopes	Fine-loamy, mixed, isohyperthermic Cumulic Haplustolls
965	PtA	Pulehu cobbly clay loam, 0 to 3 percent slopes	Fine-loamy, mixed, isohyperthermic Cumulic Haplustolls

Appendix 4   Corn tissue Zn concentration by dry-ashing and its ratio
to wet-digested Zn concentration.

Soil	Zn applied (mg/kg)	Zinc conc (mg/kg)			Ratio of wet-digested Zn/dry-ashed Zn		
		Seedling	Leaf	Seed	Seedling	Leaf	Seed
Paaloa	0	6.8	–	–	1.42	–	–
	1	12.1	12.1	20.3	1.26	1.22	0.96
	3	19.7	16.4	27.6	1.17	1.24	0.98
	9	36.3	39.3	35.2	1.15	1.13	0.98
	27	65.0	99.8	49.5	1.13	1.15	0.91
Keahua	0	6.6	5.2	–	1.49	1.25	–
	1	10.8	9.3	14.2	1.44	1.20	1.18
	3	11.7	10.8	18.1	1.59	1.20	1.02
	9	41.6	17.8	22.2	1.13	1.18	1.08
	27	84.3	53.0	41.3	1.13	1.09	0.94

Appendix 5   Sorghum tissue Zn concentration by dry-ashing and its
ratio to wet-digested Zn concentration.

Soil	Zn applied (mg/kg)	Zinc conc (mg/kg)			Ratio of wet-digested Zn/dry-ashed Zn		
		Seedling	Leaf	Seed	Seedling	Leaf	Seed
Paaloa	0	6.3	8.9	4.6	1.68	1.32	1.30
	1	19.1	17.9	9.1	1.24	1.08	1.19
	3	19.3	21.7	11.2	1.38	1.05	0.91
	9	38.6	23.1	14.7	1.11	1.19	0.93
	27	79.7	36.2	26.1	1.11	1.17	1.02
Keahua	0	6.3	12.3	7.2	1.52	1.26	1.06
	1	17.4	17.9	10.2	1.57	1.12	1.06
	3	25.2	20.8	10.8	1.08	1.12	1.18
	9	32.2	22.0	14.3	1.10	1.18	1.06
	27	62.8	31.9	16.4	1.23	1.09	1.31

Appendix 6   Millet tissue Zn concentration by dry-ashing and its
ratio to wet-digested Zn concentration.

Soil	Zn applied (mg/kg)	Zinc conc (mg/kg)			Ratio of wet-digested Zn/dry-ashed Zn		
		Seedling	Leaf	Seed	Seedling	Leaf	Seed
Paaloa	0	6.0	9.4	8.8	1.76	1.05	1.46
	1	28.6	34.1	20.2	1.33	1.10	1.09
	3	32.0	33.3	18.6	1.34	1.15	1.25
	9	37.1	49.6	26.1	1.23	1.12	1.21
	27	79.8	86.0	53.1	1.24	1.05	0.96
Keahua	0	5.4	8.1	9.8	1.79	1.08	1.32
	1	26.9	23.4	11.0	1.43	1.04	1.36
	3	32.1	22.0	10.9	1.35	1.15	1.33
	9	41.2	27.1	17.1	1.53	1.21	1.23
	27	83.6	49.4	26.8	1.31	1.06	0.98

Appendix 7   Rice tissue Zn concentration by dry-ashing and its ratio
to wet-digested Zn concentration.

Soil	Zn applied (mg/kg)	Zinc conc (mg/kg)			Ratio of wet-digested Zn/dry-ashed Zn		
		Seedling	Leaf	Seed	Seedling	Leaf	Seed
Paaloa	0	8.4	–	15.2	1.45	–	1.15
	1	15.2	–	22.2	1.36	–	1.05
	3	18.8	–	26.8	1.39	–	1.00
	9	35.6	–	32.7	1.18	–	1.05
	27	62.7	–	42.7	1.36	–	1.03
Keahua	0	9.5	9.3	10.6	1.48	1.11	1.13
	1	12.9	14.3	13.7	1.72	1.04	1.13
	3	18.2	15.8	16.8	1.85	1.08	1.11
	9	31.6	25.1	22.7	1.82	1.14	1.17
	27	54.2	25.4	32.8	1.80	1.25	1.09

Appendix 8   Wheat tissue Zn concentration by dry-ashing and its ratio
             to wet-digested Zn concentration.

Soil	Zn applied	Zinc conc (mg/kg)		Ratio of wet-digested Zn/dry-ashed Zn	
	(mg/kg)	Seedling	Seed	Seedling	Seed
Paaloa	0	11.2	15.3	1.13	0.94
	1	17.0	20.9	1.15	0.89
	3	22.2	28.3	1.10	1.03
	9	29.6	40.4	1.03	1.10
	27	40.0	68.3	1.08	1.04
Keahua	0	9.6	12.1	1.13	1.26
	1	17.4	15.8	1.06	1.12
	3	22.3	25.4	1.03	1.10
	9	29.0	34.9	1.05	1.12
	27	37.8	55.5	1.07	1.06

Appendix 9   Sugarcane tissue (75 days age) Zn concentration by
             dry-ashing and its ratio to wet-digested Zn concentration.

Soil	Zn applied (mg/kg)	Zinc conc (mg/kg)		Ratio of wet-digested Zn/dry-ashed Zn	
		Leaf blade	Leaf sheath	Leaf blade	Leaf sheath
Paaloa	0	10.6	4.0	1.96	2.70
subsoil	1	17.1	10.1	1.57	1.41
	3	19.7	13.7	1.73	1.42
	9	26.5	22.3	1.38	1.15
	27	26.0	35.5	1.42	1.14
Keahua	0	6.7	3.5	2.13	2.19
subsoil	1	9.1	5.9	2.03	2.01
	3	10.0	7.5	2.53	1.37
	9	14.2	12.5	1.89	1.28
	27	19.5	17.3	1.46	1.24
Keahua	0	11.4	5.5	1.80	2.25
surface	1	12.2	8.9	1.66	1.94
soil	3	12.4	9.6	1.84	2.00
	9	12.8	15.9	1.81	1.98
	27	22.8	24.0	1.33	1.50

Appendix 10   Soybean tissue Zn concentration by dry-ashing and its
              ratio to wet-digested Zn concentration.

| Soil	Zn applied (mg/kg)	Zinc conc (mg/kg) Leaf	Seed	Ratio of wet-digested Zn/dry-ashed Zn Leaf	Seed
Paaloa	0	6.9	24.3	1.18	1.15
	1	10.3	24.6	1.16	1.16
	3	17.6	33.1	1.08	1.17
	9	25.7	43.9	1.12	1.07
	27	43.0	65.5	1.10	1.03
Keahua	0	6.0	18.0	1.21	1.28
	1	9.8	21.0	1.04	1.17
	3	16.6	35.6	1.01	1.04
	9	24.0	40.8	1.02	1.08
	27	33.6	52.2	1.20	1.03

Appendix 11   Cowpea tissue Zn concentration by dry-ashing and its
              ratio to wet-digested Zn concentration.

| Soil	Zn applied (mg/kg)	Zinc conc (mg/kg) Leaf	Seed	Ratio of wet-digested Zn/dry-ashed Zn Leaf	Seed
Paaloa	0	7.3	13.1	1.10	1.30
	1	12.3	269	1.12	1.07
	3	15.0	27.3	1.12	1.10
	9	19.0	40.2	1.16	1.00
	27	26.4	53.2	1.07	1.01
Keahua	0	6.5	12.0	1.24	1.32
	1	7.0	15.5	1.18	1.20
	3	11.6	20.2	1.25	1.23
	9	18.5	33.1	1.30	1.07
	27	28.4	40.8	1.14	1.14
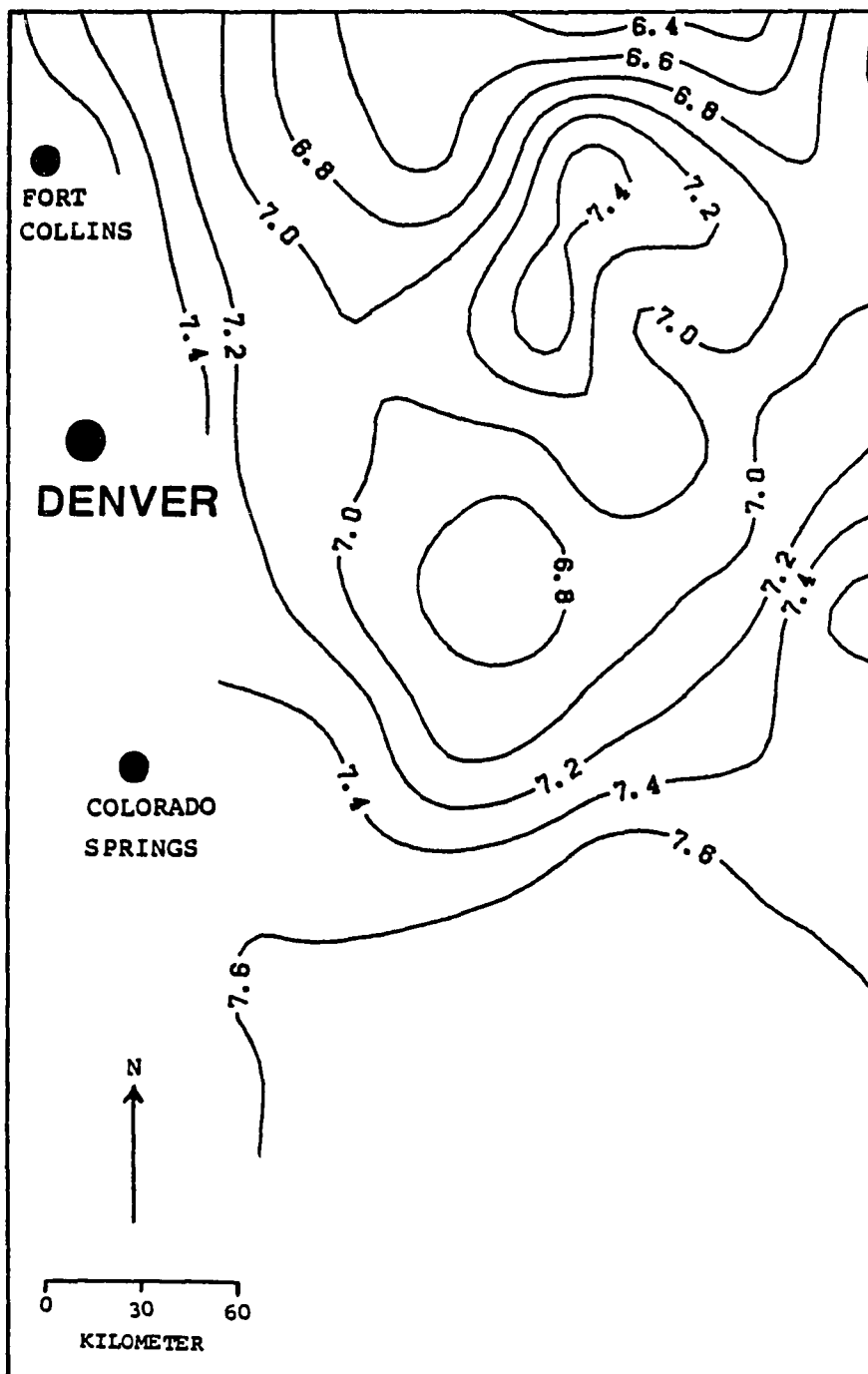
Appendix 12   Isarithm map of pH of topsoils by isotropic
block kriging, Colorado.
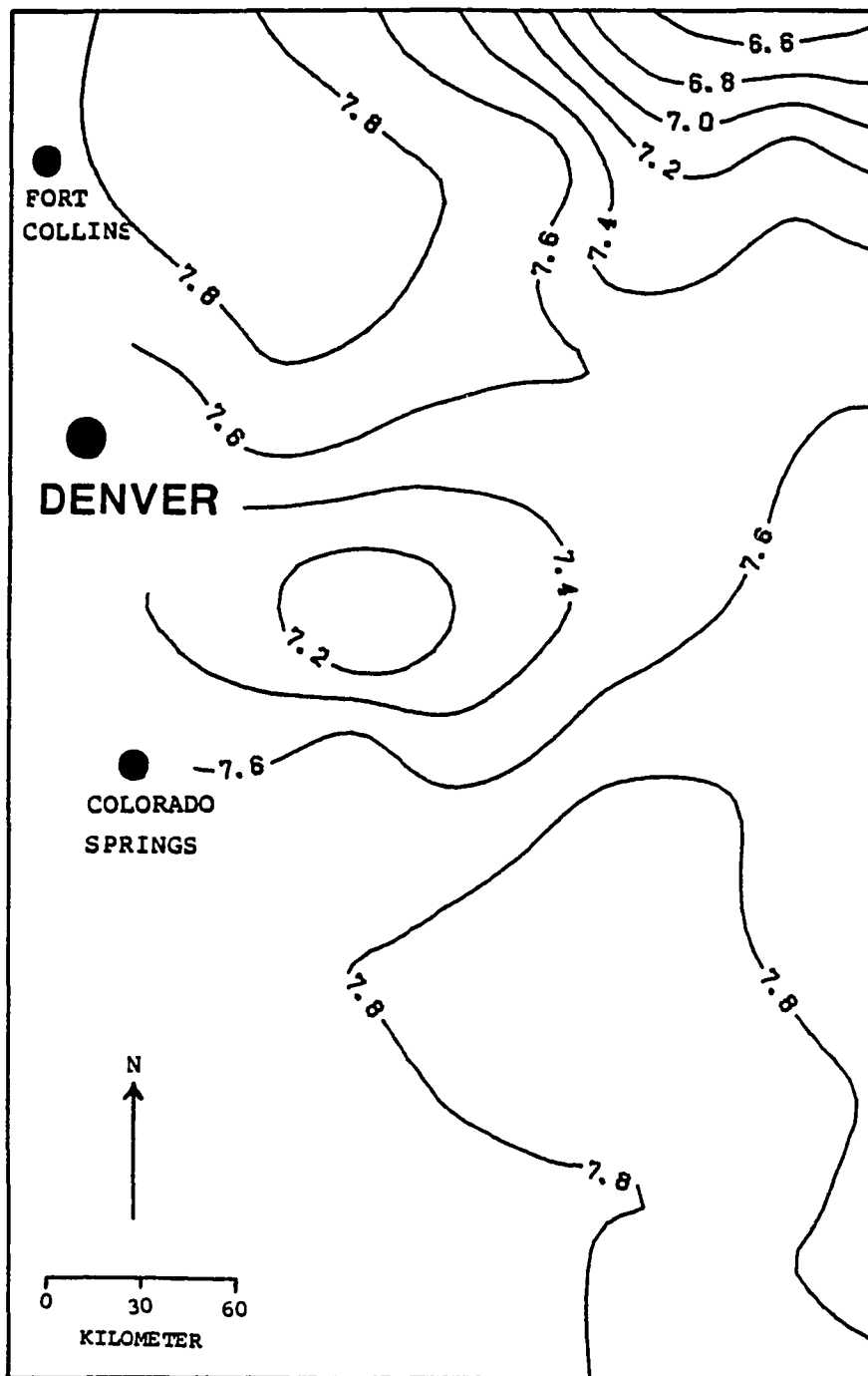
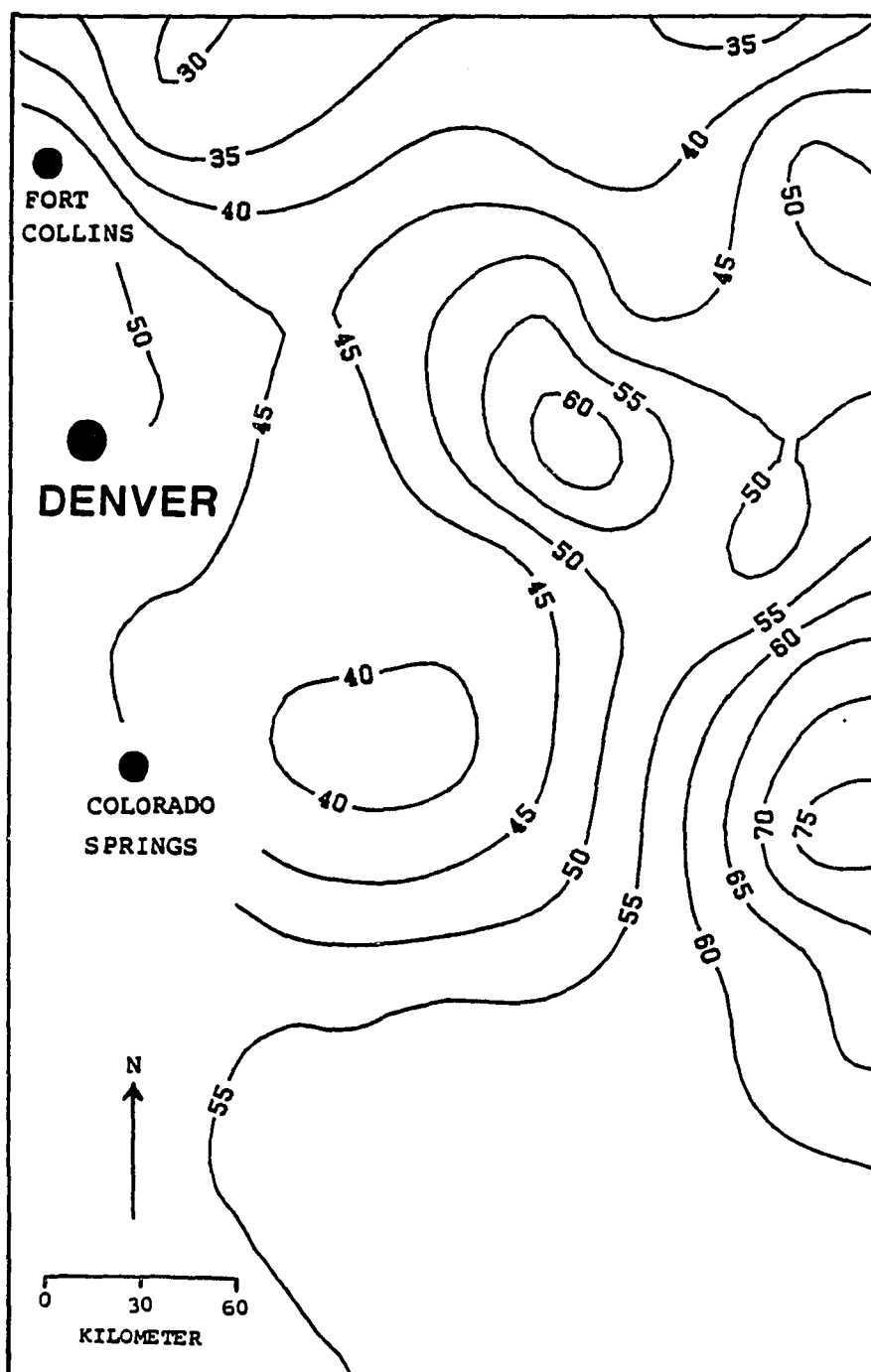Appendix 13 Isarithm map of pH of subsoils by isotropic
             block kriging, Colorado.
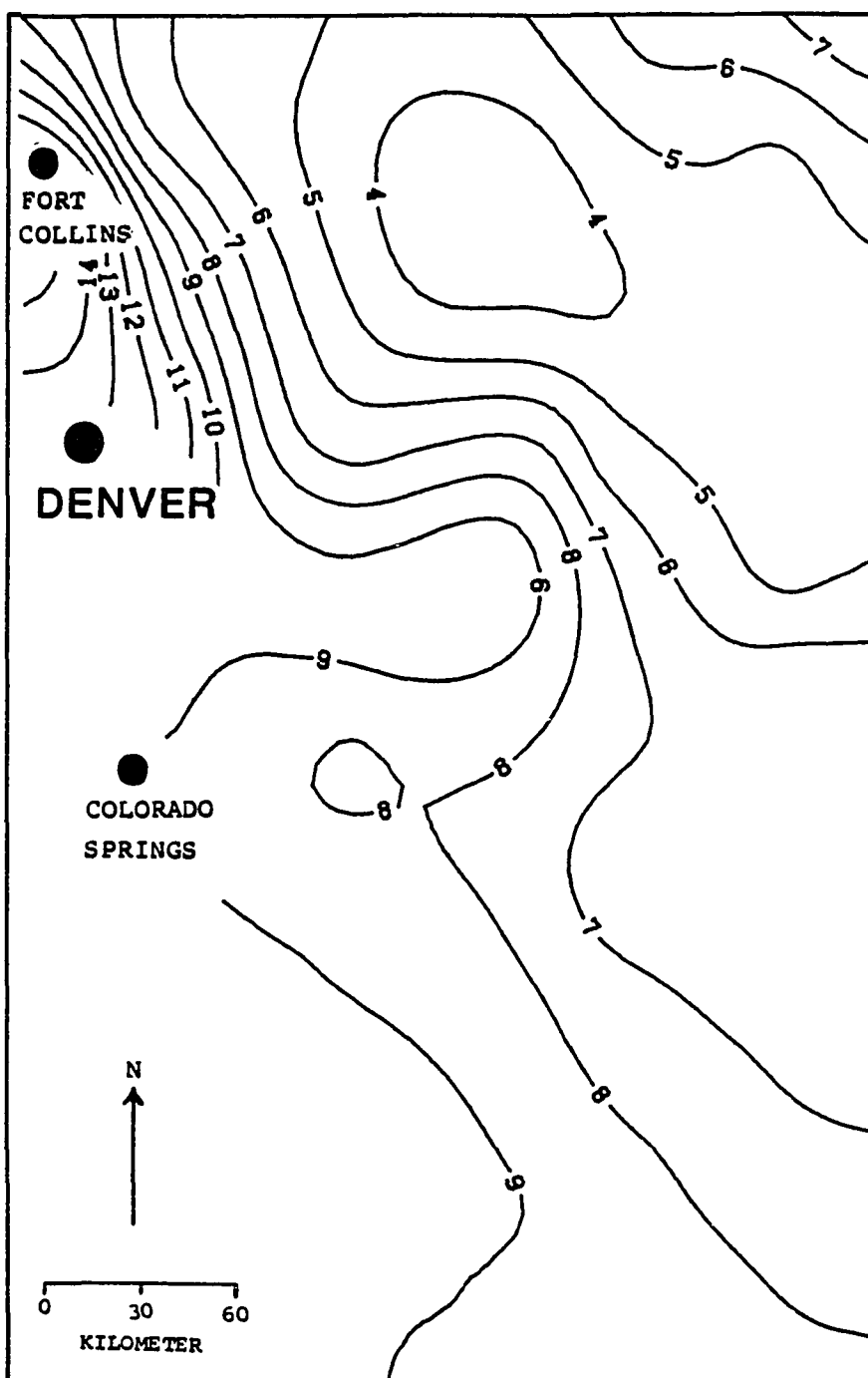
Appendix 14   Isarithm map of Fe status (mg/kg) of subsoils
by isotropic block kriging, Colorado.

Appendix 15 Isarithm map of Mn status (mg/kg) of wheat seeds
by isotropic block kriging, Colorado.

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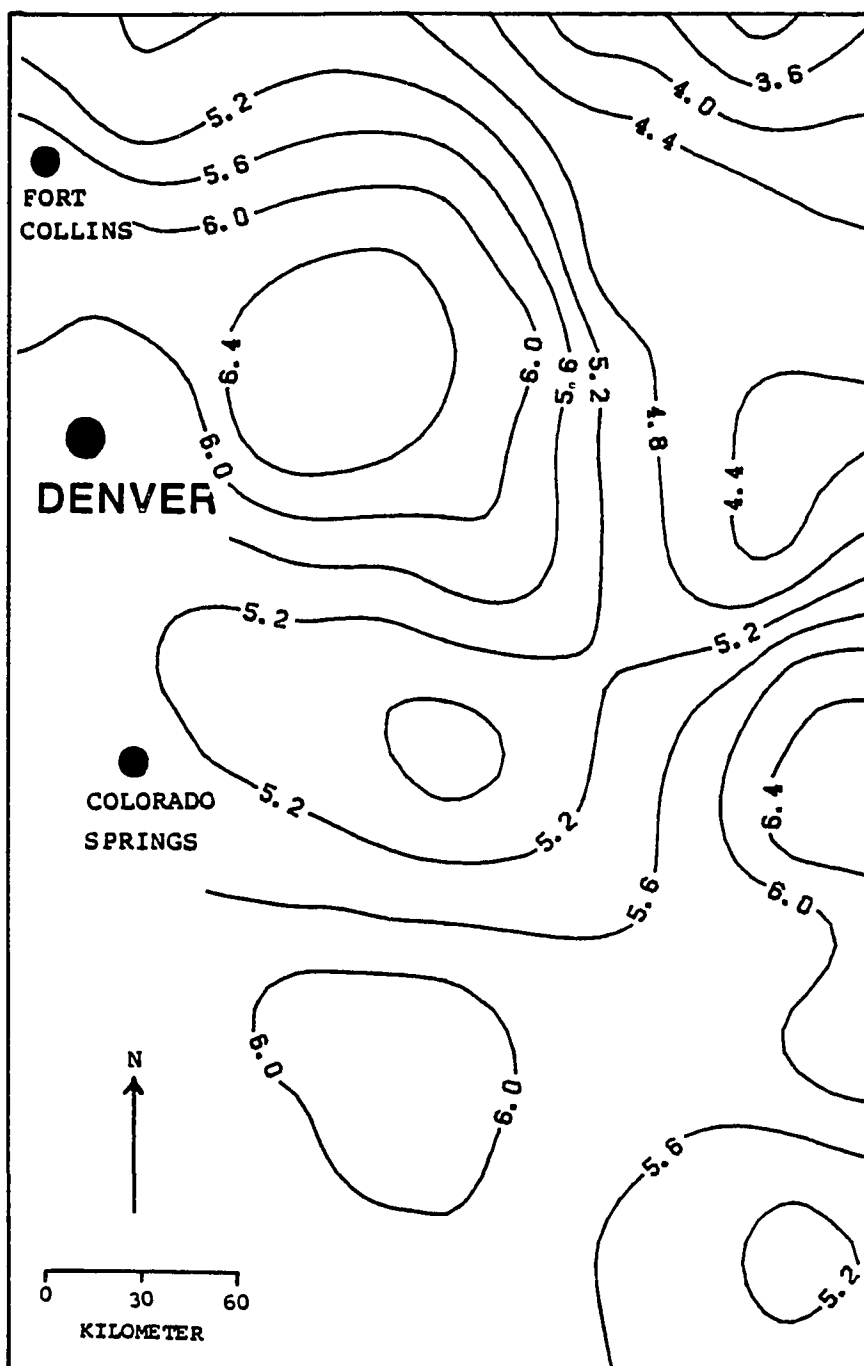
Appendix 16 Isarithm map of Cu status (mg/kg) of wheat seeds
by isotropic block kriging, Colorado.
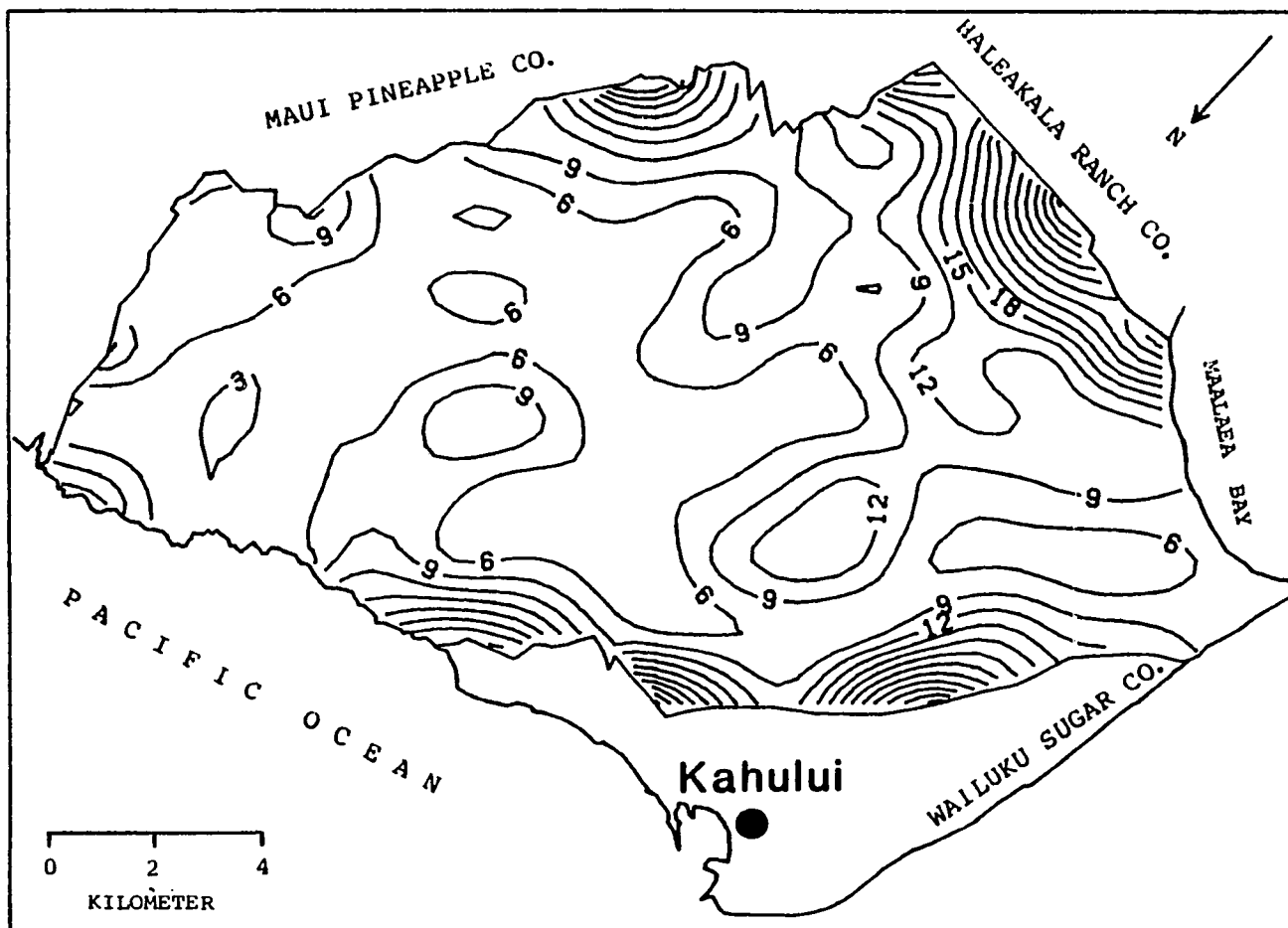
Appendix 17 Estimation variances of surface soil Zn for isotropic block
kriging, HC&S, Maui, Hawaii. Isarithims in mg/kg.

Appendix 18   Estimation variances of subsoil Zn for isotropic block kriging,
HC&S, Maui, Hawaii. Isarithims in mg/kg.

Appendix 19   Estimation variances of Zn content leaf blade (dry-ashed) for
                isotropic block kriging, HC&S, Maui, Hawaii. Isarithms in mg/kg.
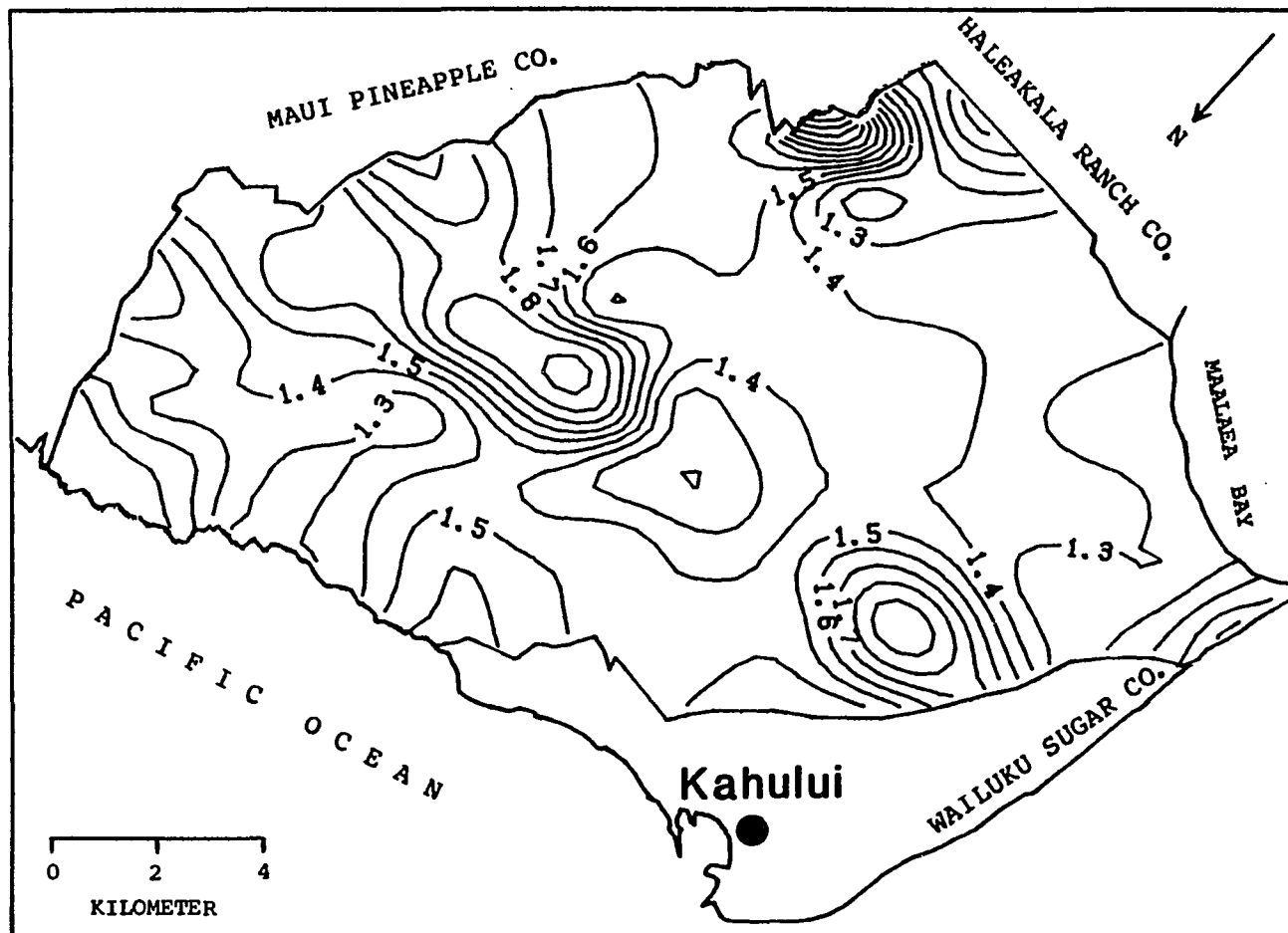
Appendix 20   Isarithm map of N status (%) of leaf blades from 70 observed
values , HC&S, Maui.
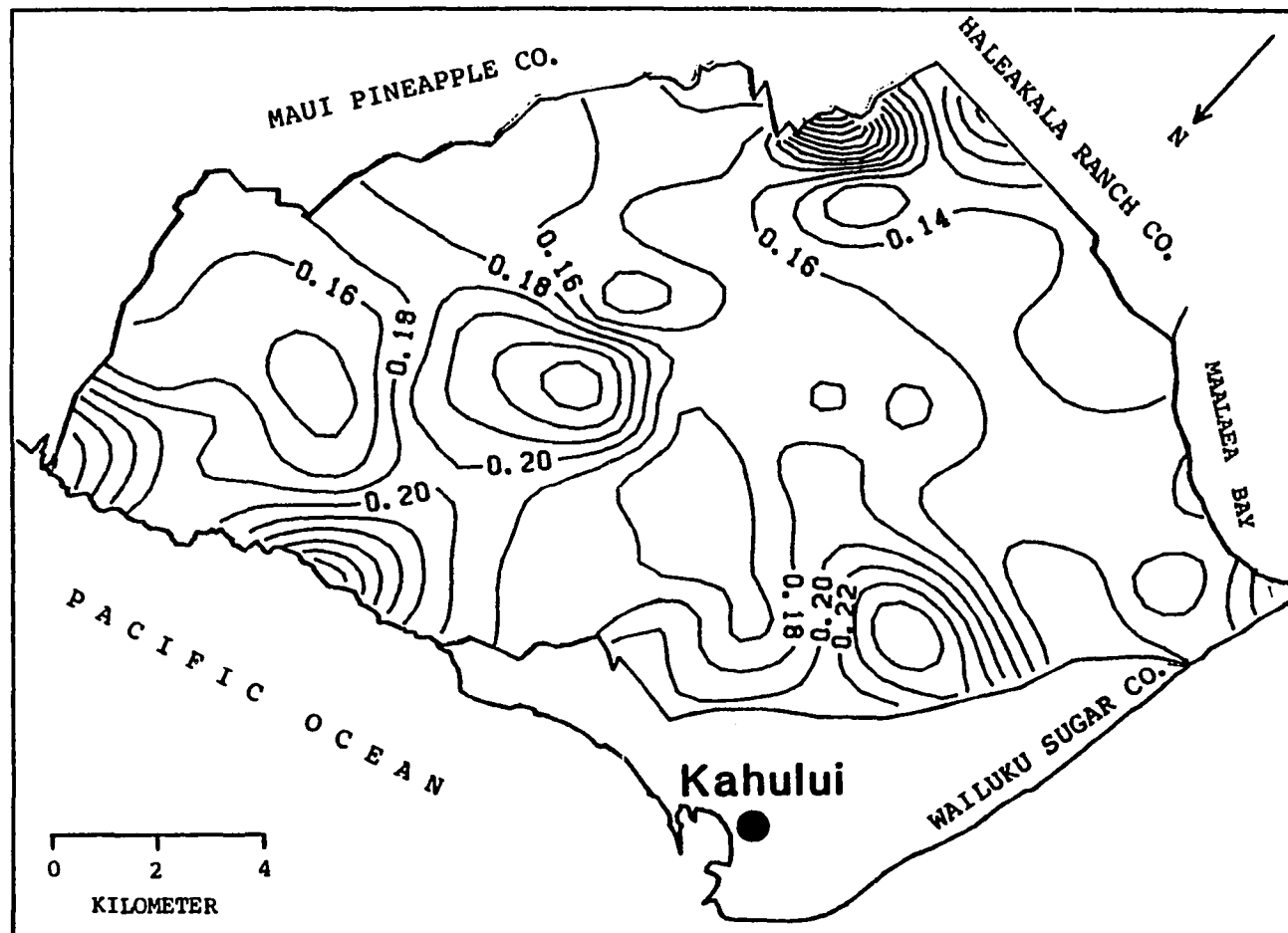
Appendix 21   Isarithm map of S status (%) of leaf blades (dry-ashed) from 70
observed values, HC&S, Maui.
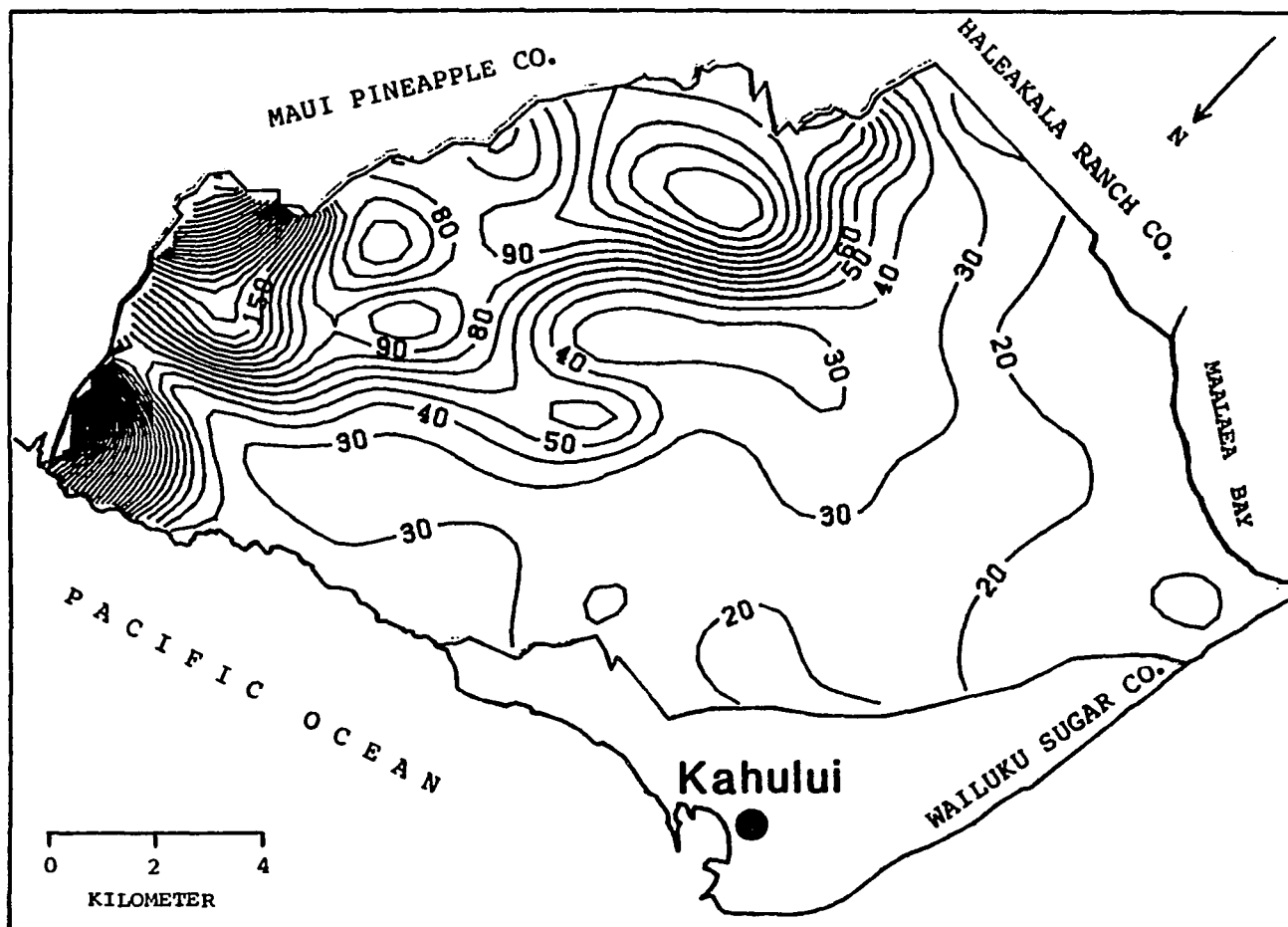
Appendix 22   Isarithm map of Mn status (mg/kg) of leaf blades (dry-ashed) from
70 observed values, HC&S, Maui.
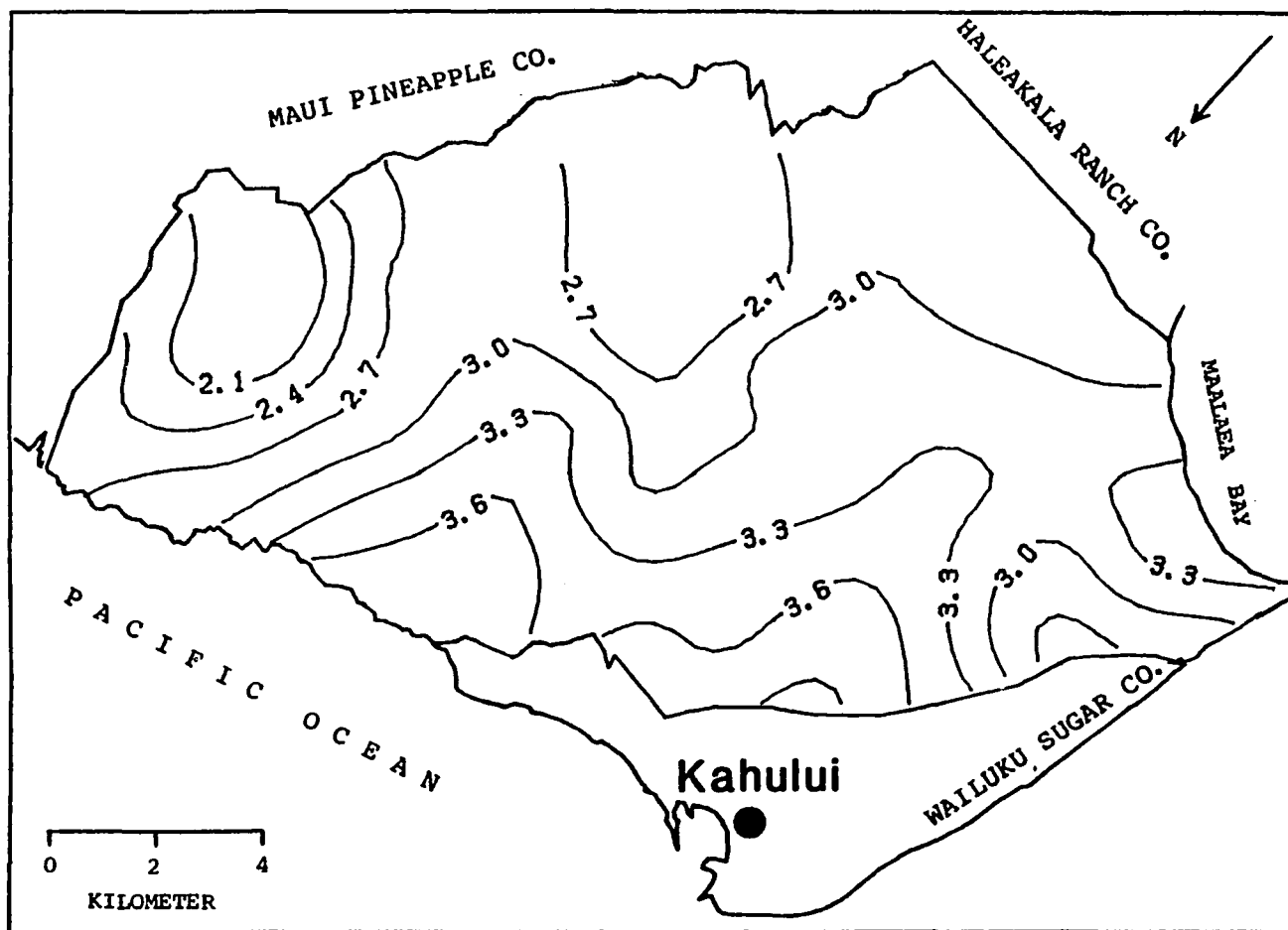
Appendix 23   Isarithm map of K status (%) of leaf sheaths by isotropic block kriging, HC&S, Maui.
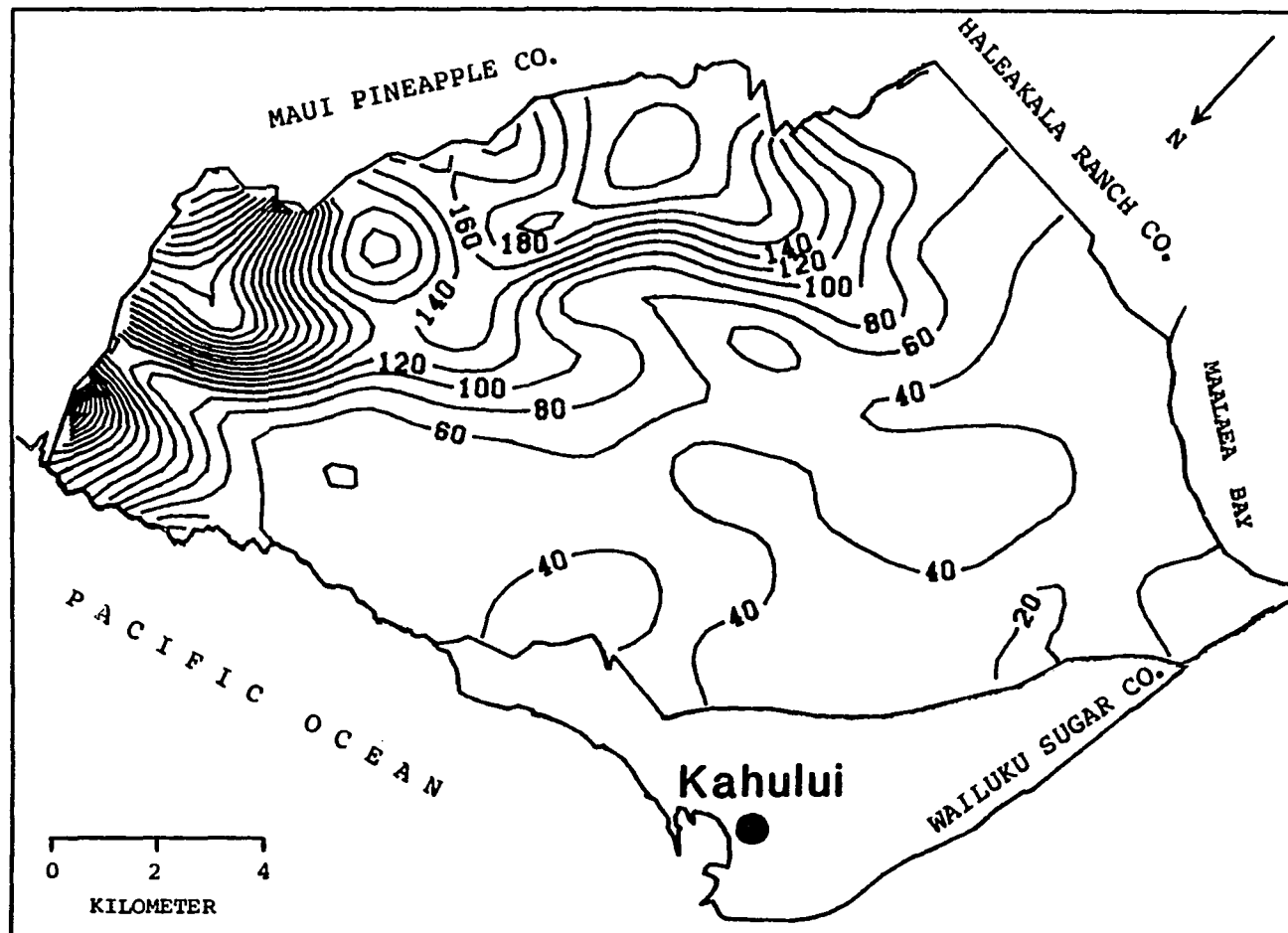
Appendix 24   Isarithm map of Mn status (mg/kg) of leaf sheaths by isotropic block kriging, HC&S, Maui.
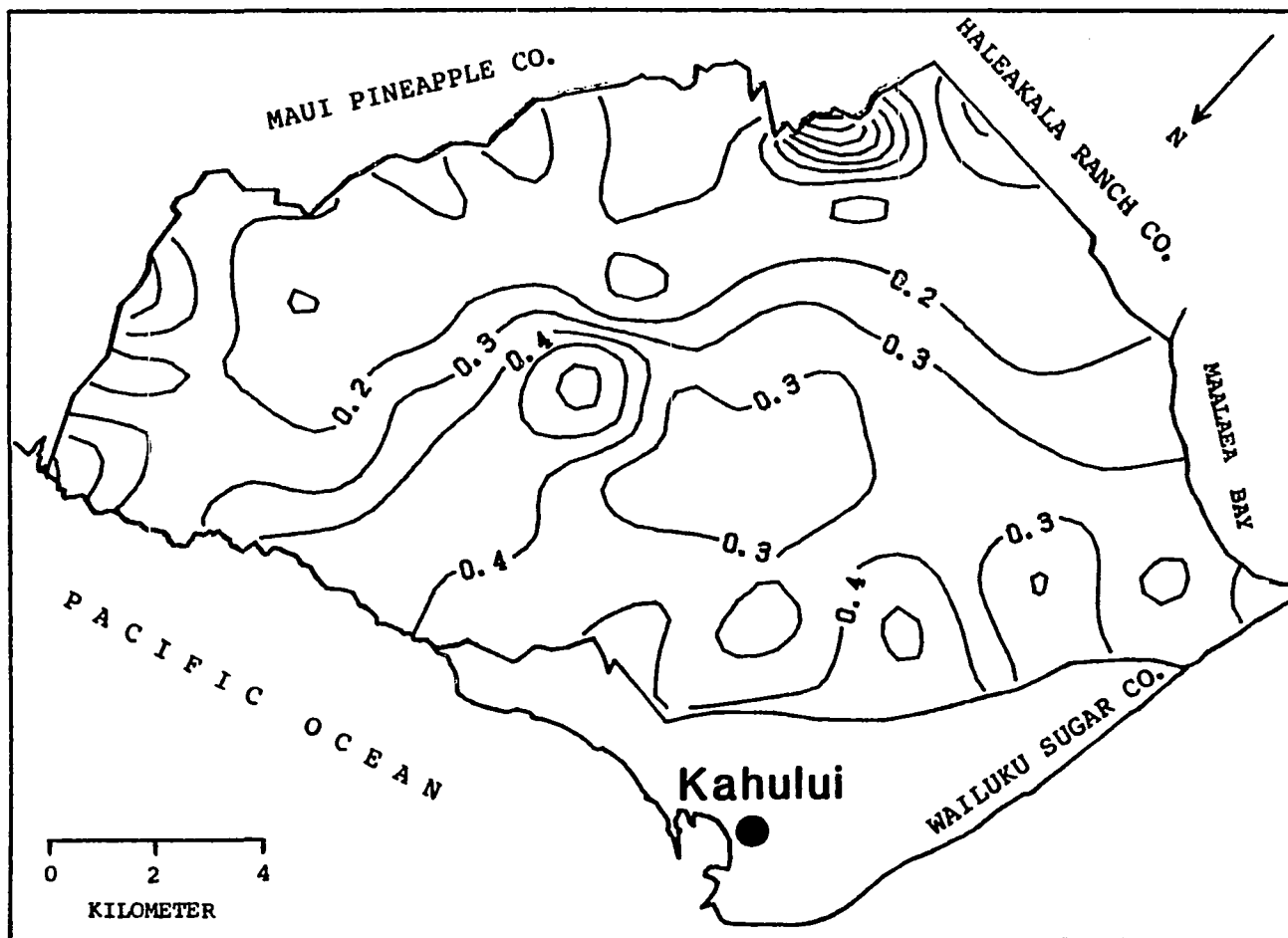
Appendix 25   Isarithm map of S status (%) of leaf sheaths from 70 observed
values, HC&S, Maui.
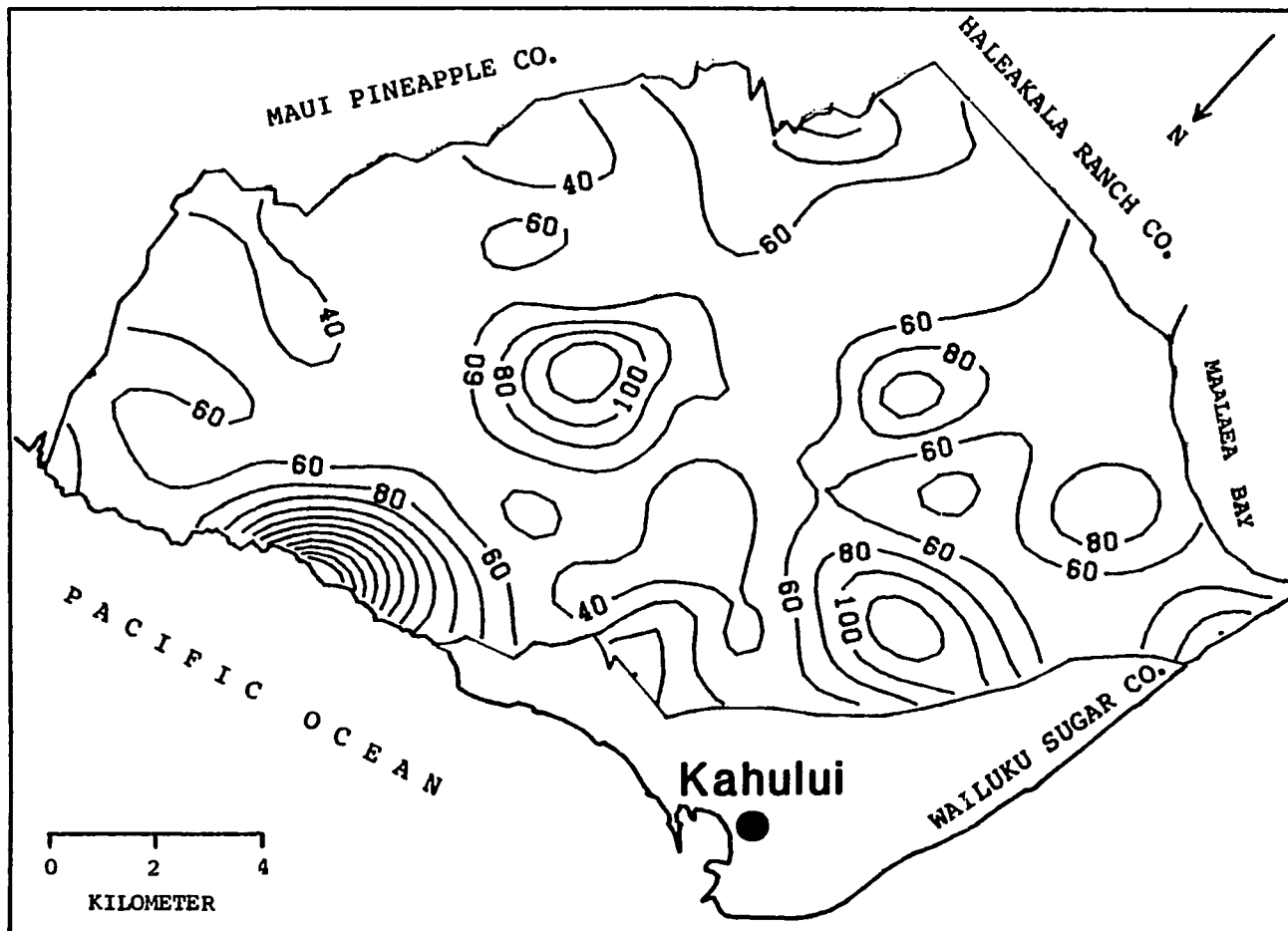
Appendix 26   Isarithm map of Na status (mg/kg) of leaf sheaths from 70
observed values, HC&S, Maui.
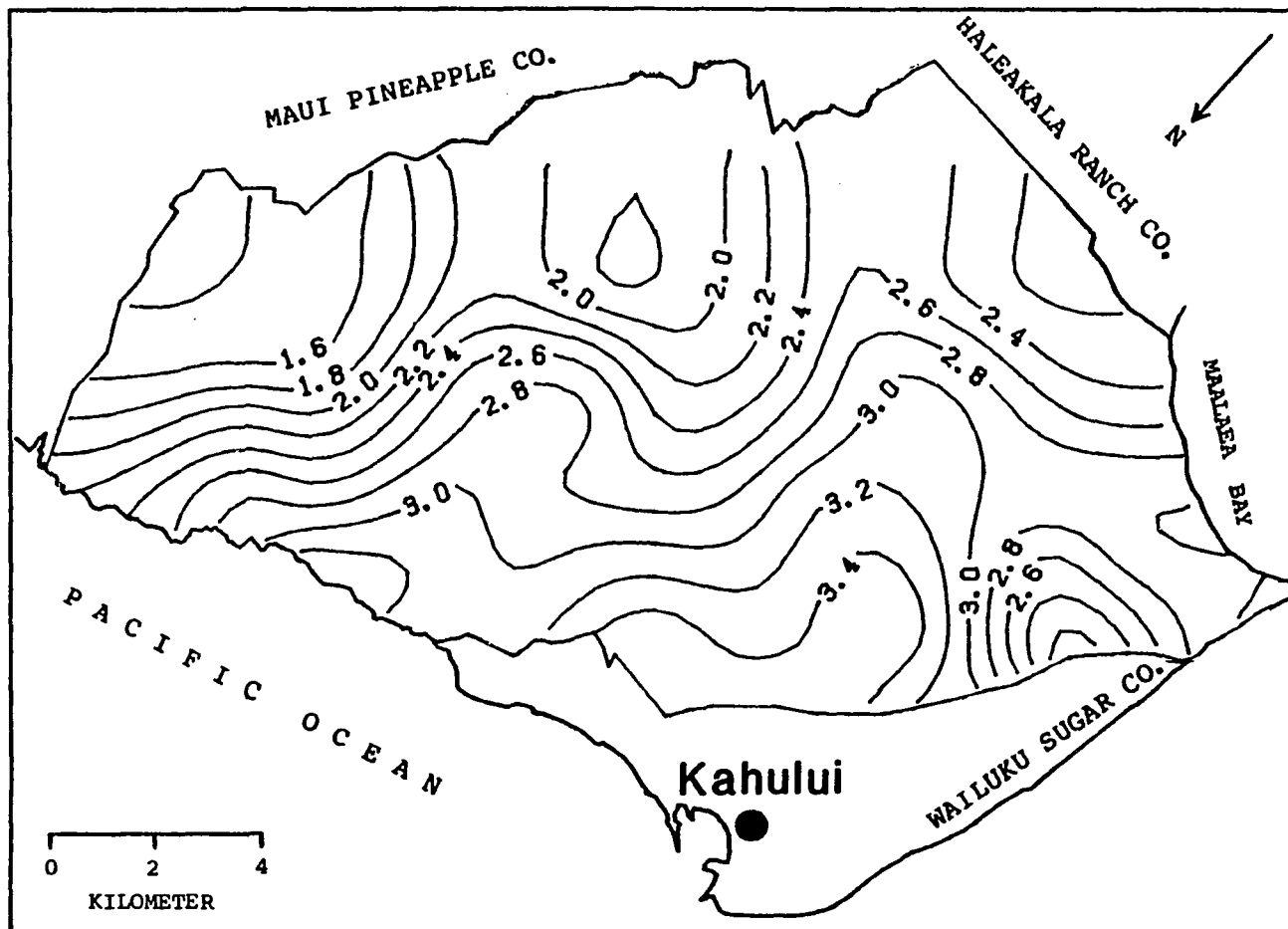
Appendix 27   Isarithm map of silica status (%) of leaf sheaths by isotropic
                block kriging, HC&S, Maui.
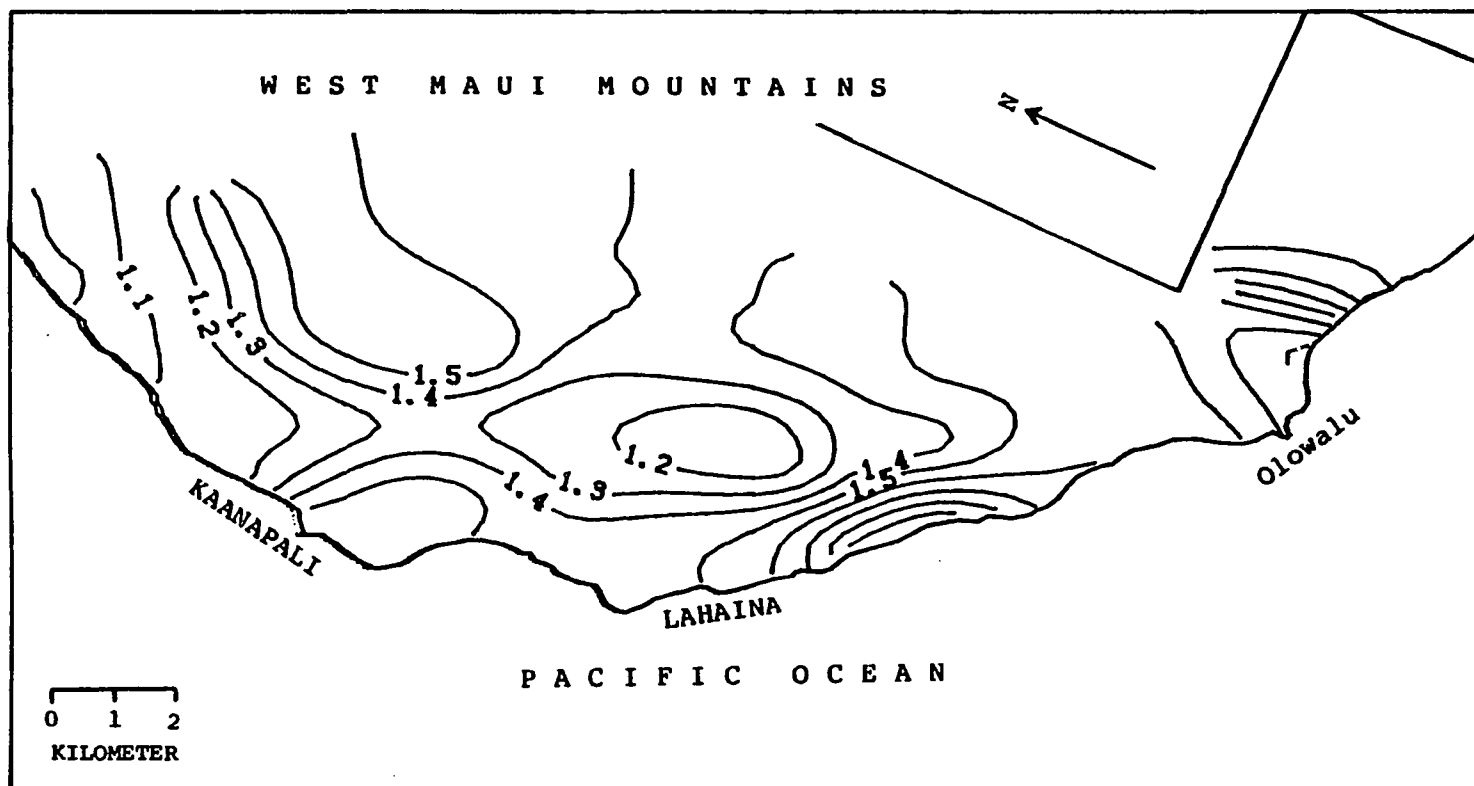
Appendix 28   Isarithm map of N status (%) of leaf blades from 30 observed
               values, Pioneer Mill Company, Maui.
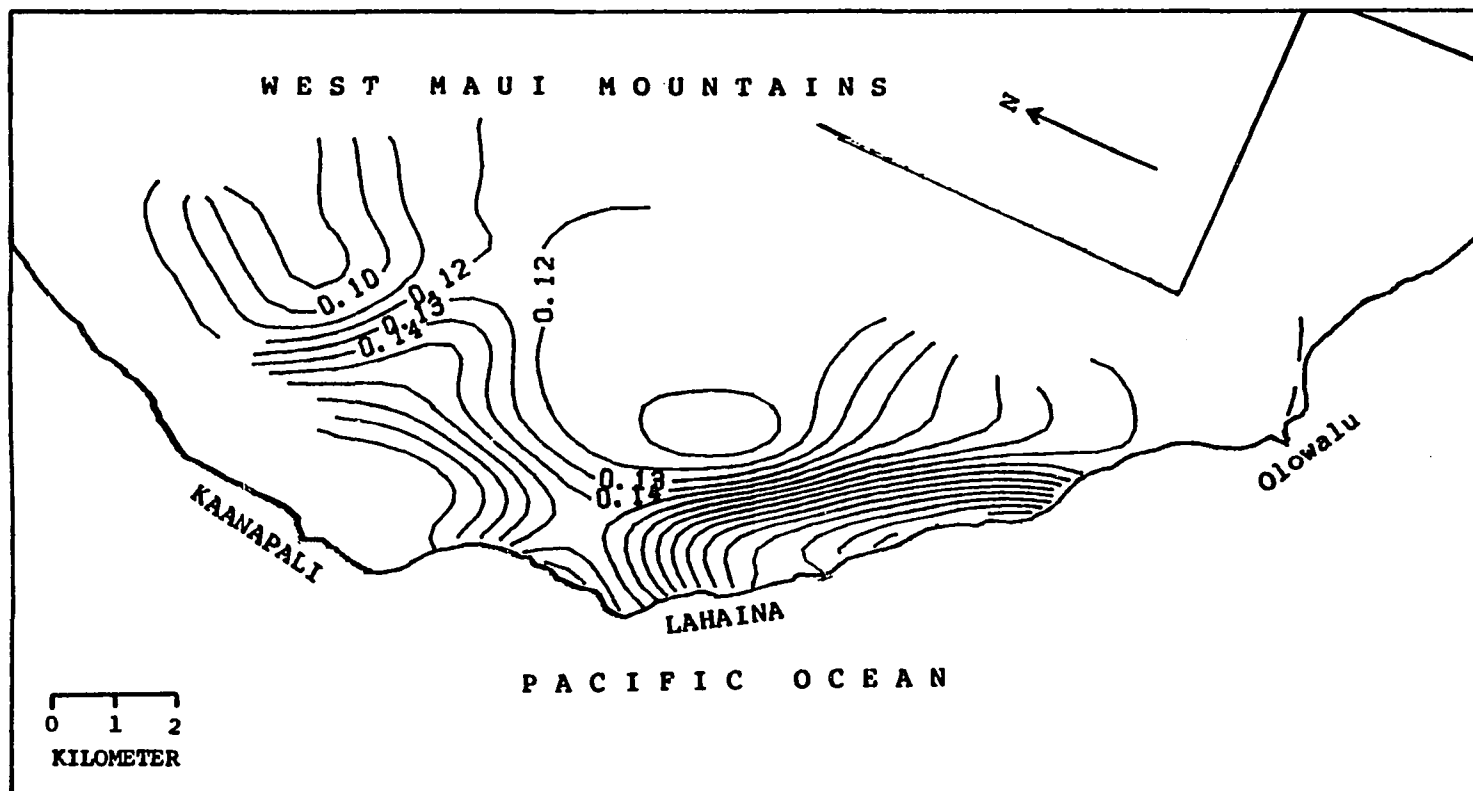
Appendix 29   Isarithm map of S status (mg/kg) of leaf blades (dry ashed) from
30 observed values, Pioneer Mill Company, Maui.
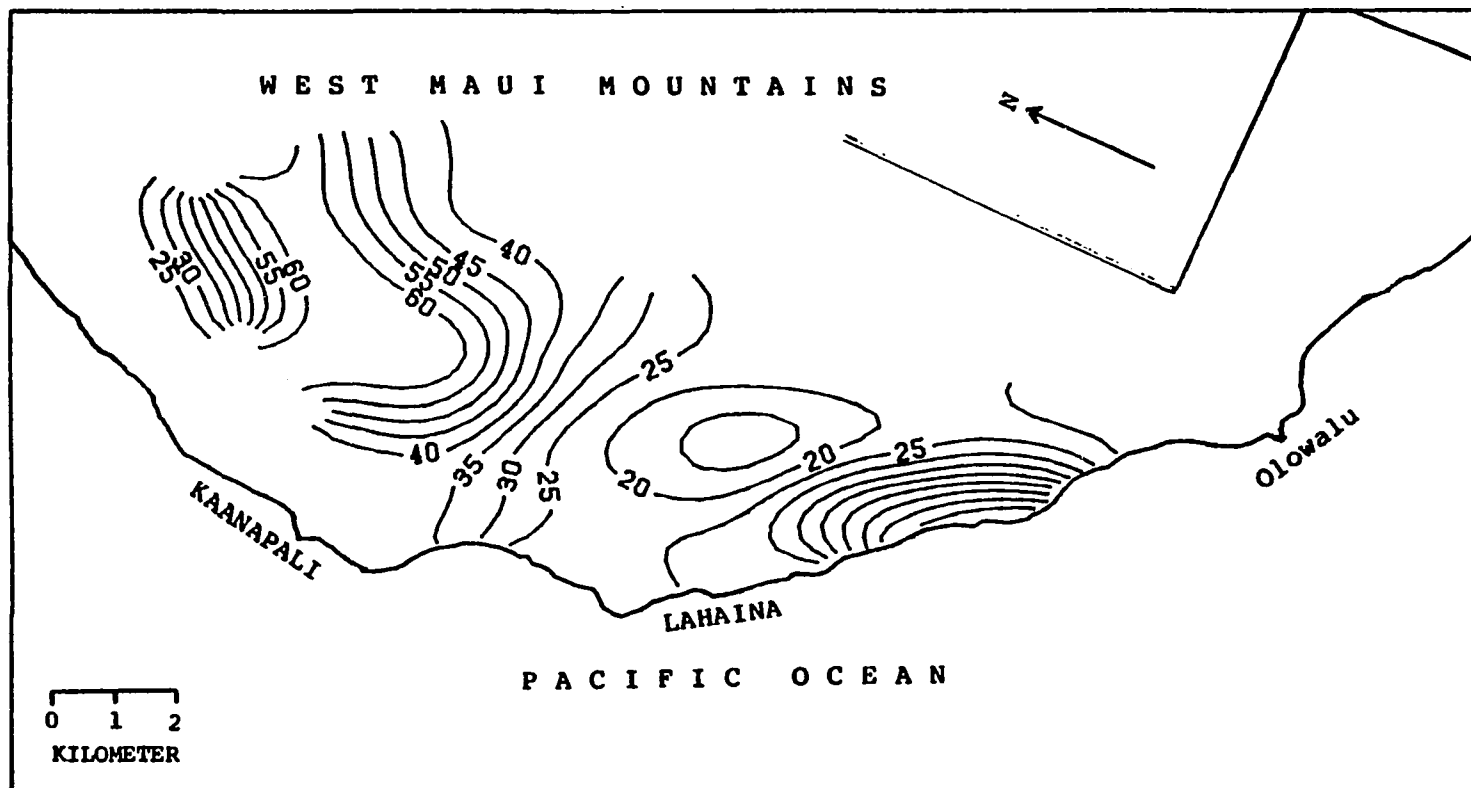
Appendix 30   Isarithm map of Mn status (mg/kg) of leaf blades (dry-ashed) from
30 observed values, Pioneer Mill Company, Maui.

WEST MAUI MOUNTAINS

N

—170—
130
160
140
210
KAANAPALI
140
150
140
LAHAINA
Olowalu

PACIFIC OCEAN

0 1 2
KILOMETER
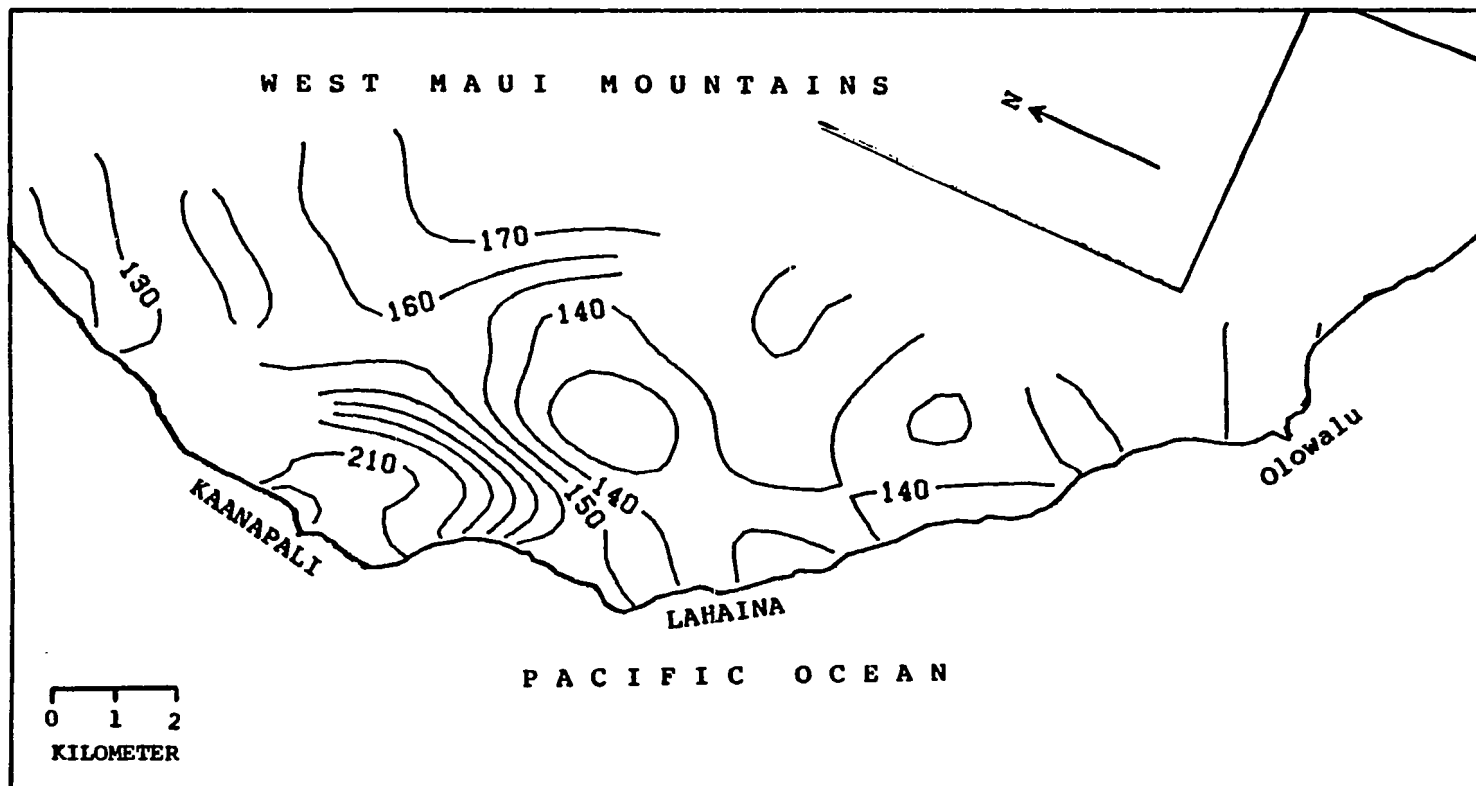
Appendix 31   Isarithm map of Na status (mg/kg) of leaf blades (dry-ashed) from
30 observed values, Pioneer Mill Company, Maui.
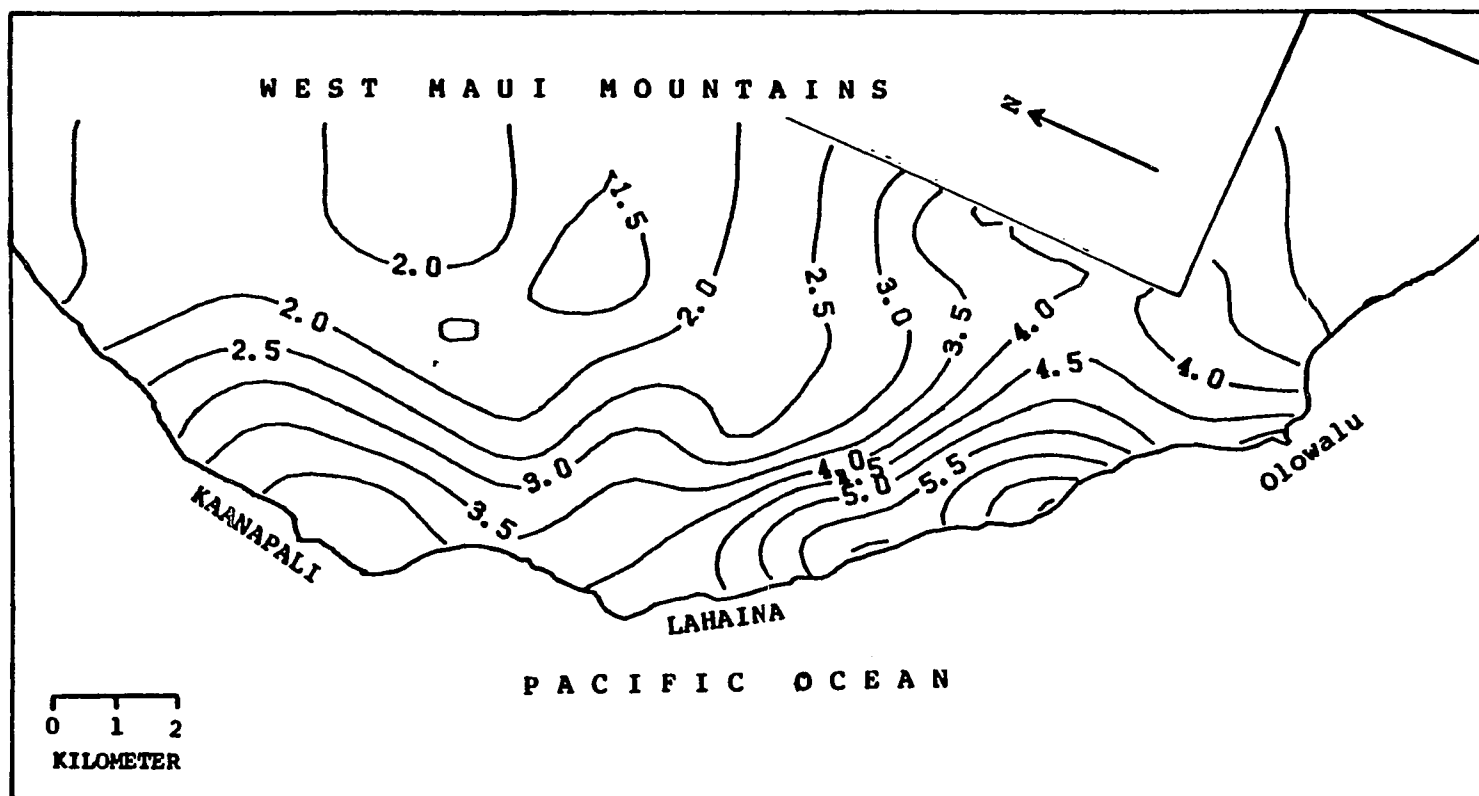
Appendix 32   Isarithm map of silica status (%) of leaf blades by isotropic
block kriging, Pioneer Mill Company, Maui.
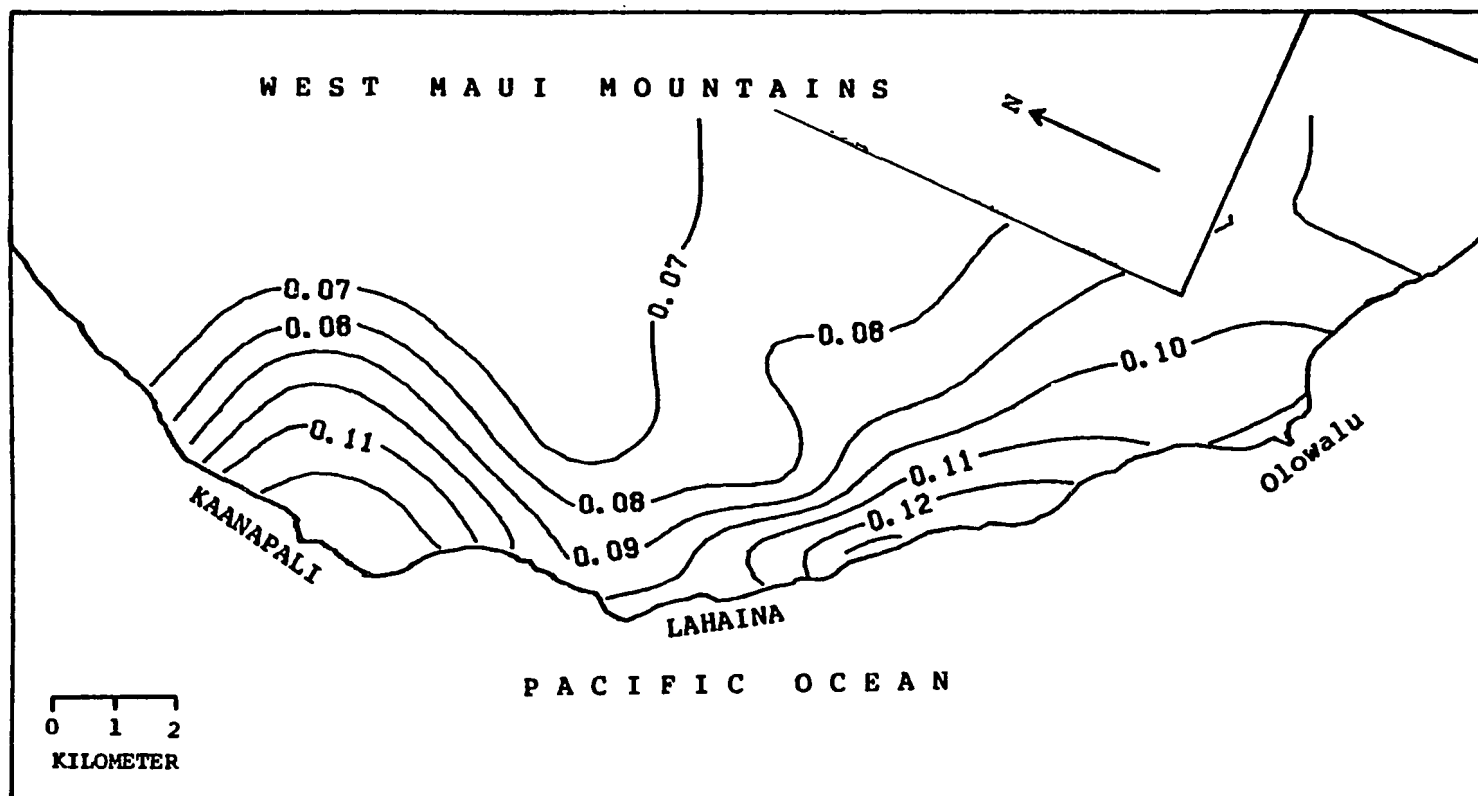
Appendix 33 Isarithm map of P status (mg/kg) of leaf sheaths (dry-ashed) by isotropic block kriging, Pioneer Mil Comapany, Maui.

WEST MAUI MOUNTAINS

N

2

2

2

2

2

2

2

2

KAANAPALI

3 3

2

3 2

3 2

2

4

Olowalu

LAHAINA

PACIFIC OCEAN

0 1 2
KILOMETER
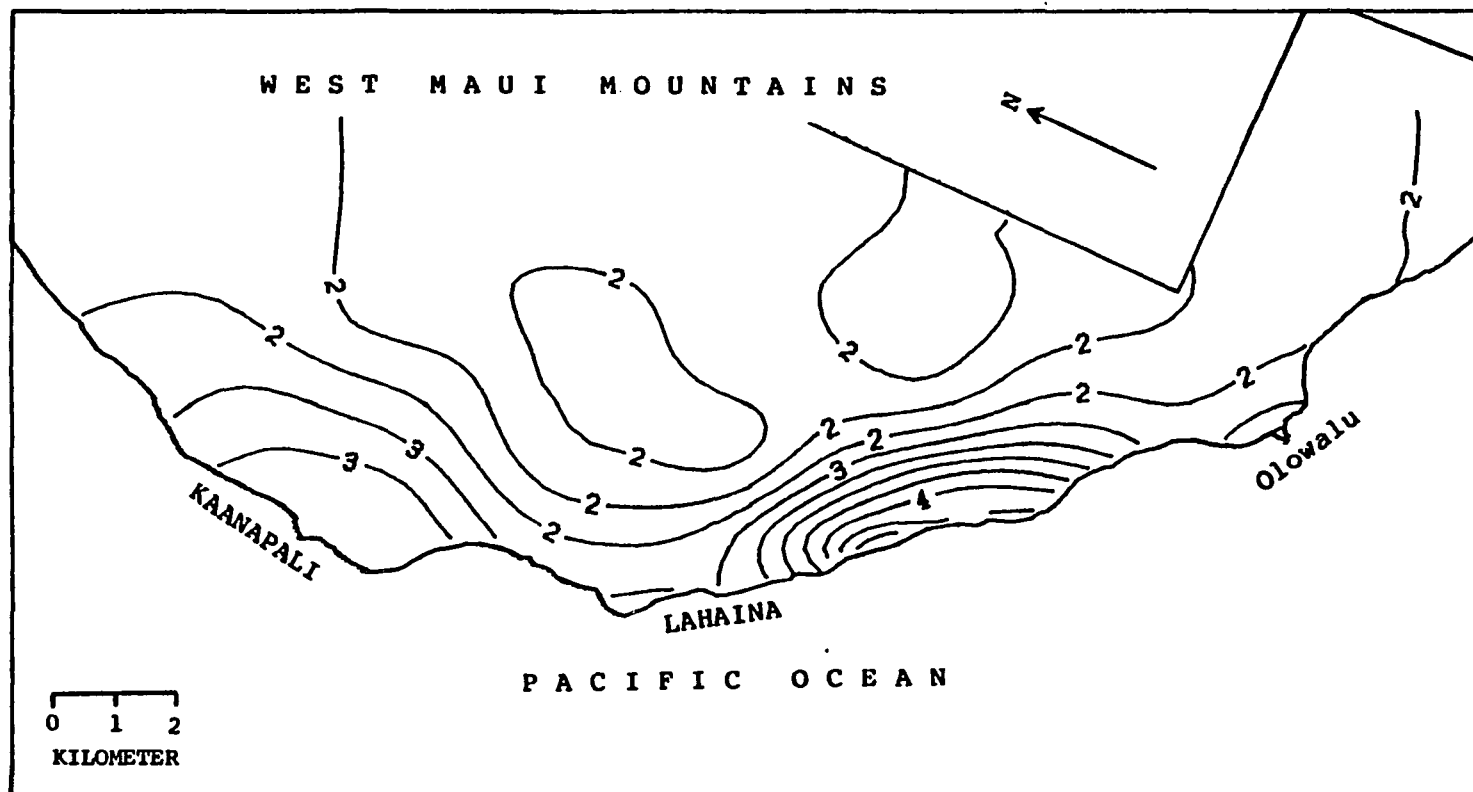
Appendix 34 Isarithm map of K status (mg/kg) of leaf sheaths (dry-ashed) by
isotropic block kriging, Pioneer Mil Comapany, Maui.
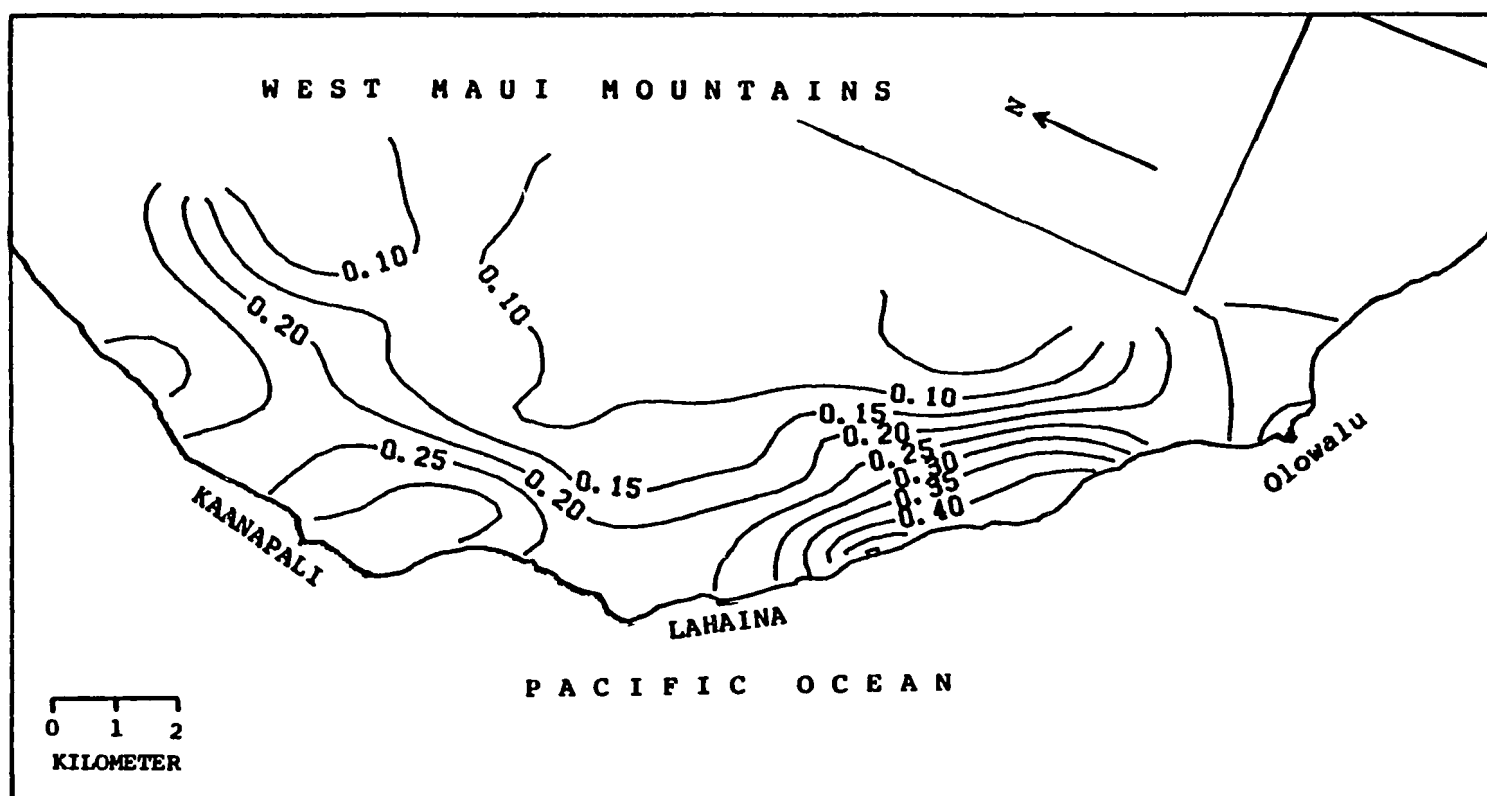
Appendix 35 Isarithm map of S status (mg/kg) of leaf sheaths (dry-ashed) from
30 observed values, Pioneer Mil Comapany, Maui.
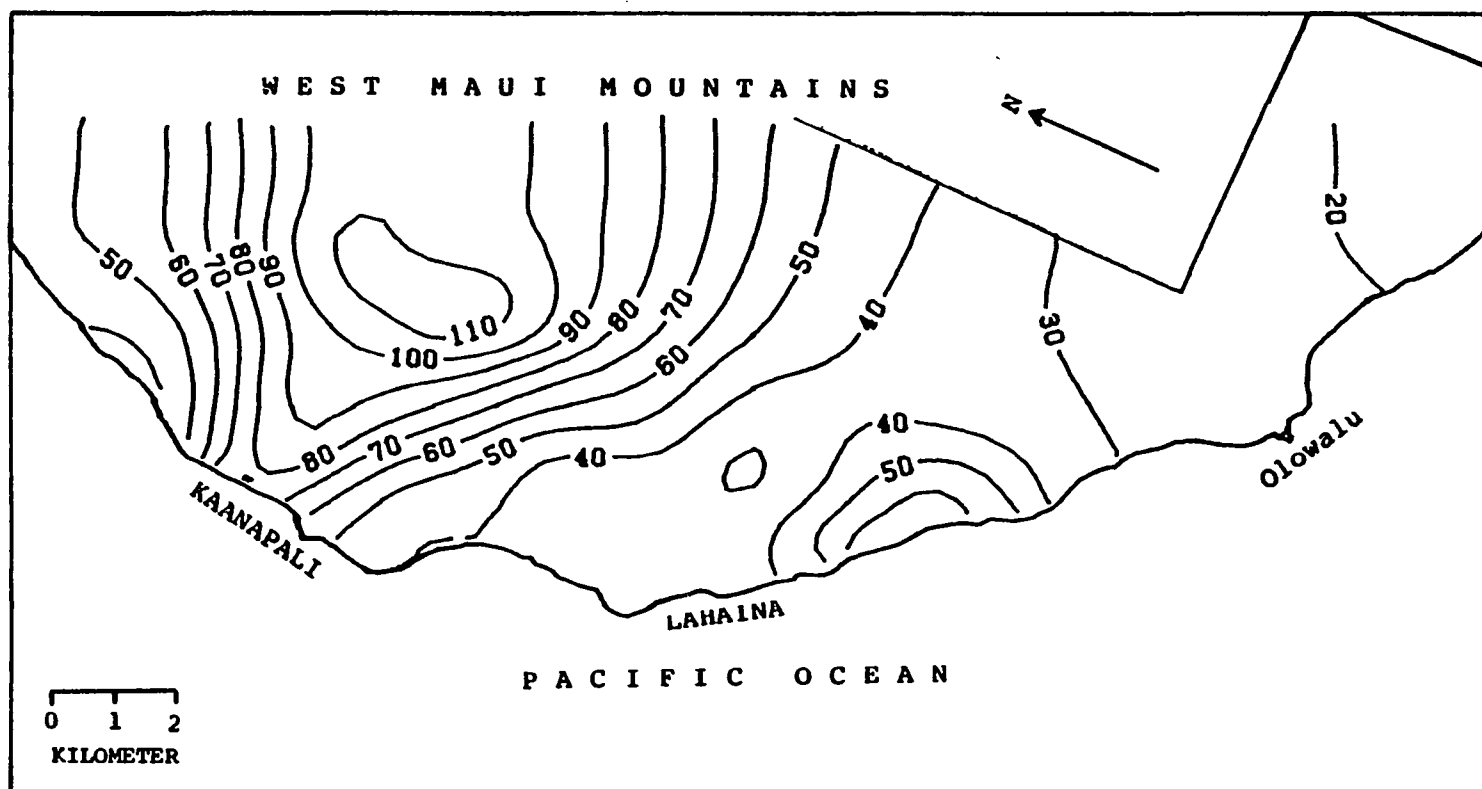
Appendix 36 Isarithm map of Mn status (mg/kg) of leaf sheaths (dry-ashed) by isotropic block kriging, Pioneer Mil Comapany, Maui.
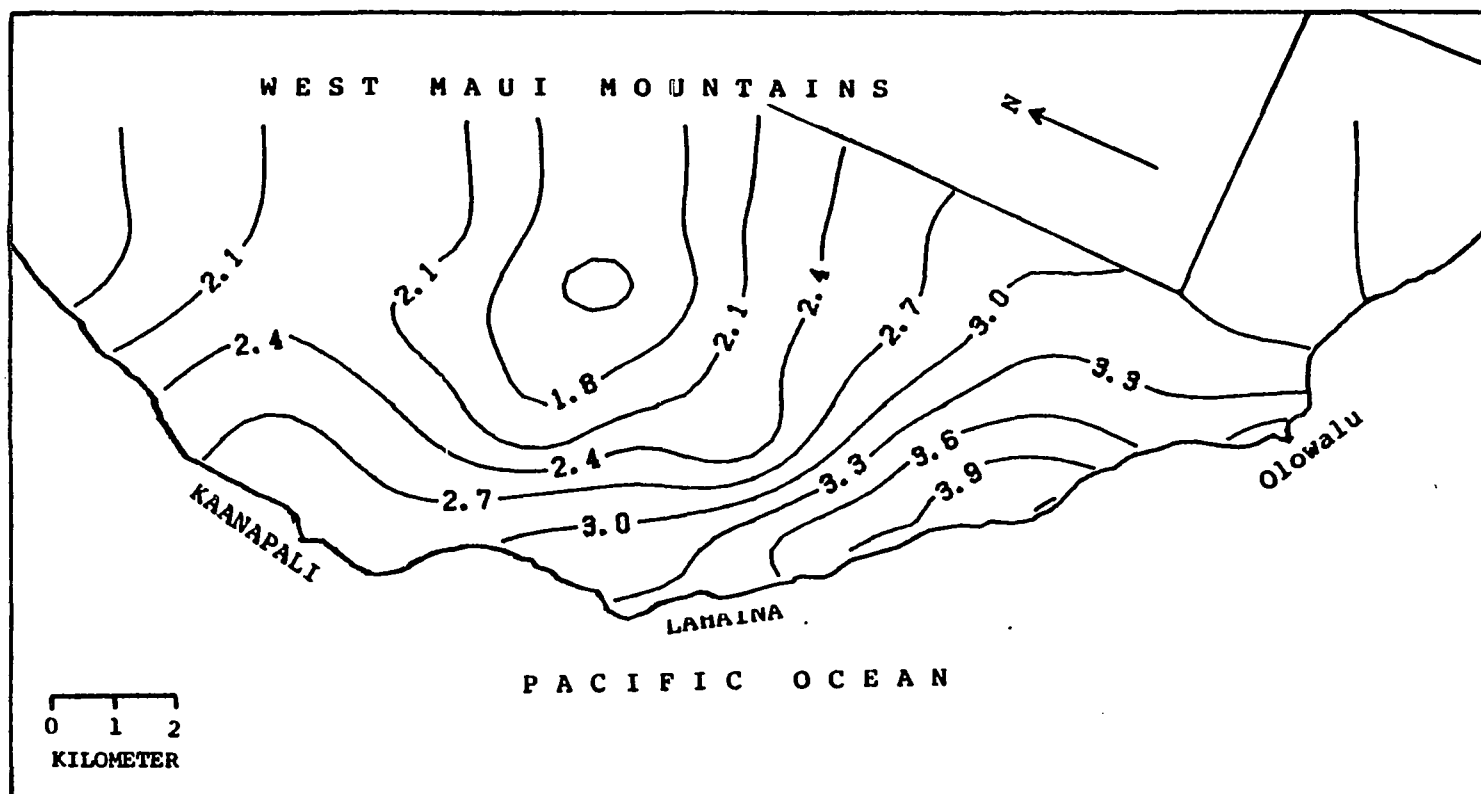
Appendix 37   Isarithm map of silica status (%) of leaf sheaths (dry-ashed) by
isotropic block kriging, Pioneer Mil Comapany, Maui.

GLOSSARY OF GEOSTATISTICAL TERMS

Block kriging: In block kriging, a value for an area or block, V, with its center at x_o is estimated rather than at points, as in punctual kriging.

Cokriging: Similar to one variable being autocorrelated in either space or time, when two or more variables are measured for the same domain, they may be correlated to each other or cross-correlated two by two. This allows values of one variable to be estimated using the measured values of all the variables. This estimation method, called cokriging, is particularly useful when one variable is more difficult to measure than the other variable and consequently has fewer samples than the other variables with which it is cross-correlated.

Degree of continuity: Continuity is a characteristic of a region-alized variable. It is reflected in the rate of increase of the semi-variogram for small values of h (lag distance). Changes may occur slowly, in which case the growth of the semi-variogram is gentle, regular from zero. In other cases rapid changes occur over a short distance. The continuity may also be completely non-existent, resulting in a pure nugget effect (no definite structure; samples are independent of each other).

Drift: Physically the drift represents the trend of the function over the geometric field.

Estimation Error/Variance: Both kriging and cokriging, like any other mthod of estimation, involve an error. This error is due to the fact that the variable to be estimated is generally somewhat different from the estimated value.

The estimation error, $e(x)_k$, is thus defined as the difference between the measured $z(x_k)$ and estimated $z^*(x_k)$ values for the same location x_k.

Geostatistics: The application of theory of regionalized variables to problems in geology and mining has led to the more popular name geostatistics. Geostatistics is used to augment classical statistical methods in analyzing spatial or temporal random variables. Geostatistics is based on the concept that a sample value is expected to be affected by its position and its relationship with its neighbors. This means that samples collected close together should be more alike than samples collected farther apart.

Interpolation: Estimation of a missing functional value by taking a weighted average of known functional values at neighbouring points is called interpolation. It also implies "within" a range rather than outside a range which would be extrapolation.

Isarithmic mapping: Isarithmic mapping is often known as 'contouring', by analogy with the mapping of topograthic height. But topographic contours are usually drawn to join points of equal measured height, whereas soil isarithms join points of inferred equal value.

Isotropic/Anisotropic: When variability of a particular property is identical in all directions of a two-dimensional space, the semi-variance, $Y(h)$, is dependent only on the distance, h, between measured pairs. In this case the semi-variogram is said to be isotropic. It becomes anisotropic when its variability is not the same in every direction. When the physical phenomenon under study is anisotropic, the semivariograms for different directions are different.

Jack-knife technique: This is a technique of cross-validation where the value at a measured site is estimated using the surrounding known site (n-1) and the estimate compared to the known value.

Kriging: Kriging is a technique of making optimal, linear, unbiased estimates of regionalized variables at unsampled locations using the structural properties of the semi-variogram and the initial set of data values. Each estimate is a weighted average of the observed values in its neighborhood. The diameter of the surrounding

neighborhood from which the observed values are drawn is defined by the range of spatial dependence identified from the semi-variogram.

Nested semi-variogram: A semi-variogram is nested if it is described by the sum of two or more mathematical equations (models) because of the presence of intermeshed structures.

Nugget variance: Ideally, the experimental semi-variogram should pass through the origin but very often the fitted equation approximating the semi-variogram will intersect the vertical axis at some point between zero and the sill. This intercept, or "nugget variance", C_0, is caused by both measurement error and micro-variation of the property, which can not be detected at the scale of sampling.

Punctual kriging: The punctual kriged estimate, $z(x)_o$, of the variable Z at any location, x_o, is a weighted average of the sample values $z(x_1)$, $z(x_2)$, . . ., $z(x_n)$ occurring within the surrounding estimation neighborhood. The radius of the neighborhood is generally determined by the range of the semi-variogram. Points beyond this distance are not spatially related to x_o and receive minimal weighting so they have little influence on the kriged estimate.

The kriged estimate can be written as:

$$z(x_o) = \varepsilon \sum_{i=1}^{n} A_i z(x_i)$$

where n is the number of sample values, $z(x_i)$ involved in estimation of the unsampled points, x_o, and A_i are weights. The weights are chosen so that they sum to 1 thereby ensuring that the estimate, $z(x_o)$, of the true value, $z(x_o)$, is unbiased and the estimation variance is minimized.

Range: The distance at which samples become independent of one another is denoted by a and is called the range of influence of a sample. This distance corresponds to the maximum range over which sample values are spatially related. Beyond the distance where $\gamma(h)$ approximates the sill, the spatial dependence of sample values is essentially nil.

Regionalized variable: A regionalized variable is a numerical space function which varies from one place to the next with apparent continuity but which varies in a manner that cannot generally be represented by an ordinary workable function.

Regionalized variable theory: This is a theory in which a regionalized variable varies from one place to the next with apparent continuity, the variations of which cannot generally be represented by an ordinary workable function.

Sample variance, s^2: The most common measure of dispersion, and

the best for most purposes, is the standard deviation and its square,

the variance. Variance is the arithmetic average of the squares of the

deviations from the mean in a frequency distribution.

$$s^2 = \frac{\varepsilon X^2 - (\varepsilon X)^2/n}{n - 1}$$

Semi-variance, $\gamma(h)$: In geostatistics, the semi-variance, $\gamma(h)$,

quantifies the spatial dependence of the variable.

The $\gamma(h)$ is defined as one-half the expected value of the

squared difference between the random function z at sampling

locations x and xh where the vector h represents the direction and

distance between sampling locations, i.e.,

$$\gamma(h)=1/2 \; \varepsilon[z(x)-z(x+h)]^2.$$

In practice, the function v(h) computed for all values of h

is the semi-variogram defined as:

$$\gamma(h)=1/2N(h) \sum_{i=1}^{N} [Z(x_i)-z(x_i+h)]^2.$$

Semi-variogram: Semi-variogram, γ, is a graph (and/or mathematical

formula) describing the expected difference in value between pairs

of samples with a given relative orientation.

The semi-variogram for a given direction is usually displayed

as a plot of semi-variance, $\gamma(h)$, versus distance, h. The semi-

variance increases as distance between sample locations increases. At some distance, a, $\gamma(h)$ no longer increases and the samples are no longer spatially related. At the range of spatial dependence $\gamma(h)$ becomes more or less stable and will correspond to the classical statistical variance, s^2, of the variable.

Sill: 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.

The sill consists of the nugget or random variance and a component that represents the range of variance due to spatial dependence in the data.

Simple kriging (Punctual kriging): This is an interpolation technique which uses the spatial autocorrelation of the data to estimate the phenomenon studied at unknown locations.

Spline interpolation: This is the interpolation of a smooth curve such as a topographic contour by fitting simple curves represented by mathematical formulas to portions of the overall curve in a manner providing smooth transition between adjoining sections.

Stationarity: A regionalized variable is stationary if the

statistics on the random variables $z(x_i + h)$ are the same for every vector h. According to the number k of statistical moments that are constant, the variable is called stationary of order k.

A random function $z(x)$, $x \in A$ is stationary if its multivariate distribution is invariant by translation within the space or area A. Consequently its moments are also invariant by translation.

Second order stationarity / Stationarity of order 2: A random function $z(x_i)$ is stationary of order 2 when:

i) the expected value $\varepsilon\{z(x)_i\}$ is the same all over the field of interest and does not depend on the position x. Mathematically,

$\varepsilon\{z(x_i)\} = m$ for all x_i inside area S.

ii) for each pair of random variables, $\{z(x_i),$

$z(x_i + h)\}$, the covariance function, C(h), exists

and depends on h.

$C(h) = \varepsilon\{z(x_i)\ z(x_i + h)\} - m^2$ for all x_i

inside area S.

Strict stationarity: It is the most restrictive kind of stationarity which assumes no systematic trends or drift over the estimation body. The common geostatistical measure of spatial dependence, the semi-variogram, is robust or tolerant of departures from strict stationarity.

Universal kriging: Universal kriging is a form of interpolation
that takes account of local trends in the data when minimizing the
error associated with estimation. The presence of such trends or
drifts is revealed by structural analysis.

Vector, h: In geostatistics, h is a vector with both distance and
direction. The vector h represents the distance and direction
separating pairs of points.

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