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SOIL NUTRIENT-PLANT NUTRIENT RELATIONSHIPS OF A SHORTGRASS ECOSYSTEM

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ABSTRACT

This study investigates the relationships of soil nutrients and plant nutrients of blue grama and wheat.

Multiple regression and three multivariate techniques were used for comparisons. The three multivariate techniques were discriminant analysis, factor analysis, and canonical correlation.

The multiple regression analyses and factor analyses proved to be the most helpful and informative in this study. The multiple regression related soil nutrients and plant nutrients; and the factor analyses pointed out relationships between two or more plant variables or between two or more soil variables. The discriminant analyses and canonical correlation results were less useful and biologically meaningful.

Relationships indicated for possible further study of blue grama soil nutrients-plant nutrients were the plant variables calcium, potassium, and iron. Soil variables of interest are potassium, soil texture, acidity, nitrate, copper, and sulfate.

Wheat plant variables of interest are calcium, potassium, manganese, copper, nitrogen, phosphorus, and sulfur. Wheat soil variables of importance are pH, electrical conductivity, manganese, sulfate, phosphorus, potassium, organic matter, and soil texture.

The null hypotheses for this study were that there are no relationships between plant nutrient concentrations and soil nutrient concentrations. The null hypotheses, except in the case of potassium, cannot be rejected as a result of the study. This

indicates that modeling plant nutrient concentrations as functions of soil nutrient concentrations would be very difficult and would probably have poor results.

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INTRODUCTION

The shortgrass plains of the United States, estimated at 113,316,000 ha, are larger than any other western vegetation region. About 71% of the area is used for grazing (Stoddart and Smith 1955). Most of the remainder is cultivated and wheat (*Triticum aestivum* L.) is the major crop.

The main objectives of the United States International Biological Program Grassland Biome are to study various states of grassland ecosystems to determine the interrelationships of structure and function, to determine the variability and magnitude of rates of energy flow and nutrient cycling, and to encompass these parameters and variables in an overall systems framework of mathematical models (Van Dyne 1969).

Primary producers are an important trophic level of any ecosystem. The primary producer fixes energy by photosynthesis, which is internally utilized or passed on through other trophic levels. Without mineral nutrients in the growth medium it would be impossible for the primary producers to carry on photosynthesis.

A better understanding of the nutrient medium of primary producers and nutrient contents of primary producers is necessary to interpret the interrelationships of primary producers and other trophic levels. This knowledge will help elucidate the role of primary producers in energy flow and nutrient cycling of an ecosystem. This basic information can then be used as driving or input variables and state variables to the overall systems framework of mathematical models.

The objective of this study was to obtain a better understanding of soil nutrient-plant nutrient relationships of a shortgrass ecosystem and to point out promising areas for modeling efforts. Due to limitations of manpower and finances in any study not all nutrients or species can be studied in detail. In order to investigate the effects of many nutrients, therefore, a "shotgun" approach was used to sample many soil-plant situations and study the interrelationships between soil nutrients and plant nutrients through multivariate analysis techniques. Blue grama (*Bouteloua gracilis* H.B.K. Lag) and wheat were studied as examples of the native and cultivated lands, respectively.

LITERATURE REVIEW

Soil Nutrient-Plant Nutrient Relationships

The problem for ecologists reviewing the literature on nutrients, particularly the micronutrients, is largely that of synthesizing fragmentary and incomplete knowledge gained in different disciplines. These include botany, ecology, agriculture, horticulture, biogeochemistry, geochemical prospecting, and forestry.

Most plant nutrition studies have been developed in agriculture. Even in agriculture little attempt has been made to mathematically express the function of nutrients in relation to growth; consequently any theoretical attempt to apply the "systems analysis approach" to the role of nutrients in a grassland ecosystem is somewhat speculative.

Nutrients essential to plants include the macro elements--carbon (C), hydrogen (H), and oxygen (O); primary elements--nitrogen (N), phosphorus (P), and potassium (K); secondary elements--calcium (Ca), magnesium (Mg), and sulfur (S); and micro elements--iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), and molybdenum (Mo). In addition to these, other elements have been shown to be essential for the normal growth of certain plants. Evidence of their essential requirement for growth in the majority of plants is lacking. These elements include sodium (Na), aluminum (Al), silicon (Si), chlorine (Cl), gallium (Ga), and cobalt (Co). (Devlin 1966, Whitehead 1966).

In terms of mineral nutrients, plant life on land is dependent on (1) the nutrient pool of the soil, (2) the weathering process to replace nutrients that must be lost from the soil by transport in moving water, and (3) inorganic nutrients in precipitation, which become part of the nutrient function of natural and agricultural communities (Whittaker 1970).

In addition to these, the nutrient content of herbage is influenced by several other factors. Among these are differences due to species and variety (Thomas et al. 1952, Fleming 1963, Butler et al. 1962, Vose 1963), maturity (Thomas et al. 1952, Beeson and McDonald 1951), seasonal variation and temperature (Reith et al. 1964, Nielsen and Cunningham 1964), moisture supply (Kilmer et al. 1960), fertilizer application (Price and Moschler 1965, Cook 1965), pasture management (Whitehead 1966), and soil type (Reith and Mitchell 1964, Mitchell 1964).

The response of plants, both in growth and nutrient content, to various levels of soil nutrients under natural conditions are difficult to find in the literature. Numerous references are available with controlled levels of soil nutrients, singly and in many combinations to determine interactions.

Nitrogen

Herbage N contents are usually in the range of 1.5-4.5%. The critical level of nitrate-N for grass is thought to be about 0.14% (Wit et al. 1963).

Dijkshoorn (1969) reports all plants grown with ammonium have lower values for cation:anion balance than when nitrate is the source of N. Rahman et al. (1960) reported that applications of ammonium nitrate markedly increased percentage N in cut ryegrass and that the increase was mainly in the form of non-protein N. Nielsen and

Cunningham (1964) reported that percentage N in Italian ryegrass was increased more by nitrate-N than by ammonium-N. Kurtz et al. (1961) found the N uptake was less from NO_3^- than from NH_4^+ fertilizers, probably due to N losses through leaching and denitrification.

Applications of N decreased the percentage of P and increased the percentage of K in the forage. Applications of N and P_2O_5 were highly effective in increasing the total N, P, K, and Ca removed in the forage (Kapp et al. 1949). Lavin (1967) reported N fertilization increased forage production, P content, crude protein, moisture content, and soil nitrates. Phosphorus and N-P interaction were not significant.

Phosphorus may have no effect on herbage N contents (Reith et al. 1964) or may increase percentage N in grass when N supply is adequate, or decrease percentage N supply is inadequate (Hanway and Moldenhauer 1965). In 1964, Reith et al. found that in the absence of applied N, K had no affect on N content and in the presence of fertilizer N, K application often reduced the N content.

Species differ considerably in their tendency to accumulate nitrate, and the highest quantities generally occur in the pre-flowering period. Nitrate absorption is encouraged when the soil solution is acid, and when P is relatively deficient. Sulfur is involved in the utilization of N, and deficiency of S therefore tends to bring about an increase in nitrate accumulation. Relatively low temperatures and low light intensities also tend to promote nitrate accumulation since these factors reduce utilization to a greater extent than uptake (Whitehead 1966).

Twice as many instances of herbage containing more than 0.07% nitrate-N when calcium nitrate was applied instead of ammonium sulfate was reported by Kershaw (1963). Application of K has been reported by MacLeod (1965) as reducing herbage nitrate content.

Phosphorus

The P content of herbage varies less widely than the contents of most other elements under normal conditions. It is rather unusual to obtain values outside the range 0.1-0.5% P, although very low values can occur in herbage growing on very deficient soils. Grass in the vegetative stage has an adequate P content if the total H_2PO_4 content is greater than 0.22% P (Wit et al. 1963).

Various N P K treatments have been found by Stewart and Holmes (1953) to have no effect on herbage P contents. Reith et al. (1964) agreed that N application had no affect on P content of herbage but other investigations show a depression of herbage P contents by N applications (Mortensen et al. 1964, MacLeod 1965). Dee and Box (1967) found that P fertilization did not increase protein content of herbage. A general trend for KCl applications to reduce percentage P slightly was reported by Reith et al. (1964). Other workers have found no consistent effect of K on herbage P contents (Gardner et al. 1960, Rahman et al. 1960, Koehler et al. 1957).

Potassium

The K content of herbage plants is usually in the range 1-4%, the dominant factor being the available supply in the soil. Wit et al. (1963) considered grasses at the vegetative stage of growth to have a critical K level of 1%, when the cation:anion balance is otherwise correct. MacLeod (1965) considered the optimum K content of 3 grasses grown alone was above 2%. The actual value was influenced by N supply, which would influence the cation:anion balance.

Seay et al. (1949) found a linear relationship between the percentage of K contained in alfalfa and the logarithm of pounds of exchangeable K per acre in the soil. Phosphorus usually has little effect on herbage K content (Reith et al. 1964, Hemingway 1961, Gardner et al. 1960). Stewart and McConaghy (1963) reported that the K content of ryegrass increased with increasing soil acidity.

Calcium

Grass usually has Ca levels in the range of 0.4-1.0%. Wit et al. (1963) reports the critical level of 0.1% for Ca. Trials with nitrochalk by Reith et al. (1964) indicated that its effect on Ca content of herbage was dependent on K supply: when K was adequate to allow a full yield response to N, percentage Ca was reduced; when there was a slight shortage of K, Ca content was little changed; and when the response to N was restricted by lack of K, percentage Ca was increased.

The form in which N is taken up is significant, since Nielsen and Cunningham (1964) showed in pot experiments that the Ca content of Italian ryegrass was greatly increased by nitrate-N but slightly decreased by ammonium-N. The Ca content of grass was reduced with applications of KCl (Gardner et al. 1960). Doll et al. (1963) reported that although rate of liming (to pH 6.2 or 6.6) affected the level of exchangeable Ca in the soil, there was no consistent change in the Ca content of maize (corn) and wheat.

Magnesium

The critical Mg level for grass in the vegetative stage is 0.06% as suggested by Wit et al. (1963). Usually herbage contents are in the range of 0.08-0.30%. Magnesium deficiencies occur most commonly on soils of 3 general types: (1) light sandy soils with low Mg contents, (2) acid soils, and (3) soils with high levels of K. Reith et al. (1964) reported that ammonium sulfate applications increased the Mg content of grass. However, Mortensen et al. (1964) found that ammonium nitrate up to 500 lb. N had no effect on the Mg content of orchard grass. Gardner et al. (1960) reported similar results with grass and grass-clover herbage. Nielsen and Cunningham (1964) found that the Mg level of Italian ryegrass was increased by nitrate-N but not by ammonium-N.

Phosphorus often has no significant effect on Mg content (Reith et al. 1964, Gardner et al. 1960). Potassium application is reported by Reith et al. (1964) and Gardner et al. (1960) to cause an appreciable decrease in herbage Mg. Sodium chloride application reduces herbage Mg content but to a lesser extent than KCl (Hemingway 1961).

Sulfur

Sulfur contents of herbage are usually within the range of 0.20-0.45% (Ensminger 1958). Dijkshoorn and Van Wijk (1967) reported that S- and N- fractions, on a gram atom basis, occur in organic forms in a ratio of about 0.032 and that this is the same as the S:N ratio in the proteins.

Low levels of sulfate-S in plant material may indicate S deficiency and are more easily determined than total-S contents (Whitehead 1966). Dijkshoorn et al. (1960) states that S deficiency is likely to occur in perennial ryegrass when the sulfate-S concentration is below 0.032%.

In mixed pastures, grasses compete more effectively than legumes for sulfur (Walker 1957). In a S-deficient area of New Zealand, Walker et al. (1956) observed that grasses can compete intensively with clovers for sulfate to the point of luxury consumption, and that this is reflected in their inorganic S contents.

No consistent variations in ryegrass S content with ammonium nitrate and potassium sulfate applications were found by Rahman et al. (1960). Jensen (1963) has suggested that when the S in precipitation amounts to more than 10/kg/ha per year, plant deficiencies are unlikely to occur.

Iron

Analysis for Fe content of grass herbage with values of more than 500 ppm suggests contamination and smaller values may include traces of soil (Whitehead 1966). Underwood (1962) reported pasture grasses usually contain 100-200 ppm compared to a range of 50-285 ppm occurring in the grass from Hemingway's (1961) study.

Soil pH is the most important factor governing plant uptake of Fe, deficiency in plants being due to the low availability of insoluble oxides and phosphates, and therefore most likely to occur on calcareous soils (Whitehead 1966). Hemingway (1961) found that N P K fertilizers had no appreciable effects.

Manganese

Herbage Mn contents are usually within the range 25-200 ppm (Whitehead 1966). Plant uptake of Mn is considerably influenced by soil factors, particularly pH and drainage status. Deficiencies are often associated with well-drained calcareous soils in which Mn forms insoluble oxides. Mitchell et al. (1957) found that poorly drained soils increased the Mn content of ryegrass. Manganese toxicity in plants, suggested by a content of more than 1000 ppm, generally occurs on very acid soils, and can often be rectified by liming (Mitchell 1964). Reith and Mitchell (1964) reported liming a soil from pH 5.2 to 6.2 reduced the average Mn content of herbage about one-half.

Stewart and Holmes (1953) found that various N P K applications had no pronounced effect, though N in the presence of P did appear to cause a slight decrease in Mn content. An increase in grass Mn content from applying ammonium sulfate was reported by Hemingway (1961).

Zinc

Grass content of Zn is usually 15-60 ppm. Miller et al. (1964) reported that the Zn content of coastal bermudagrass was increased by levels of N above 400 lbs./A.

Karlsson (1952) reported that heavy applications of P and K had no effect on the Zn content of pasture plants, nor had applications of Mn, Cu, Co, and Mo. However, Thorne (1957) stated that P applications reduced Zn availability to various crops. Reith and Mitchell (1964) and Miller et al. (1964) reported inverse relationships between Zn content of grasses and soil pH.

Copper

Plant species may differ appreciably in Cu content but the extent of the difference is influenced by the available Cu supply. Copper content of herbage is usually within the range of 2-15 ppm. Plant deficiencies are most likely to occur on peat and very sandy soils (Whitehead 1966).

Hemingway (1961) found that ammonium sulfate increased the Cu content of grass. Whitehead (1966) reports that conflicting results have been obtained on the influence of N on herbage Cu contents. Hemingway (1961) reported little, if any, effect on herbage Cu contents but Reith and Mitchell (1964) found that lime sometimes reduced herbage Cu contents.

Boron

Grasses usually contain 1-5 ppm B. Plant deficiency of B occurs most often on acid soils in humid regions, due to leaching, but B can also be made unavailable by excessive liming. Dible and Berger (1952) and Stinson (1953) both reported that B content of alfalfa decreased as soil moisture became limiting.

Molybdenum

Molybdenum contents of herbage vary usually in the range of 0.1-4 ppm. Davies (1956) discusses factors influencing the soil supply of available Mo. pH is particularly important and herbage content can be increased several fold by liming. He also reported that Mo deficiencies are most likely to occur on podsolic soils and calcareous sands, which have low total quantities of Mo, on soils with high Fe contents, and with high anion exchange capacity combined with low pH, where availability is low.

Hemingway (1961) reported ammonium sulfate caused a decrease of about 59% in Mo content, while the effects of superphosphate and potassium chloride were small and irregular. The influence of ammonium sulfate was probably due partly to a pH effect and partly to the sulfate ion which exerts a depressing action on Mo uptake. Phosphate was found, by Davies (1956), to increase Mo uptake.

Cobalt

The usual range of Co in herbage is 0.02-0.3 ppm. Wright and Lawton (1954) found no correlation between plant content and soil content of Co and that varying applications of N P K had no effect on the Co content of timothy. Liming, however, caused a decrease in plant uptake. An inverse relationship has been shown to exist between Co content of herbage and soil pH (Mokragnatz and Filipovic 1961).

Soil Acidity

Deficiencies of Ca, Mg, and K occur most commonly on soils with low cation exchange capacities, which are often acid. However, herbage contents of Mg and K are often higher on acid than on calcareous soils, probably due to less competition by Ca. Magnesium deficiency may be induced or accentuated by high levels of K.

Deficiencies and excesses of trace elements are closely related to soil type. The total content of the elements are important, although factors such as pH and waterlogging can effect plant uptake.

Low pH tends to increase the availability of the metallic trace elements and of B, and to decrease the availability of Mo. Mitchell (1963) found that liming a sandy soil from pH 5.6 to pH 7.0 may reduce the Mn and Co content of herbage by almost half. Stewart and McConaghy (1963) reported no significant effect of pH on the herbage contents of Zn and Cu. That Mo content of herbage may be increased 2-3 times by one application of lime to an acid soil was reported by Reith and Mitchell (1964).

General

With elements other than N, P, K, and Fe deficiencies are most likely to occur where total soil supplies are low; and in marginal situations, deficiencies become more likely as intensity of management is increased, the inducing of higher yields of herbage accelerates the depletion of soil reserves.

Table 1 was prepared to summarize the relationships of soil nutrients and variables to plant nutrients reviewed in the literature.

Statistical Methods

Four types of statistical comparisons were to be made with the data collected for this experiment. These were discriminant analysis, principal component analysis or factor analysis, multiple

Table 1. A summary of the relationships of soil nutrients to plant nutrients and literature citations.

Soil	Plant N	Plant P	Plant K	Plant Ca	Plant Mg	Plant S	Plant Fe	Plant Mn	Plant Zn	Plant Cu	Plant B	Plant Mo	Plant Co
N	+(69)[1/] NO_3 +(64) NH_4 +-(64) NO_3 +-(52) NH_4 +(52) +(53)(46)	-(46)(63)(57) +(53)(46) 0(81)(70)	+(46) 0(70)(34)(30)	NO_3 +(64) NH_4 -(64) +(46)	0(63)(64) +(64)	0(69)	0(35)	0(81) -(81) +(35)	+(56)	+(35) +(94) -(94)		-(35)	0(97)
P	0(70) + if N OK(70) - if N low(70) 0(13)	0(81)	0(70)(34)(30)		0(70)(30)		0(35)	0(81)	0(47) -(86)			0(35) +(12)	0(97)
K	N -(70)(57) 0(70)	0(81) -(70)	+(75)	-(70)(30) 0(70)	-(70)(30)	0(69)	0(35)	0(81)	0(47)			0(35)	0(97)
S	+(94)				+(70)								
Fe												-(12)	
Mn									0(47)				
Cu									0(47)	+(94)			
Na					-(34)								
Mo									0(47)				
Co									0(47)				
pH	+(94)		-(82)	6.2 to 6.6 0(47)			-(94)	-(59)(70)	-(71)(56)	0(35) -(71)	-(94)	+(12)	-(61)

0 An addition of soil nutrient results in neither increase or decrease of nutrient in plant.
\+ An addition of soil nutrient results in an increase of nutrient in plant.
\- An addition of soil nutrient results in a decrease of nutrient in plant.
+- Both positive and negative results noted.
1/ Numbers in parenthesis refer to the reference number in the Literature Cited.

regression, and canonical correlation. Each of these techniques, except multiple regression, is a multivariate technique for elucidating, interpreting, and comparing large sets of data. The multiple regression model is multivariable, not multivariant. A multivariable model is one which expresses a relationship of 2 or more "independent" variables and one "dependent" variable. The error term associated with the "dependent" variable is assumed to be normally distributed, with a mean of zero, and with a common variance. A multivariate model is one which has 2 or more "dependent" variables. It may have "independent" variables in addition. The error terms associated with each "dependent" variable is assumed to be normally distributed and with a mean of zero.

Finney (1956) stated that basic measurements or derived quantities could be used as variates in various multivariate statistical techniques. He also was very specific that variates be defined only by someone familiar with the purpose of the experiment and not deduced purely from statistical analysis of the numerical values of the basic measurements.

The discussions on the various procedures are not intended to develop the ideas in a mathematical sense, thus equations are not specifically included. The objective, rather, is to briefly describe and compare the usage of the methods in ecological studies. For a more detailed description and definitions the reader is referred to Kendall (1968) and Seal (1964).

Discriminant Analysis

Discriminant functions are used in sorting a collection of objects into classes on the basis of several standard measurements on each object. Suppose that we can measure variates $x_1, \ldots, x_p$ on an object and know that it belongs to one or the other of 2 populations in which these variates are normally distributed. A rule for assigning a measured object to one or the other of these populations is needed. Such a rule amounts to partitioning the p-dimensional space in which $x_1, \ldots, x_p$ are coordinates into 2 decision sets, mutually exclusive and exhaustive, and assigning to 1 population all objects whose coordinates fall into one of the sets and assigning the other objects to the other population.

As the discriminant function exceeds or falls short of some fixed value an individual is assigned to one class or the other. This is a more efficient method of classification than any other (Hotelling 1964).

Sinha and van Bronswijk (1970), working with Canadian and Japanese populations of the long-haired mite, determined that when several morphometric characters can be combined into a single discriminant function, differences between 2 species can be more accurately determined than by considering individual characters separately.

Jameson et al. (1970) used discriminant analysis to show the probability of a transect falling within groups which were previously described by experienced range examiners. They found such an approach requires less field time and was more satisfactory than range condition scorecards.

Factor and Principal Component Analysis

Seal (1968) reported principal component analysis (PCA) is intended to achieve a parsimonious summarization of a random sample from a single universe of multivariate normal measurements in contrast to factor analysis which implies an attempt to elicit the underlying normal multivariate structure of a universe that can be sampled with respect to many correlated variates.

Ferguson (1954) said, "In a factor problem one is concerned about how to account for the observed correlations among all variables in terms of the smallest number of factors and with the smallest possible residual error." He defined parsimony in terms of the number of factors required to account for the observed correlations. The most parmimonious solution had the smallest number of factors.

The results of the PCA is to produce a linearly transformed set of variates, called "principal components," which are mutually independent. Seal (1964) suggests that it is doubtful whether a PCA should be applied to x-variates measuring different entities, e.g., a combination of lengths, weights, and 'pseudo-variates.'

Conclusions drawn by Seal (1964) about PCA are:

(i) A PCA should not be based on variables measured on different scales. Completely different types of results are obtained when the units are changed or when the variates are standardized.

(ii) The first eigenvalue usually accounts for a considerable proportion of the total variability.

(iii) The variance-covariance matrix provides a simpler summarization than the correlation matrix.... It is reasonable to suppose that with such a single scale the use of direct measurements (rather than their standardized equivalents) is biologically more meaningful.

(iv) When most of the covariances are positive the first eigenvector will generally have only positive components and will thus be an indicator of general 'size.' This suggests that the biologist will require at least two eigenvectors--which, it will be remembered, are uncorrelated--to summarize his data.

(v) If the off-diagonal elements of a correlation matrix are approximately equal the interpretive value of a PCA of this matrix is dubious.

Factor analysis has been described by Seal (1964) as "a statistical technique for reducing a large number of correlated variables to terms of a small number of uncorrelated variables. The correlated variables consist usually of measurements for observable traits; the uncorrelated variables (called "factors") are abstract hypothetical components."

Factor analysis and principal component analysis are very much alike. Seal (1964) distinguishes factor analysis from principal component analysis by two characteristics of factor analysis:

(i) Each of the p original variates is supposedly analyzable into $m<p$ mutually uncorrelated "common factors" with an uncorrelated residual ('unique') component which is not correlated with any of the remaining p-1 variates.

(ii) The m orthogonal axes of "common factors" may be rotated to new orthogonal or oblique axes to conform with theoretical ideas underlying the formulation of the model.

Lawley and Maxwell (1963) emphasize another difference--"that whereas a principal component analysis is variance-orientated a factor analysis is covariance-orientated." Principal component analysis is concerned primarily with the distribution of the individuals in relation to the axes of greatest variance in the data; factor analysis is concerned with exploring patterns of relationships among the variables.

Kendall (1968) stated that in component analysis we begin with the observations and look for components in the hope we may be able to reduce the dimensions of variation and also that our components may be given a physical meaning. In factor analysis we work the other way around; we begin with a model and determine whether it agrees with the data and, if so, estimate its parameters.

Psychologists have used factor analysis of a series of p carefully chosen tests to "extract" the hidden "factors of the mind" that are exercised in answering test questions (Guilford 1968). Seal (1964) is of the opinion that no such claim can be made when factor analysis is applied to biological data.

Austin (1968) stated that the variable contributing the greatest variance will determine the principal axis, which may or may not be ecologically meaningful. This effect may be avoided by using the correlation matrix, where the variables are standardized to zero mean and unit variance.

Morrison (1967) suggested that the number of components, in PCA, be computed until some arbitrarily large proportion (perhaps 75% or more) of the variances had been explained. His experience also was that if that proportion cannot be explained by the first 4 or 5 components, it is fruitless to persist in extracting more vectors. Even if the later characteristic roots are sufficiently distinct to allow easy computation of the components, the interpretation of the components may be difficult if not impossible.

At present, significance tests for principal component analyses are only available for data which are strictly multivariate normal in their distribution. In view of this, vegetation and vegetational parameters considered in principal component analysis and factor analysis should probably be considered as a means of simplifying these in such a way that the construction of hypothesis regarding the causal environmental factors is correspondingly simplified, and nothing more (Austin 1968).

Ivimey-Cook and Proctor (1967) compared principal component analysis and rotated solutions (factor analysis) of floristic lists from 94 quadrats. Their conclusion was that the PCA of the correlation matrix reflected respectively abundance (or ecological amplitude), soil moisture, and base status; the fourth and fifth components could not be simply interpreted. A rotated solution for 5 factors gave 5 axes readily interpretable in ecological terms, corresponding to 5 recognizable vegetation types. The rotated solution appeared to be more informative of floristic relationships within the data than the principal component solution.

Norris (1971) reported that mapping by a set of properties would give the required soil units for a soil survey undertaken to delineate units with a limited and defined range of soil variation. He found good visual groupings of principal component scores. Student's T-test and analysis of variance supported these visual impressions. The first 3 components of each set of data extracted about the same amount of variance (57 to 59%), suggesting similar degrees of variability. His conclusion was that his data supported the assumption that the variation of soil can be characterized by the variation of relatively few soil properties.

Ferrari, Pijl, and Venekamp (1957) hypothesized a possible use of factor analysis. In regression analysis one is often faced with the difficulty of having to make a choice from among a large number of independent factors. It is often impossible to make a choice on theoretical grounds only. A choice must be made as it is impossible to include every factor in the regression analysis. If the variables are properly selected, by studying the result of a factor analysis it is possible to make a fairly justified choice of the independent factors which can be included in the subsequent regression analysis.

Holland (1968) used PCA to investigate the relationships of 2 sets of plant analysis data. He reported it was possible to form a set of mutually-independent derived variables which may validly be used in regression studies, or analyzed separately for the assessment of treatment effects. The magnitude of the problem is thus reduced and a considerable body of data is effectively summarized. The functions defining these new variates provided a basis for inference concerning the nature of the interrelationships between the concentrations of different elements in plant tissues. He emphasized that by virtue of the empirical nature of the approach, any such inferences must be speculative and will require further justification by direct experimentation.

Principal component analysis, in Holland's examples, provided a valid and informative approach to the interpretation of the chemical composition of leaves and other tissues. This was done in a

completely objective manner, free of any restrictions concerning the number of elements which might be examined simultaneously.

Goodall (1954) was of the opinion that at most 5 orthogonal "factors" could represent the plant distributions for classification of vegetation.

Van Bronswijk and Sinha (1971) in a study of insect populations in stored-grain ecosystems considered principal component loadings greater than 0.20 significant; this seemed to be a rather arbitrary figure. In their analysis, the first 5 principal components explained 96.7% of the variability; the first component accounted for nearly 58% of the variability.

Multiple Regression

Steel and Torrie (1960) said that when interest is primarily in estimation or prediction of values of one character from knowledge of several other characters, multiple regression and correlation give the combined effect of several variables on the one of primary concern.

Draper and Smith (1966) discuss the theory and techniques of regression analysis. Regression analysis is essentially one of developing a mathematical model involving one or more "independent" variables to account for much of the variability in a "dependent" variable.

A common use of this technique is to predict a "dependent" variable from several "independent" variables. Another use has been to determine how strong relationships are between "dependent" and "independent" variables.

"Independent" will be used in this paper to denote variables used in predicting "dependent" variables. "Independent" variables are soil variables and "dependent" variables are plant variables.

Linear regression analysis assumes straight line relationships in which the effects of "independent" variables are additive. Great care must be taken that relationships found by regression analysis are not inferred to be cause and effect relationships, based on the statistical analyses alone.

Watt (1968) criticized linear regression in general for not working well with biological data since they account for only additive effects. These procedures are relatively simple and useful if interpreted correctly, however.

Least-squares analysis is most often used to determine values for the coefficients of a linear regression model. This technique minimizes the sum of squared differences between measured and predicted values of the "dependent" variable.

The correlation coefficient (R) may be computed to determine how well the computed regression fits the data used to develop it. The coefficient of determination (R^2) may also be used. The coefficient of determination multiplied by 100 also tells the percent variation of the data explained by the model.

Several methods of determining regression equations are available. Among these are the forward selection procedure, the backward elimination procedure, the stepwise procedure, and all possible regressions procedure. Draper and Smith (1966) discuss these procedures thoroughly.

They recommended the stepwise procedure as the best method of regression analysis. According to others, however, this may not be completely true because there are advantages and disadvantages in the use of each method. Baker (1968) discusses some of these advantages and disadvantages.

A frequent mistake made is assuming that because a factor isn't important in a regression model it isn't important in the relationship the model is used to approximate or the response it is used to predict. If the sampling procedure doesn't include a wide range of values for a factor, that factor may or may not be included in the regression model. Important factors also may not be included in a regression model because they are weakly correlated with the "dependent" response when taken singly, but when taken together their interaction may be very important in explaining the response.

The most common fault in interpreting regression analysis is in assuming cause and effect relationships between "independent" and "dependent" variables. The technique may, however, be used as a guide to further research of cause and effect relationships.

Canonical Correlation

Canonical correlation analysis offers a more realistic means than those of simple correlation and multiple regression analysis in revealing complex interrelationships in a natural ecosystem. This analysis, instead of using one criterion at a time, assesses the maximum correlation between linear functions of a set of criterion variables (y's) and a composite set of predictor variables (x's).

Kendall (1968) stated one might perform a component analysis on both y's and x's and then investigate the relationships of the transformed variables. In canonical analysis the x's and y's are transformed to new variables which are orthogonal (independent) but not so as to maximize the variance. Instead the covariances (or correlations) are maximized between certain members of the two sets while reducing the others to zero. The canonical correlation algorithm defines the values of the coefficients such that the correlation between the two linear functions is a maximum. Thus the relationships between the two groups is reduced to its simplest form.

Seal (1964) discussed canonical analysis as developed by Bartlett (1938). An advantage he mentioned was that the p-variates may be different types of measurements (e.g., one a length, another a volume, a third a score, and etc.). He also suggests that the number of dimensions required for a comparison of groups of p-variate observations will be less than that required for the summarization of any one of the groups by principal component analysis.

Francis and Campion (1971) give an unusually clear, concise description of canonical correlation analysis with an example comparing abiotic (soil water, average precipitation, and average air temperature) and biotic factors (biomass of seven plant functional groups).

METHODS AND MATERIALS

Description of Study Site

The study area is located in Weld County, Colorado. Blue grama samples were collected on Central Plains Experimental Range (CPER), Pawnee Site, US-IBP Grassland Biome.[1/] The sampled plots were in Township 10 N., Ranges 65 and 66 W. The wheat samples were collected four miles west of Pierce, Colorado in Township 8 N., Ranges 66 and 67 W.[2/] All samples for both blue grama and wheat were collected on sandy loam soils of the Ascalon series. Soil profiles were examined and mapped by James Crabb and the soil survey staff of the U.S. Department of Agriculture Soil Conservation Service (SCS). A description of the Ascalon series typical profile is given in Appendix A.

The long time average annual precipitation on the CPER is 310 mm (Bertolin and Rasmussen 1969). About 80% of the precipitation occurs during the summer months of May through September. Most of the storms during this period are light thundershowers, but the greatest fluctuations are caused by storms greater than 25 mm. Thirty year mean monthly precipitation is shown in Fig. 1 (Bartos 1971).

Mean maximum and minimum monthly temperatures are given in Fig. 2 (Jameson and Bement 1969).

1/ The Pawnee Site is located on the Central Plains Experimental Range (Agricultural Research Service, USDA) and adjacent areas of the Pawnee National Grassland (Forest Service, USDA).

2/ Wheat was sampled on private lands. Thanks go to the close cooperation of the operators of farms sampled.

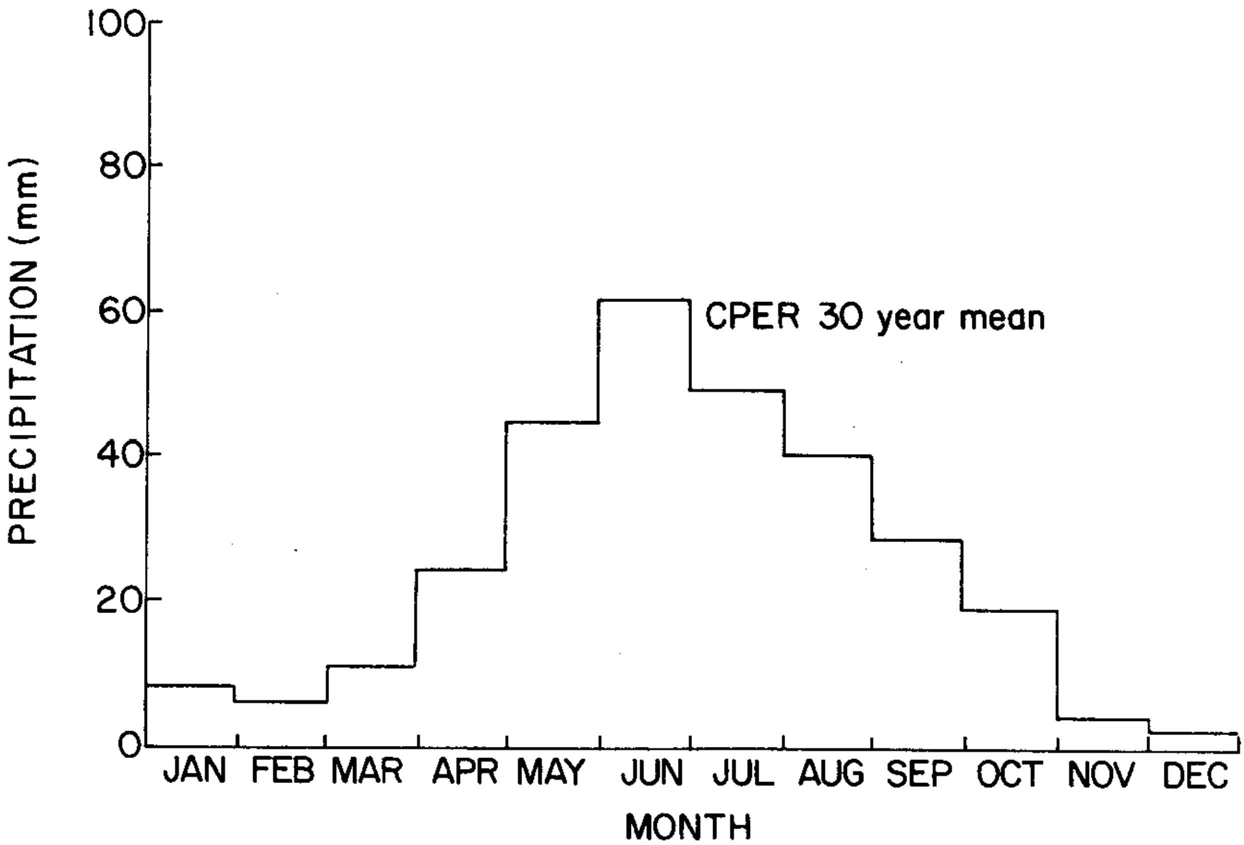

Fig. 1. 30 year mean monthly precipitation at Central Plains Experimental Range (CPER).

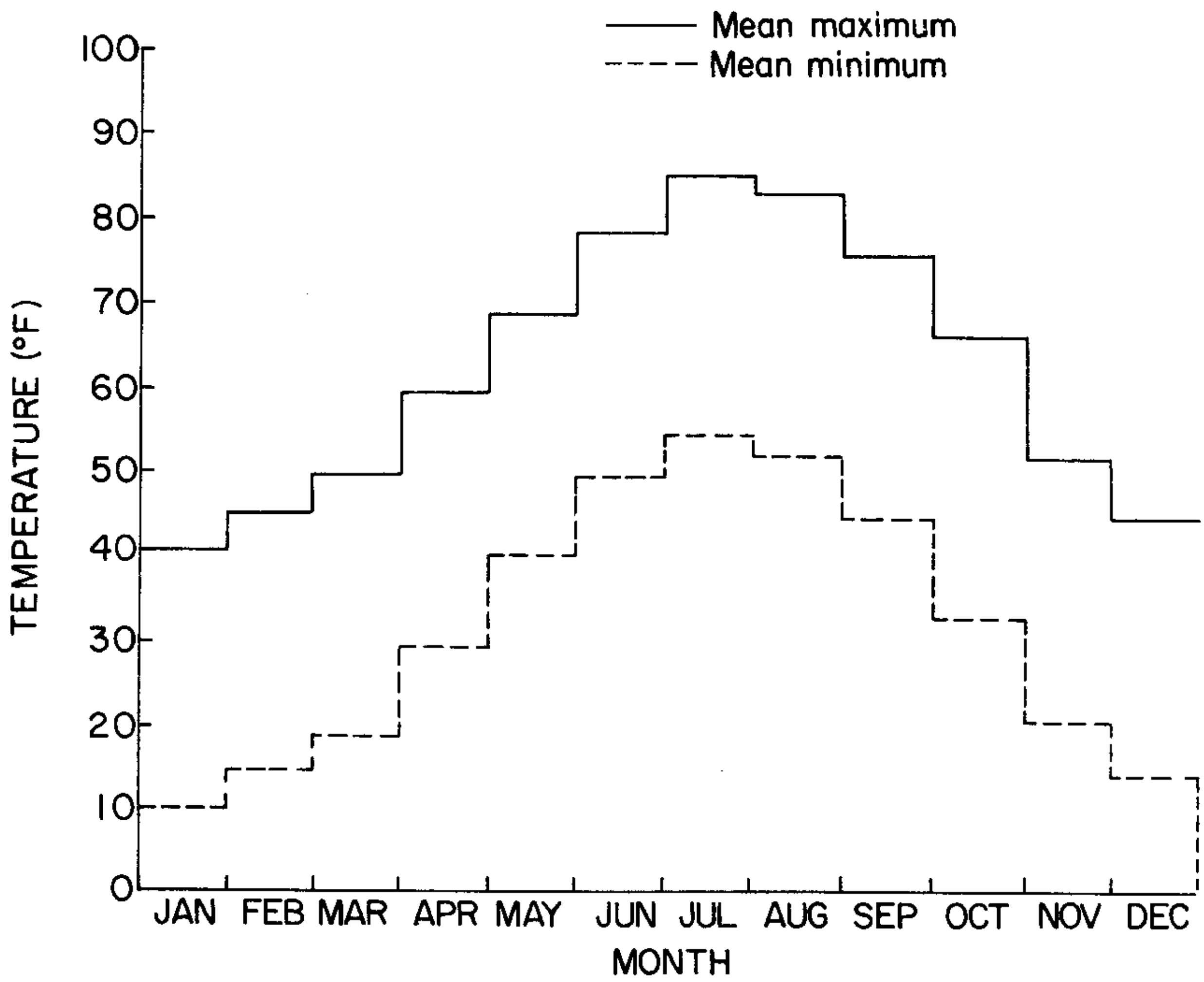

Fig. 2. Mean maximum and minimum monthly temperature for Central Plains Experimental Range (CPER).

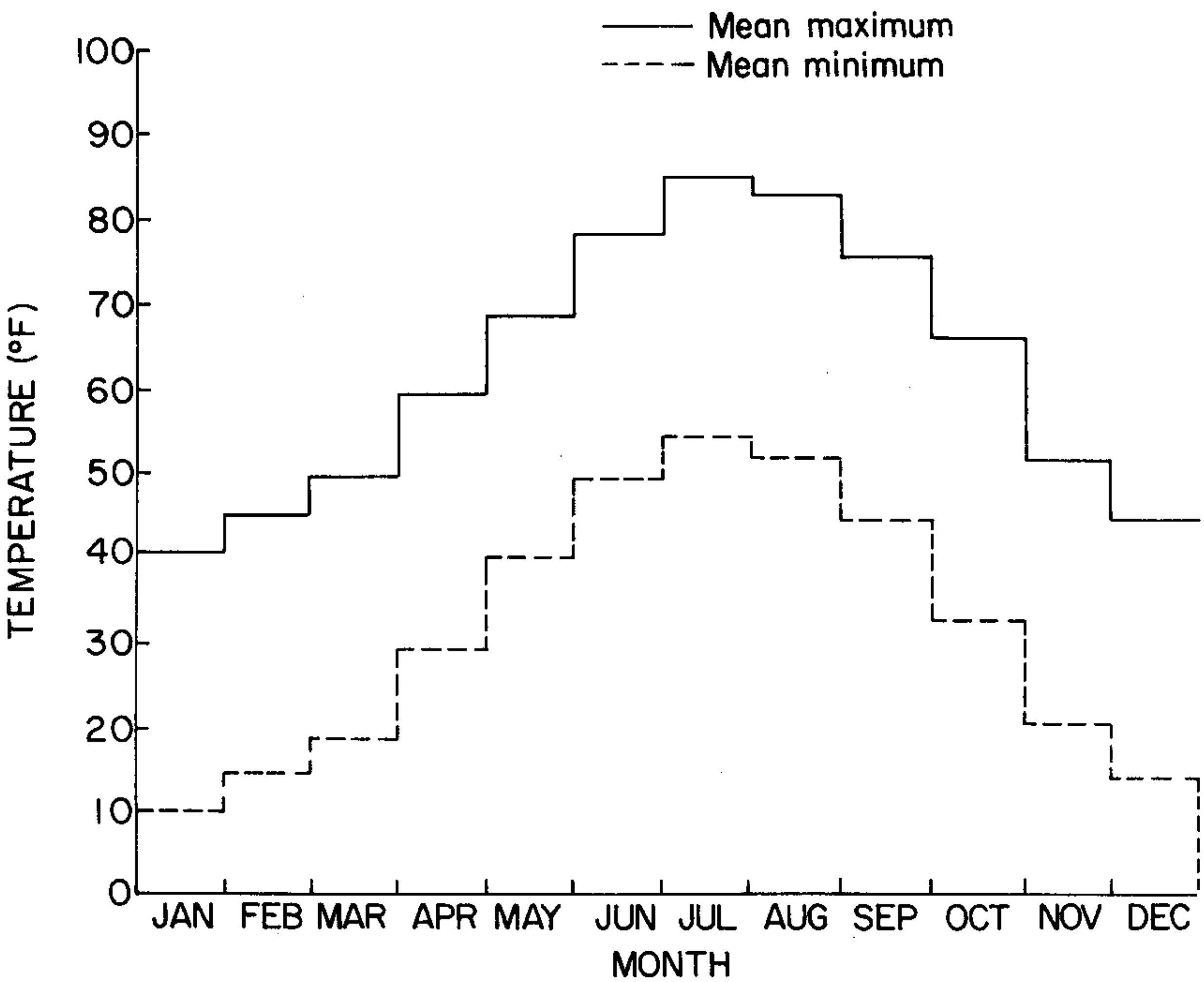

Fig. 2. Mean maximum and minimum monthly temperature for Central Plains Experimental Range (CPER).

The native shortgrass plains vegetation is basically blue grama and buffalograss (*Buchloe dactyloides*), supplemented in many areas by threadleaf (*Carex filifolia*) and needleleaf sedges (*Carex eleocharis*).

The Ascalon series has a rather uniform vegetation cover. Major grasses are blue grama, buffalograss, red threeawn (*Aristida longiseta*), and western wheatgrass (*Agropyron smithii*). Sun sedge (*Carex heliophila*) is the major grass-like plant. Forbs that are prominent on the Ascalon series are scarlet gaura (*Gaura coccinea*), evening-primrose (*Oenthera coronopifolia*), scarlet globemallow (*Sphaeralcea coccinea*), and slimflower scurfpea (*Psoralea tenuiflora*). Major shrubs or shrub-like species include fringed sagewort (*Artemisia frigida*), broom snakeweed (*Gutierrizia sarothrae*), and plains pricklypear (*Opuntia polycantha*). A complete plant list is given by Dickinson and Baker (1972).

A more complete description of the Pawnee Site is given in Jameson and Bement (1969). They include, in addition to topics discussed here, mammals, birds, and insects.

Field Sampling and Sample Preparation

In order to minimize variation in soil characteristics other than chemical characteristics all soil samples were collected on Ascalon soils. The area 6.4 km west of Pierce was the closest wheat area to the CPER that had been mapped by the Soil Conservation Service (SCS) Soil Survey Staff. The wheat samples were collected in this area. The blue grama samples were collected on the CPER.

Soil Survey maps were obtained from the SCS for the area west of Pierce and the CPER. Sampling sites were chosen by plotting on maps within the Ascalon soil series. The blue grama sites sampled were sometimes adjusted in the field to obtain as pure a stand of blue grama as possible within the immediate area of the site chosen on the map.

Paired soil and plant samples were collected for blue grama and wheat. Each pair of soil and plant samples were collected at the same time.

Each soil sample was a composite of 5 soil cores (7.5 cm x 10 cm). The cores were sieved through 32-mesh Tyler screens and the included roots separated out. The soil was air-dried and then thoroughly mixed and stored in paper cartons until chemical analyses were completed.

The wheat plant samples were collected between June 27, 1970 and July 3, 1970 when the grain was in soft to medium hard dough. They were clipped at ground level and put into paper bags for 1 to 3 hours. Then they were quickly rinsed two times in deionized water, oven dried at 50°C, and ground in a Wiley mill with a 40-mesh stainless steel screen.

The blue grama plant samples were collected between July 27, 1970 and August 7, 1970. They were clipped at ground level, placed in plastic bags and frozen until they could be hand separated. The separation consisted of removing all dead material and all species other than blue grama. The samples were then quickly rinsed 2 times in deionized water, oven dried at 50°C, and ground in a Wiley mill with a 40-mesh stainless steel screen.

The washing procedure used for plant samples was to remove dust, soil particles, and other foreign materials. Washing had the potential of leaching, hence was kept to a minimum. Also to prevent contamination of samples from dirty wash water the water was changed after every 2 or 3 samples.

Chemical Analysis

Both blue grama and wheat soil samples were analyzed by the Colorado State University Soil Testing Laboratory for 16 variables. These were pH, electrical conductivity (Cond), lime, organic matter (OM), P, K, nitrate (NO_3), Zn, Fe, Cu, Mn, percent sand, percent silt, percent clay, sulfate (SO_4), and cation exchange capacity (CEC).

The blue grama and wheat plant samples were analyzed for Ca, Mg, K, Na, Zn, Mn, Fe, Cu, N, P, and total S. Plant analyses were done by the Range Forage Analysis Laboratory of Colorado State University except for total plant sulfur which was done by the Soil Testing Laboratory. Abbreviations and symbols for soil and plant variables throughout this paper are given in Appendix B.

The soil pH determinations were made on a saturated soil paste of each sample. Using the same saturated soil paste a saturation extract was obtained and electrical conductivity in millimhos per centimeter was ascertained (Richards 1954 and Hergert 1971a).

The soil lime test used was merely a rough quantitative test consisting of adding 0.4 N. sulfuric acid to a small sample of dry soil. The degree of effervescence indicates high, medium, or low lime content (Hergert 1971a).

Soil OM determinations were made by a chromic acid oxidation of the organic carbon in the presence of concentrated sulfuric acid (H_2SO_4), centrifuging after settling 1 hour, and then reading colorimetric absorption on a Spectronic 20 at 610 mu adjusted to 100% transmission with distilled water (Hergert 1971a and Schmehl 1971).

The Na bicarbonate extraction method was used for determining available soil phosphorus. Following extraction a blue color is developed by the reduction of an ammonium phosphomolybdate complex by ascorbic acid in the presence of antimony. The color produced is stable for 24 hours. The color intensity is read at 880 mu (Hergert 1971a and Olsen et al. 1954).

Ammonium acetate extraction was the method used for determining available soil potassium. After extraction the samples were filtered and the extract read on the flame photometer (Hergert 1971a and Pratt 1965).

Soil NO_3^- determinations were made by extracting with a $CuSO_4$ solution and determining NO_3^- after removal of Cl^- with $AgSO_4$. The colorimetric determinations are read at 430 mu (Hergert 1971a and Jackson 1958).

Determination of available soil Zn and Fe was made by the diethylenetriamine pentaacetic acid (DTPA) procedure of Lindsay and Norvell (1969). Available soil Cu and Mn determinations were made on the same extracts as the above procedures for Zn and Fe. The extracts were then read by atomic absorption spectrophotometry.

The percent sand, silt, and clay was estimated using the "feel" method on moistened samples (Buckman and Brady 1969).

Sulfate, S, in the soil samples was ascertained by a procedure similar to Bardsley and Lancaster's (1965) method of acetate-soluble sulfate. Hergert (1970) used $Ca(H_2PO_4)_2$ extracting solution rather than the ammonium acetate ($NH_4C_2H_3O_2$) of Bardsley and Lancaster (1965). Colorimetric readings were made at 420 mu.

Cation exchange capacity was determined by the sodium acetate method (Hergert 1971a and Richards 1954).

The soil samples were not analyzed for calcium and magnesium because the techniques are expensive, time consuming, and not very accurate. In calcareous soils the results are also of questionable value. Available calcium plus available magnesium should be a fair approximation of cation exchange capacity.

The digestion procedure used by the Range Forage Analysis Laboratory for plant samples was with a nitric acid (HNO_3)-hydrochloric acid (HCl) mixture. One gram of sample was weighed into a 125 or 250 ml Erlenmeyer flask. Approximately 10 ml of a 15:1 (v/v) HNO_3:HCl was added making sure that all of the sample was moistened. Digestion was at 80-100°C until oxidation to a pale yellow solution, maintaining approximately 10 ml of digestion mixture.

The digestion solution was then analyzed by atomic absorption spectrophotometry and flame photometry, making necessary dilutions. Calcium, Mg, Zn, Mn, Fe, Cu, P, and Co were determined by atomic absorption. Flame photometry was used to determine K (763 mu) and Na (590 mu).

A semi-micro Kjeldahl method was used to ascertain total plant N. Crude protein can be calculated from total plant N by multiplying total plant N by 6.25.

Sulfur analysis of plant samples was done by the Colorado State University Soil Testing Laboratory (Hergert 1970). Total plant sulfur was analyzed by using the magnesium nitrate ($Mg(NO_3)_2$) method. Plant material was wetted thoroughly with $Mg(NO_3)_2$, heated to 150°C and left for 2-3 hours. The sample was cooled and placed in a sand bath, then in muffle oven at 500°C for 2 hours until white ash was produced. The sample was cooled in the muffle oven and 0.6 N. HCl added while still warm. An aliquot was taken and SO_4-S seed solution (K_2SO_4 in distilled water for a 200 ppm SO_4-S solution) added. Barium chloride was added, filtered, and sulfur content of filtrate by colorimetry at 420 mu was determined.

Statistical Analysis

This study included the use of 3 multivariate statistical techniques and multiple regression. The 3 multivariate techniques were discriminant analysis, principal component or factor analysis, and canonical correlation. The aim was to examine and elucidate as thoroughly as possible the relationship of soil nutrients on plant nutrients.

Stepwise Discriminant Analysis BMD07M (Dixon 1970a) was used for the discriminant analysis computations. The two groups (blue grama and wheat) of data with soil variables and then plant variables were used as input data. Output consists of group means and standard deviations, within group covariance matrix, and within group correlation matrix. At each step variables included and F to remove, variables not included and F to enter, U statistic and approximate F statistic to test equality of group means, and matrix of F statistics to test the equality of means between each pair of groups are printed. At certain specified steps, and after the last step, discriminant functions and the classification matrix are given. A summary table for each step includes variable entered or removed, F value to enter or remove, number of variables included, and the U statistic. Eigenvalues, canonical variables and coefficients of canonical variables are also printed. A plot of the first canonical variable against the second is obtained. Residuals and canonical coefficients are optional output.

Multiple regression analyses considering sixteen soil variables, "independent" variables, and 11 plant variables, "dependent" variables, would have been quite lengthy. All possible regressions involving one or more "independent" variables and each plant variable would have resulted in $11(2^k-1)$ comparisons, where 11 is the number of plant variables and k is the number of soil variables being considered. A stepwise multiple regression approach would have resulted in 11(k) or 176 comparisons if all soil variables were included. The available stepwise regression programs would result in a tremendous amount of output with this approach.

Factor analysis was used in an effort to meaningfully group the nonindependent variables resulting in a more parsimonious independent set of variables and to reduce the number of soil variables included in the multiple regression analyses. Both soil variables and plant variables for blue grama and wheat were examined by factor analysis.

By using factor analysis as a means of screening and reducing the number of soil variables, the number of comparisons to be made by multiple regression is reduced several fold. The program used was BMDX72 Factor Analysis from Dixon (1970b). Output from this program includes means and standard deviations, correlation or covariance matrix, eigenvalues and cumulative proportion of total variance, communalities, factor loading matrix before rotation, factor loading matrix, correlation matrix of the rotated factors, and factor scores.

Stepwise regression was chosen as the multiple regression technique to be used. The results of the factor analysis were used to reduce and select the independent variables. The soil variable in each factor most highly correlated (from the correlation matrix) to the plant variable being used as the dependent variable was selected as one of the independent variables. Program STAT38R from the Colorado State University Statistical Laboratory (Anonymous 1971) was used. The optional output of this program prior to performing the regression includes means, standard deviations, covariance matrix, correlation matrix, and variable plots. At each step output includes multiple R, standard error of estimate, and analysis-of-variance table. For variables in the equation the regression coefficient, standard error and F to remove are included. For variables not in the equation; tolerance, partial correlation coefficient, and F to enter are included. Optional output after performing the regression include list of residuals, list of the unit normal deviate form of the residuals, plots of residuals vs. input variables, plots of the unit normal deviate form of the residual vs. input variables, full normal plot of the unit normal deviate form of the residuals.

Biomedical computer program BMDX75 Canonical Analysis (Dixon 1970a) was used for the canonical correlation computations. The input data consisted of the two complete sets of data for soil variables and plant variables of blue grama and wheat. Output of this program includes means and standard deviations, canonical correlations, canonical coefficients, canonical variables evaluated for each case, and original data.

RESULTS AND DISCUSSION

Soil Samples

The results of the laboratory soil analyses are given in Appendix C. Table 2 lists the soil variables, mean, standard deviation, and coefficient of variation for each soil variable of blue grama and wheat samples. The blue grama soil samples had higher mean values for organic matter, phosphorus, nitrate, zinc, iron, copper, manganese, sand, and silt than did the wheat soil samples. The difference in nitrate content of the blue grama and wheat soils was very small. Wheat had the larger mean values for pH, conductivity, lime, potassium, clay, sulfate, and cation exchange capacity.

These results are about what was expected. Due to the mining of the heavier textured, more calcareous B horizon during tillage the wheat soil samples were expected to have higher lime contents, clay, and cation exchange capacity and less organic matter than the blue grama soil samples. Usually there are more available nutrients in the A horizon. The blue grama soil samples had higher mean values of available nutrients than the wheat soil samples except in the cases of potassium and sulfate. This is due to the blue grama soil samples being largely A horizon, whereas, the wheat soil samples were mixed A and B horizon due to tillage and erosion loss of the A horizon. Some of this could also be due to simply geographical variation, as the sites were quite widely separated. The distance between the blue grama and wheat sites sampled was 24 to 32 km.

Table 2. List of the soil variables, means, standard deviations, and coefficients of variation for the blue grama and wheat soil samples.

Variable	Mean		St. Dev.1/		C. V. (%)2/	
	BOGR3/	TRAE4/	BOGR	TRAE	BOGR	TRAE
H	6.16	7.49	.45	.438	7.32	5.84
Conductivity (mmhos/cm)	.22	.27	.06	.059	26.8	22.1
Lime	1.0	1.4	0.0	.64	0.0	46.5
Organic Matter (%)	1.35	.88	.40	.24	29.5	27.6
Phosphorus (ppm)	18.1	9.4	6.0	3.9	33.1	41.4
Potassium (ppm)	301	347	70	80	23.4	23.1
Nitrate (ppm)	.59	.54	.86	.44	144	80.6
Zinc (ppm)	.86	.35	.37	.12	42.5	35.1
Iron (ppm)	23.4	6.6	9.4	3.6	40.1	54.4
Copper (ppm)	1.02	.64	.68	.38	65.9	59.9
Manganese (ppm)	14.6	8.6	6.0	4.2	40.8	48.9
Sand (%)	66.5	63.3	6.3	7.2	9.42	11.3
Silt (%)	17.9	16.4	4.2	4.9	23.7	29.6
Clay (%)	15.6	20.3	2.5	3.7	15.8	18.3
Sulfate (ppm)	1.15	5.24	1.06	4.66	92.80	88.9
Cation Exchange Capacity (meq/100 g)	9.2	10.9	2.1	2.3	22.8	20.8

1/ Abbreviation for standard deviation.

2/ Abbreviation for coefficient of variation.

3/ Symbol for blue grama.

4/ Symbol for wheat.

The values of the standard deviations indicated blue grama soil samples to be more variable in pH, organic matter, phosphorus, nitrate, zinc, iron, copper, and manganese than the wheat soil samples. The wheat soil samples were more variable in lime, potassium, sand, silt, clay, sulfate, and cation exchange capacity. The 0.0 standard deviation of lime content of blue grama soil samples is due to the analytical technique being semi-quantitative. The analytical technique resulted in lime contents of low, medium, or high which were then assigned "pseudovariables" of 1, 2, or 3, respectively. All blue grama soil lime content was low.

Coefficients of variations calculated for blue grama soil sample variables ranged from 0.0% for lime to 144.3% for nitrate. Wheat soil sample variables had coefficients of variation ranging from 88.9% for sulfate to 5.84% for pH.

There are two major possible sources of variation in these soil samples. These are (1) the real variability of the variable analyzed for in each sample and (2) the variability inherent in the analytical technique used. The high coefficients of variation of some variables indicate that these two sources of variation are rather high. For those variables with the higher coefficients of variation and rather low levels of variables inventoried in this study, more sensitive techniques of analysis or better control of the sampling conditions may be needed. Variables indicating this possibility are lime, nitrate, zinc, iron, copper, manganese, and sulfate.

Of these variables, better analytical techniques may not help to lower the coefficients of variation for soil nitrate and sulfate, particularly nitrate. These two variables are very temperature and moisture dependent and these sources of variation may be more responsible for the high coefficients of variation than the analytical techniques. The high coefficients of variation for iron may be due to unknown sources of sample contamination.

Plant Samples

Appendix D gives the results of the laboratory analyses of the blue grama and wheat plant samples. Table 3 lists the plant variables, mean, standard deviation, and coefficients of variation for blue grama and wheat samples. Blue grama plant samples had higher contents of calcium, sodium, zinc, iron, nitrogen, phosphorus, and sulfur than did the wheat plant samples. Wheat plant samples had larger concentrations of magnesium, potassium, manganese, and copper.

The standard deviations of blue grama plant sample variables were larger than for wheat plant sample variables for calcium, zinc, iron, copper, and phosphorus. Wheat plant sample variables with higher standard deviations than blue grama samples were magnesium, potassium, sodium, manganese, nitrogen, and sulfur.

The coefficients of variation for blue grama plant sample variables ranged from 112.22% for copper to 12.42% for sulfur. Wheat plant sample variables coefficients of variations ranged from 70.72% for zinc to 22.34% for potassium. The means of the

Table 3. List of plant variables, means, standard deviations, and coefficients of variation for the blue grama and wheat plant samples.

Variable	Mean (%)		St. Dev.1/		C. V. (%)2/	
	BOGR3/	TRAE4/	BOGR	TRAE	BOGR	TRAE
Magnesium	.0611	.0971	.0114	.0528	18.7	54.4
Calcium	.275	.0882	.0453	.0334	16.5	37.9
Potassium	.528	.542	.0905	.123	17.2	22.3
Sodium	.00853	.00630	.00266	.00271	31.0	42.9
Zinc	.00166	.00085	.00161	.000604	97.1	70.7
Manganese	.00201	.00409	.000813	.00110	40.5	26.9
Iron	.0103	.00613	.00797	.00337	77.2	54.9
Copper	.00022	.00031	.000248	.000200	112	65.4
Nitrogen	1.54	1.14	.239	.285	15.5	24.8
Phosphorus	.141	.104	.0327	.0243	23.1	23.4
Sulfur	.138	.115	.0172	.0297	12.4	25.8
					41.057	40.859

1/ Abbreviation for standard deviation.

2/ Abbreviation for coefficient of variation.

3/ Symbol for blue grama.

4/ Symbol for wheat.

coefficients of variation for blue grama and wheat soil sample variables were 41.96% and 40.86%, respectively.

Some of the plant variables, like some of the soil variables, have high coefficients of variation, indicating the possible need for better analytical techniques when such low levels are present. Variables indicated are zinc, iron, and copper. Zinc and copper are particularly low as evidenced by standard deviations as large or larger than the means. The analytical method used for plant zinc is considered a good method and should be satisfactory and sensitive enough for zinc detection. The high variability of the iron analyses results are probably related to contamination of the samples. Copper may really be the only variable of the three in which there may need to be a better analytical method. Other variables for which the coefficient of variation seemed satisfactory for either blue grama or wheat but was poor for the other species occurred. Coefficients of variation for wheat levels of magnesium, calcium, and sodium were high while the coefficients of variation for these variables in blue grama were considerably lower. The coefficient of variation for the manganese content of blue grama was considerably higher than it was for wheat.

The results obtained for phosphorus analysis of the plant materials are questionable because the digestion used was a HNO_3-HCl mixture; perchloric acid digestion would have been more desirable.

The results of calcium and magnesium analysis of plant materials may also be suspect. Atomic absorption for these elements is susceptible to phosphorus interference unless blanketed out by strontium, which was not done for these samples.

The levels of copper found in the plant material was very low and approached the lower limit of the analytical techniques.

Discriminant Analysis

Discriminant analysis was used to determine whether there was a difference in the blue grama and wheat sets of data. Program BMD07M Stepwise Discriminant Analysis, used with both sets of plant data resulted in a complete separation of all samples. It also showed that after two steps there was already a complete discrimination between the two sets. The two variables included in these two steps were plant calcium and plant manganese. The relative magnitudes of importance indicated that plant calcium was about 15 and plant manganese was about 1. The blue grama plant samples had about 3 times more calcium than the wheat plant samples but the wheat samples had about twice as much manganese as the blue grama samples.

The stepwise discriminant analysis for soil variables showed one wheat soil sample to be more like the blue grama samples than like the other wheat soil samples. This discrimination occurred in step number seven, at which time the variables being included in the discrimination were pH, organic matter, potassium, nitrate, zinc, manganese, and silt. Two obvious differences of this sample were in pH and organic matter contents. The pH of this sample was 6.3 compared to a wheat mean pH of 7.49 and a blue grama mean pH of 6.16. The blue grama soil mean organic matter content was 1.35% and wheat mean organic matter content was .88%. The organic matter content of this soil sample was 1.7%.

Factor Analysis

The factor analysis (BMDX72 Factor Analysis) for all variables of blue grama or wheat samples showed that the factors extracted were either a plant factor or a soil factor. In no instance were there plant and soil variables in the same factor.

The factor analysis for blue grama soil samples revealed that 4 factors explained 75.0% of the variation in the data set and included all variables in relatively high loadings (Table 4).

Included in the first factor and accounting for 34.8% of the variability were organic matter, potassium, silt, clay, and cation exchange capacity. This is relatively realistic, as one expects strong positive relationships between organic matter, clay, and cation exchange capacity. Silt is closely related to clay also. The relationship with potassium is also reasonable as one expects the available cations to increase as cation exchange capacity increases.

The second factor incorporated pH, conductivity, phosphorus, iron, and manganese. This factor explained an additional 23% of the variation. This second factor is also reasonable as phosphorus, iron, and manganese availability, particularly iron and manganese availability, is related to pH. Conductivity somewhat clouds the other relationships included in this factor.

Factor three was comprised of nitrate, zinc, and copper and accounted for another 10% of the variation. Nitrogen, zinc, and

Table 4. Results of the factor analysis (the rotated factor matrix) for blue grama soil samples.

Variable	Factor			
	1	2	3	4
pH	.108	.858	-.201	.008
Conductivity	.211	.666	.450	.047
Organic Matter	.894	.002	.095	.128
Phosphorus	-.024	-.654	.556	.038
Potassium	.806	.055	.058	-.273
Nitrate	-.037	-.086	.709	-.135
Zinc	.271	-.173	.766	-.028
Iron	.030	-.696	.570	.160
Copper	.195	-.140	.773	.071
Manganese	.476	-.741	.256	-.126
Silt	.724	-.014	.328	.261
Clay	.802	-.102	.170	.053
Sulfate	.110	.013	-.060	.938
Cation Exchange Capacity	.920	.123	-.076	.092

copper have been shown to be related by Miller et al. (1964), Hemingway (1961), and Whitehead (1966).

The fourth and last factor included only sulfate and accounted for another 8% of the variability.

The factor analysis for wheat soil variables (Table 5) included five factors explaining 78% of the variation. Factor one included the variables pH, conductivity, iron, manganese, and sulfate. These variables are much the same variables as were included in factor two of the blue grama soils. Sulfate is included in this factor compared to phosphorus included in the similar blue grama soil factor. There is probably a relationship here because the major available ions of phosphorus and sulfur are the negatively charged divalent anions ($HPO_4^{=}$ and $SO_4^{=}$). This factor included 31% of the variation of the data.

The second factor contained the variables clay and cation exchange capacity and explained an additional 21% of the variability. This factor seems straightforward; as clay content of a soil increases the cation exchange capacity increases.

Lime, phosphorus, potassium, zinc, and copper were included in the third factor and added another 11% of the variation. This factor seems to be unexplainable, with anomalies of the data being expressed. Normally one would expect relationships between lime, phosphorus, zinc, and copper but potassium is not necessarily related to these other variables.

Factor four contained the variables organic matter and silt and accounted for an additional 8% of the variability. Nitrate was

Table 5. Results of the factor analysis (the rotated factor matrix) for wheat soil samples.

Variable	Factor				
	1	2	3	4	5
pH	-.928	-.072	-.131	.066	-.003
Conductivity	-.577	.278	.086	-.526	.050
Lime	-.362	-.315	-.545	-.237	.216
Organic Matter	.043	-.289	.040	-.749	-.233
Phosphorus	.284	.448	.622	.183	-.007
Potassium	.087	.122	.708	-.360	.136
Nitrate	-.130	-.013	-.069	-.088	-.896
Zinc	.196	-.104	.845	-.100	.052
Iron	.917	-.026	.141	-.040	.154
Copper	.060	-.590	.650	.105	.113
Manganese	.857	.007	.341	-.096	.244
Silt	.282	-.498	.063	-.606	.391
Clay	.023	-.910	-.095	-.038	-.064
Sulfate	-.558	-.302	-.402	-.111	.174
Cation Exchange Capacity	-.116	-.863	-.067	-.262	.025

the only variable included in the fifth factor and added 7% to the amount of variability explained.

The blue grama plant variables were factored into 5 factors by the factor analysis (Table 6). These factors included 68% of the data variability. The first factor contained calcium and magnesium and accounted for 18% of the variation. Included in the second factor were zinc and copper which explained an additional 15% of the variability. The variability included in factor three was 12% and consisted of the variables potassium and sodium. Manganese, nitrogen, and phosphorus were in factor four and an additional 12% of the variation was included. The last factor explained 10% of the variability and included iron and sulfur.

The factor analysis of wheat plant variables resulted in four factors (Table 7). These factors included 65% of the variation of the data; or 25%, 14%, 14%, and 12% of the data variability was accounted for by factors one, two, three, and four, respectively. Factor one included magnesium, potassium, and sulfur. Sodium, manganese, and copper were included in factor two. Variables contained in factor three were zinc, nitrogen, and phosphorus and in factor four calcium and iron were included.

Table 8 is a summary of the factor analyses results showing the variables included in each factor and the percent variation explained.

Multiple Regression

Multiple regression was used to investigate the relationships of soil variables and plant variables.

Table 6. Results of the factor analysis (the rotated factor matrix) for blue grama plant samples.

Variable	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
Calcium	-.808	-.125	.137	-.153	.187
Magnesium	-.836	.041	-.167	.119	-.223
Potassium	-.165	-.174	.870	.089	.044
Sodium	.315	.207	.659	.007	-.095
Zinc	.069	.784	-.181	.152	-.048
Manganese	-.334	.131	.207	.760	-.220
Iron	.216	.304	-.041	.045	.760
Copper	-.020	.791	.243	-.083	.104
Nitrogen	-.265	.212	.322	-.329	.017
Phosphorus	.216	.024	-.042	.767	.292
Sulfur	-.288	-.319	.012	.048	.582

Table 7. Results of the factor analysis (the rotated factor matrix) for wheat plant samples.

Variable	Factor			
	1	2	3	4
Calcium	.003	-.238	-.024	.842
Magnesium	.827	-.415	-.157	-.063
Potassium	.634	-.810	-.322	.046
Zinc	.141	.060	.668	-.066
Manganese	.434	-.543	.277	.382
Iron	-.040	.505	.027	.667
Copper	-.089	-.505	-.001	.003
Nitrogen	.269	.166	.781	.254
Phosphorus	.195	.023	-.505	.044
Sulfur	.760	.107	.131	.015

Table 8. Summary of the factor analyses results showing the variables included in each factor and the percent variation explained.

Factor	BOGR Variables	Variation Explained (%)	TRAE Variables	Variation Explained (%)
		Soil Variables		
1	OM, K, Silt, Clay, CEC	34	pH, Cond., Fe, Mn, SO_4	31
2	pH, Cond., P, Fe, Mn	23	Clay, CEC	21
3	NO_3, Zn, Cu	10	Lime, P, K, Zn, Cu	11
4	SO_4	8	OM, Silt	8
5			NO_3	7
		Plant Variables		
1	Ca, Mg	18	Mg, K, S	25
2	Zn, Cu	15	Na, Mn, Cu	14
3	K, Na	15	Zn, N, P	14
4	Mn, N, P	12	Ca, Fe	12
5	Fe, S	10		

Each plant variable was used in a multiple regression analysis as the "dependent" variable. The "independent" variables in each analysis were chosen from the results of the factor analysis. The single variable in each factor most highly correlated, from the simple correlation matrix, to the dependent variable was included as an "independent" variable in the multiple regression analysis.

The "independent" variables were not totally independent in this regression analysis. To achieve total independence the factor scores of the factor analysis would have had to be the "independent" variables. In this regression analysis the factor analysis was used only as a screening procedure to reduce the number of "independent" variables and to insure a high degree of independence.

The regression models were significant for blue grama plant variables in only three cases. These were calcium, potassium, and iron (Fig. 3).

The significant "independent" variables included in the regression model for plant calcium were clay and sulfate (Fig. 3). The coefficient of determination for the model was .162 and the correlation coefficient was .403 (Table 9).

Clay content may be related to plant calcium because as the clay increases the cation exchange capacity would be expected to increase. As cation exchange increases the base saturation (Ca) of the soil solution would be expected to decrease and hence available calcium would be decreased. The positive relationship between plant calcium and soil sulfate could indicate the presence of available calcium in the form of $CaSO_4$.

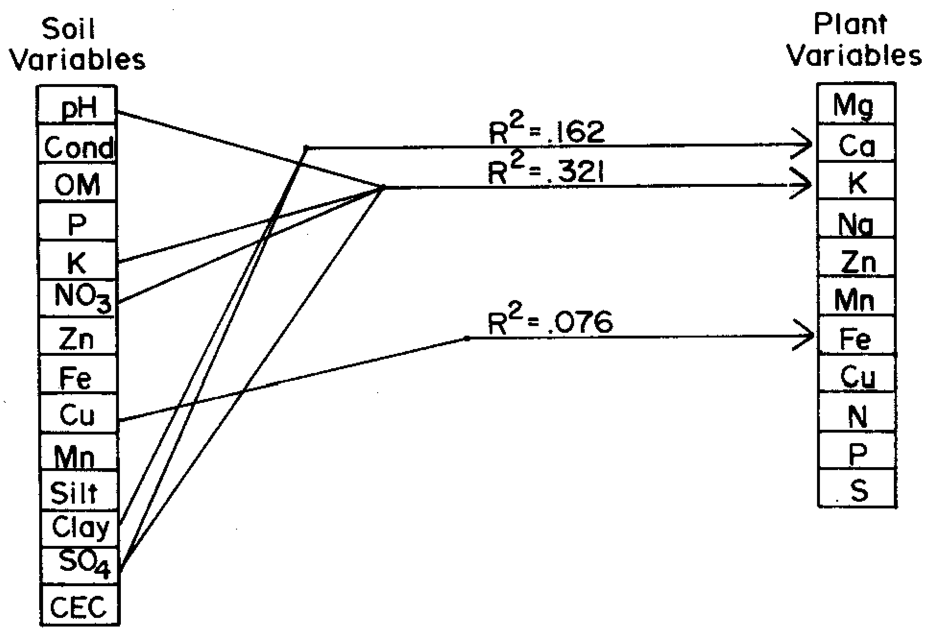

Fig. 3. Relationship of soil variables and plant variables and coefficients of determination for blue grama.

Table 9. Equations relating the blue grama nutrient contents to blue grama soil variables and coefficients of determination (R^2).

Plant Nutrient	Equation	R^2
Ca	$\hat{Y} = .356 - .006\ \text{Clay} + .011\ SO_4$	.162**
K	$\hat{Y} = -.131 + .087\ \text{pH} + .0003\ \text{K} + .023\ SO_4 + .017\ NO_3$	.321**
Fe	$\hat{Y} = .007 + .003\ \text{Cu}$	.076*

* Significant at $\alpha = .05$.

** Significant at $\alpha = .01$.

The regression model for plant potassium included four soil variables (Fig. 3). These were potassium, pH, nitrate, and sulfate (Fig. 3). The coefficient of determination was .321 and the correlation coefficient was .566.

The literature indicates pH to have a negative relationship with plant potassium, but these regression analyses indicated a positive relationship. The pH and electrical conductivity of the soil were positively related in the same factor. The regression analysis may, more realistically, be relating plant potassium to conductivity, nitrate, and sulfate. This situation may be a result of a higher salt content in the outer solution.

The wheat plant samples had more variables that were significantly correlated with soil variables than did the blue grama plant samples. Calcium, potassium, manganese, copper, nitrogen, phosphorus, and sulfur each were significantly correlated to one or more soil variables.

Plant calcium was correlated with conductivity and silt (Fig. 4). The correlation coefficient was .535 and the coefficient of determination was .286. The regression equations relating the wheat plant nutrient contents to wheat soil nutrients are given in Table 10. The correlation of soil conductivity with plant calcium is probably a result of high electrical conductivity being related to a high base content in solution.

Plant potassium was correlated with conductivity, potassium, and organic matter (Fig. 4) with a correlation coefficient of .418 and a coefficient of determination of .175. Plant potassium is expected to be positively related to soil available potassium.

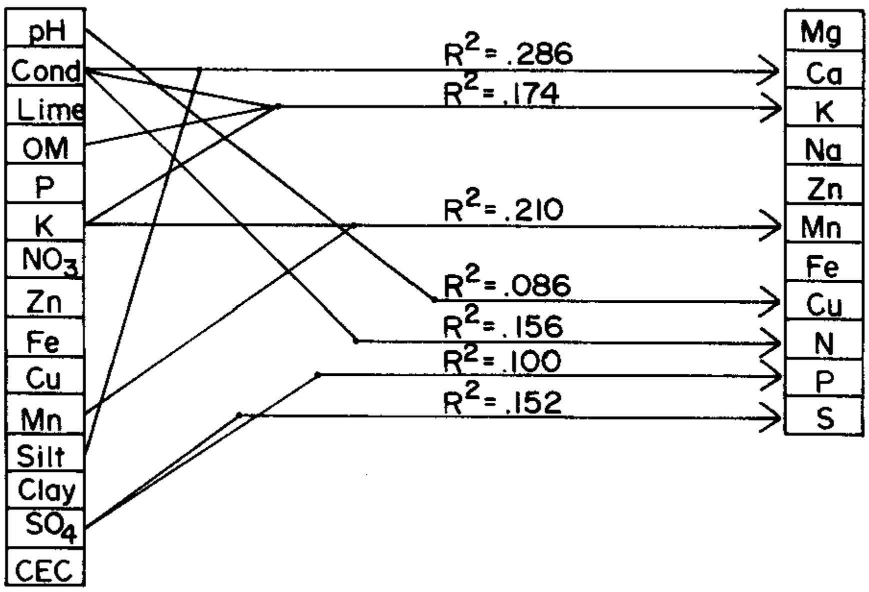

Fig. 4. The relationships of soil variables and plant variables and coefficients of determinations for wheat.

Table 10. Equations relating the wheat nutrient contents to wheat soil variables and coefficients of determination (R^2).

Plant Nutrient	Equation	R^2
Ca	$\hat{Y}$ = .077 + .210 Cond. - .003 Silt	.286**
K	$\hat{Y}$ = .437 + .538 Cond. - .152 OM + .0003 K	.174**
Mn	$\hat{Y}$ = .00245 + .00001 K - .00008 Mn	.210**
Cu	$\hat{Y}$ = .0007 + .0001 pH	.086*
N	$\hat{Y}$ = .636 + 1.910 Cond.	.156**
P	$\hat{Y}$ = .095 + .002 SO_4	.100**
S	$\hat{Y}$ = .075 + .003 P + .002 SO_4	.152**

* Significant at α = .05.

** Significant at α = .01.

The positive relationship of conductivity and plant potassium is probably related to a high solution base content reflected by increased electrical conductivity.

Plant manganese was correlated with manganese and potassium (Fig. 4). The correlation coefficient was .459 and the coefficient of determination was .210. The negative relationship of plant manganese and soil manganese and potassium is apparently irrational.

Plant copper was correlated with pH (Fig. 4) with a correlation coefficient of .293 and coefficient of determination of .086. It is reasonable to expect soil pH to have an effect on plant copper content. It was found in this study to be a positive relationship but Reith and Mitchell (1964) reported an increase in soil pH to decrease plant copper, while Hemingway (1961) found soil pH not to effect copper content of herbage.

Plant nitrogen was correlated with conductivity of the soil (Fig. 4) with a correlation coefficient of .395 and a coefficient of determination of .156. Plant phosphorus was correlated with soil sulfate (Fig. 4) with a correlation coefficient of .316 and a coefficient of determination of .100. These two relationships are not readily explained.

Plant sulfur was correlated with soil phosphorus and sulfate (Fig. 4). The regression coefficient was .390 and the coefficient of determination was .152. Soil sulfate is positively related to plant sulfur but the role of phosphorus and its relationship to plant sulfur is not clearly understood.

The results of the multiple regression were not very good. Three underlying factors are partial explanations. First, was the rather narrow range of values for each soil variable. This was the result of taking all samples in the Ascalon soil which was done purposefully in an attempt to minimize the variation in physical characteristics. Second was that the system being sampled was severely moisture limited so that nutrient effects were masked. A less moisture limited system might have given more meaningful results. A third consideration that would help to explain the poor results is the lack of sufficient analytical sensitivity for some of the variables with low values.

We should always be aware that any effects attributed to a soil variable may really have been due to one of the other correlated variables in the same factor. Three other variables which should have been included to improve results, and make them more biologically meaningful were soil water content, plant water content, and plant stage of growth. These last are rather closely related and possibly the inclusion of only one would have improved the results.

Canonical Correlation

The blue grama data had a canonical correlation of .779 for the first set of canonical variables (Table 11). This set of canonical variables seemed to be relating the difference in soil potassium and clay to the potassium content of blue grama forage. The implication is that the greater the soil potassium relative to the clay content, the greater is the potassium of blue grama forage. Fig. 5 summarizes the canonical correlation results for the blue grama data set.

Table 11. The results of the canonical correlation analysis for the blue grama data set.

CANONICAL CORRELATIONS

	1	2	3	4	5	6	7
	.77869	.74543	.70949	.62817	.60294	.57010	.47788

VARIABLE	COEFFICIENTS FOR CANONICAL VARIABLES OF THE FIRST SET						
pH	.34572	.05782	.92424	.42498	-.32066	.38406	.10354
Cond.	-.21713	-.19200	.09007	-.21681	.16054	.01195	-.06724
OM	-.07141	-.05034	.22903	-1.00264	-.13279	1.33413	-.27785
P	-.33867	.74754	.63411	.48715	.07209	.55053	-.19493
K	.77845	.08357	.00581	-.27077	.99965	-.80967	.43885
NO_3	.45207	.20364	-.01885	.10168	-.31873	-.10639	-.84280
Zn	.28300	.61011	-.81982	-.34179	-.08845	.20834	.29037
Fe	.46696	-.50881	.77938	.53877	.84090	-.55837	.35607
Cu	-.59044	-.75805	.19238	.30669	.37001	.03595	-.03987
Mn	-.43801	-.24023	-.22325	-.56564	-1.01983	-.02470	.56155
Silt	.40926	-.36619	.18016	-.22108	-.04801	-.84347	-.03517
Clay	-.56287	.51351	.38614	-.52309	-.08333	.15806	-.58679
SO_4	.09996	-.32281	-.38643	-.26135	.18112	.31512	-.17336
CEC	.15241	-.12726	.00269	1.85407	-.58113	-.21667	.43571

VARIABLE	COEFFICIENTS FOR CANONICAL VARIABLES OF THE SECOND SET						
Mg	-.37520	.19371	-.04644	-.36700	.49015	.11093	-.53669
Ca	.18242	-.36216	-.64031	.60710	-.38076	.61409	.02355
K	.69327	-.28242	.41180	.30696	-.42725	.19974	-.35848
Na	.32361	.37362	-.38897	.12900	.59945	.32440	.47668
Zn	.05800	.54781	.26552	.63173	-.08546	-.31438	-.51285
Mn	-.01453	.01138	.60351	-.09503	.08489	-.12566	.34244
Fe	-.33946	-.36986	.42403	.49837	.47113	.45138	.12740
Cu	.13826	-.22604	-.04530	-.63665	.02407	.12133	-.35621
N	.24256	-.16815	-.23164	-.15228	.48729	-.39108	.08303
P	-.00397	.33791	-.25550	-.55934	-.21966	.51749	.09787
S	.08659	.45606	.08904	-.15713	.07502	.07454	-.25905

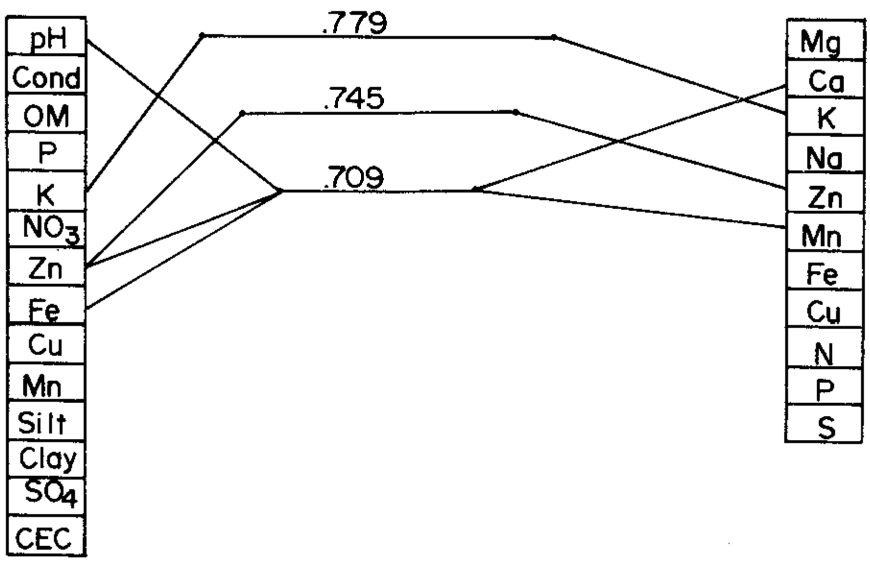

Fig. 5. Diagrammatic representation of the canonical correlation results of the blue grama data set including the canonical correlation and the variables included in each set of canonical variables.

This probably implies that as the clay content decreases the potassium in solution increases because less potassium is tied to exchange sites. This would probably result in increased potassium uptake.

The second set of canonical variables had a canonical correlation of .745 (Table 11) and related soil zinc to plant zinc, the implication is that the greater the soil zinc the greater the plant zinc content. This relationship is simple. As available zinc increases the plant uptake would be expected to increase.

The third set of canonical variables for blue grama variables related the soil variables; pH, zinc, and iron; to the plant variables; calcium and manganese (Table 11). The suggested meaning is that the higher the pH and iron content, relative to zinc content the greater would be the manganese content of the plants and the less would be the calcium content of the forage. This relationship of pH to plant manganese content is opposite the findings of Reith et al. (1964). Doll, Miller, and Todd (1963) found liming did not effect the calcium content of forage. This set of canonical variables had a canonical correlation of .709.

The anomalies of the data set seem to be creating "noise" in the results at this step of the analysis. To explain the relationships of this set of canonical variables would be very difficult.

The results of the canonical correlation analysis for wheat soil and plant variables (Fig. 6) was quite different than that of the blue grama variables.

The canonical correlation for the first set of wheat canonical variables was .779 (Table 12). This set of canonical variables

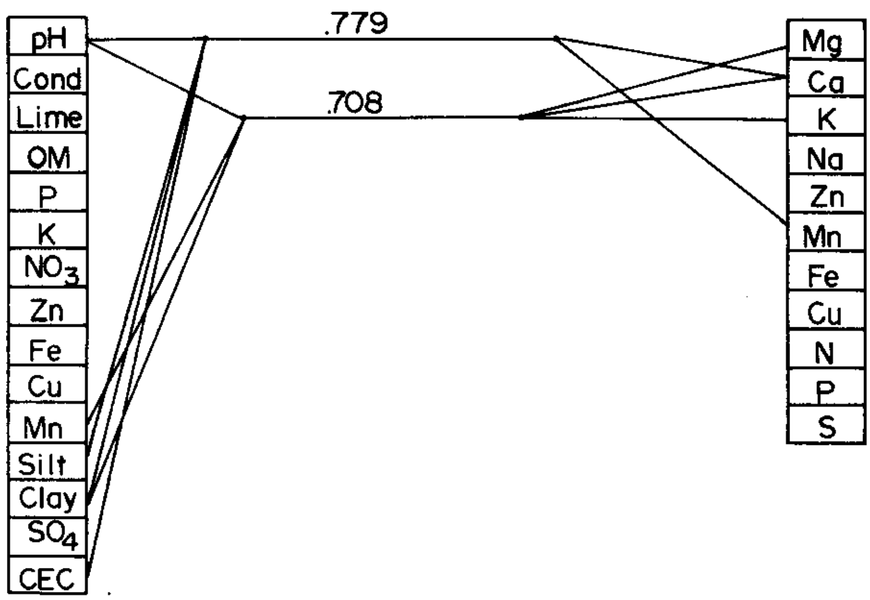

Fig. 6. Diagrammatic representation of the canonical correlation results of the wheat data set including the canonical correlation and the variables included in each set of canonical variables.

Table 12. The results of the canonical correlation analysis for the wheat data set.

CANONICAL CORRELATIONS

	1	2	3	4	5	6	7
	.77853	.70807	.65335	.62691	.59560	.53384	.38697
VARIABLE	COEFFICIENTS FOR CANONICAL VARIABLES OF THE FIRST SET						
pH	.81633	-.63760	.42683	-.24902	-.30410	-.58352	.41821
Cond.	-.58232	-.34630	-.27661	.12525	-.16491	-.62172	.23029
Lime	.48124	-.25504	.44448	-.44346	.45350	.09858	.00551
OM	-.05985	-.24377	-.11878	-.40676	.10966	.56664	-.03275
P	-.43720	-.11253	-.05618	.10191	.96115	.30961	.18540
K	-.22539	-.09343	.47829	-.75791	-.19301	-.43391	-.32570
NO_3	-.08821	-.23685	.00602	-.02537	-.45301	.24323	.00855
Zn	.53111	.22427	-.12587	.34379	-.08453	.15389	-1.35626
Fe	.46073	.06197	-.14180	-1.60281	-.93061	-.44920	.64084
Cu	-.30457	-.05290	-.23583	-.59428	.09117	-.17616	.82260
Mn	.39268	-.78841	-.55196	1.02746	.65697	-.03510	-.12393
Silt	-.84666	.35239	.83294	.29288	-.48574	.34516	.42692
Clay	-.88210	.60029	.46934	.18784	.37146	-.44760	.17819
SO_4	-.31325	-.32821	-.65203	.28238	.36028	.73581	-.40490
CEC	.85282	-.03394	-.53306	.51703	.13305	-.03568	-.67597
VARIABLE	COEFFICIENTS FOR CANONICAL VARIABLES OF THE SECOND SET						
Mg	.00877	.55730	-.08666	-.02309	.15845	-.14496	-.54282
Ca	.62626	-.71241	.01828	.64314	-.04574	.05113	.14401
K	-.37860	.50494	-.74239	.02460	.23031	-.95947	.20118
Na	-.03473	-.04625	.09230	-.05046	.50167	.11802	-.02028
Zn	.48556	.15363	-.21885	.39495	-.17141	.15068	-.53984
Mn	-.56400	-.44293	.46924	-.19975	-.35808	-.11963	-.48743
Fe	.02192	-.20448	.14157	.08058	.46143	.20154	.02610
Cu	.20822	-.05581	.28408	.11659	.54745	-.42053	.07861
N	-.48583	-.09603	.12346	.27063	-.42411	-.08757	.28142
P	-.32553	.00799	-.29214	.94990	.21361	.29027	-.03638
SO_4	.22652	-.45577	-.30159	-.86642	.26093	.68314	-.30438

related the soil variables pH, silt, clay, and cation exchange capacity to the plant variables, calcium, and manganese. The implication was that pH and cation exchange capacity had a positive relationship and silt and clay had a negative relationship with plant calcium. Plant manganese was negatively effected by an increase in pH and silt and positively effected by an increase in cation exchange capacity and clay. This is hard to explain biologically because one would expect an increased fineness of soil texture to result in an increased cation exchange capacity and hence, usually, an increase in cations available to the plants.

The simple correlation matrix showed a positive relationship between plant calcium and pH and negative relationships between plant calcium and silt, clay, and cation exchange capacity. This is again a case of pH being positively related to electrical conductivity and a high pH indicating a high base status. Also, pH and silt were shown to be positively related to plant manganese and clay and cation exchange capacity had negative relationships to plant manganese.

The second set of canonical variables (Table 12) had a canonical correlation of .708. This set of canonical variables seemed to connect soil pH, manganese, and clay to plant magnesium, calcium, and potassium. Soil manganese and pH are implied to be negatively related to plant calcium and potassium and positively related to plant magnesium. Clay was positively related to plant calcium and potassium and negatively related to plant magnesium. This is somewhat of a reversal of the first set of canonical variables and seems to be uninterpretable.

Factor Loadings vs. Sample Variance

As an aid to interpret the feasibility and probable success of modeling attempts graphs were made with the coefficient of variation plotted on the horizontal axis and factor loadings on the vertical axis. A graph was made for each set of variables and each variable of the set was plotted according to the above two values.

A high coefficient of variation would indicate in most cases that an insufficiently sensitive analytical technique was used for the low levels of the variable analyzed for in the sample and erratic results were obtained. Low coefficients of variation mean a relatively good analytical technique was used.

Relatively high factor loadings would tend to indicate a high degree of heterogeneity of the samples. Lower factor scores mean a lower degree of heterogeneity or a higher degree of homogeneity.

The blue grama soil variables (Fig. 7) with high coefficients of variation are nitrate, sulfate, and copper; indicating a possible need for better analytical techniques for these variables. Nitrate is quite variable, however, depending on temperature and moisture conditions, and different analytical techniques may not lower its coefficient of variation. All other blue grama soil variables had relatively low coefficients of variation and all variables had relatively high factor loadings. The implications are that the analytical methods used were sensitive enough for these variables and the samples were heterogenous enough for modeling purposes.

Blue grama plant variables (Fig. 8) with high coefficients of variation were iron, zinc, and copper but the factor loadings for these variables were relatively high. All other blue grama

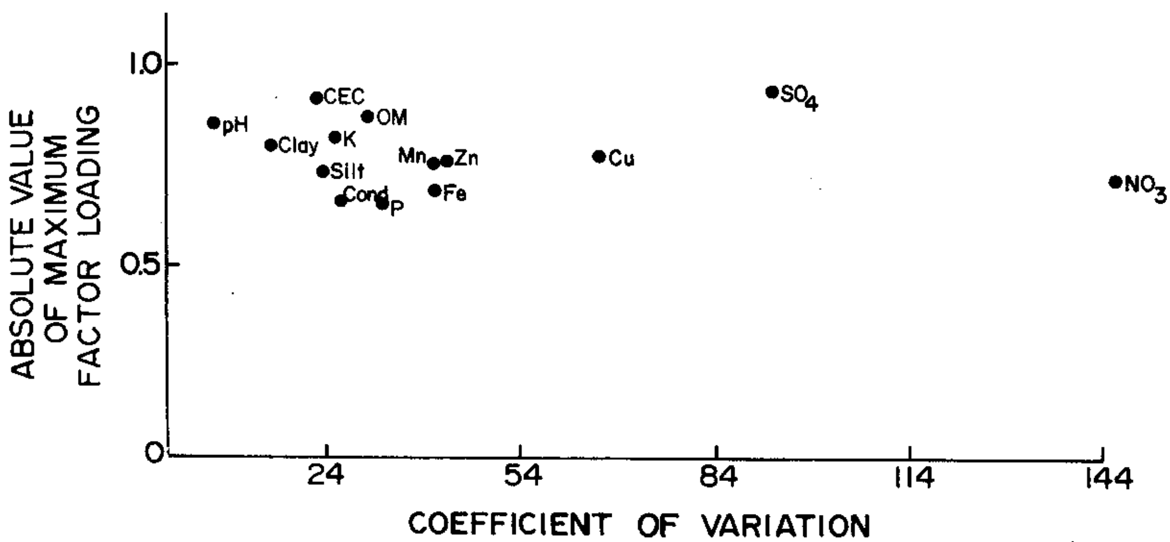

Fig. 7. Graph of coefficients of variation (reliability of analyses) and factor loadings (measure of heterogeneity of samples) for blue grama soil variables.

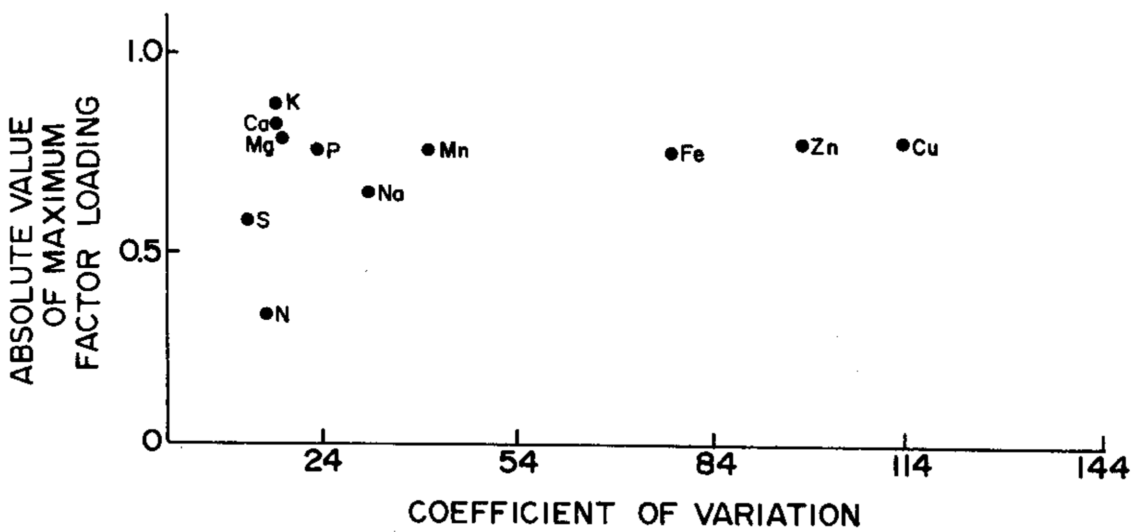

Fig. 8. Graph of coefficients of variation (reliability of analyses) and factor loadings (measure of heterogeneity of samples) for blue grama plant variables.

plant variables had low coefficients of variation pointing out the analytical methods were probably sufficient. Potassium, phosphorus, calcium, manganese, and magnesium had high factor loadings showing that modeling efforts may be successful and the samples were relatively heterogenous. Sulfur and nitrogen had low factor loadings indicating homogenous samples.

In general, the variability, as expressed by the coefficients of variation, were about the same for blue grama soil samples and wheat soil samples. The one exception to this was wheat soil nitrate variability, which was much less than blue grama soil nitrate variability.

The wheat soil variables (Fig. 9) seemed to group into about three groups. Group one had high coefficients of variation which were probably a result of moisture and temperature variations rather than poor analytical techniques. This group included nitrate and sulfate. Group two included iron, manganese, copper, lime, phosphorus, silt, and conductivity. Of this group iron, manganese, copper, lime, and phosphorus had relatively high coefficients of variation. Conductivity and silt had lower coefficients of variation but also had low factor loadings implying rather homogenous samples. Group three had coefficients of variation and factor loadings that indicated the analytical methods were sufficiently sensitive and heterogenous enough for successful modeling efforts.

The wheat plant variables (Fig. 10) all had relatively low coefficients of variation. This implies that the analytical techniques used were sufficiently sensitive for the nutrient levels found in wheat plant samples. Iron, magnesium, copper,

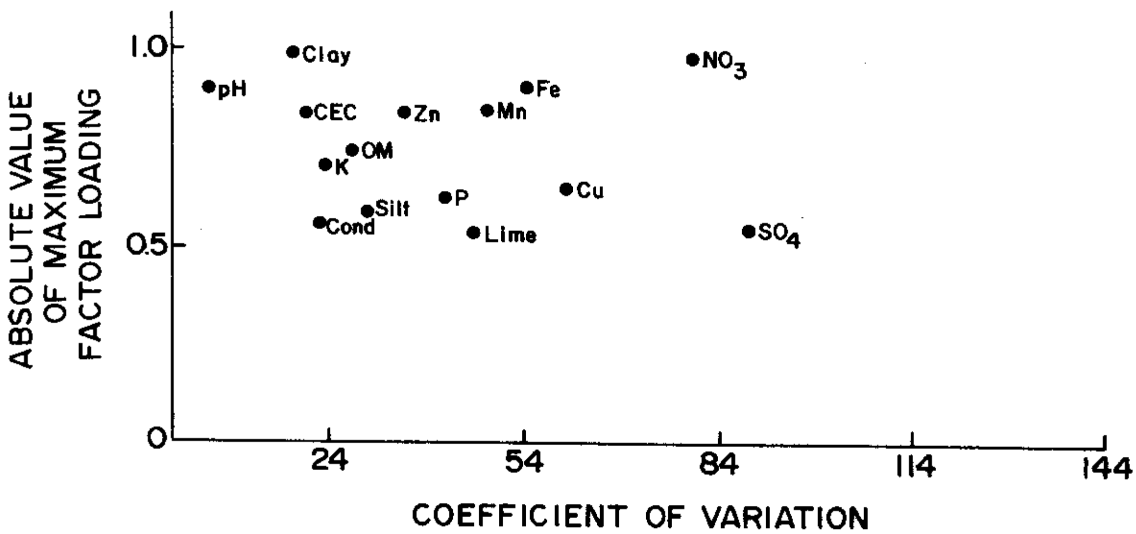

Fig. 9. Graph of coefficients of variation (reliability of analyses) and factor loadings (measure of heterogeneity of samples) for wheat soil variables.

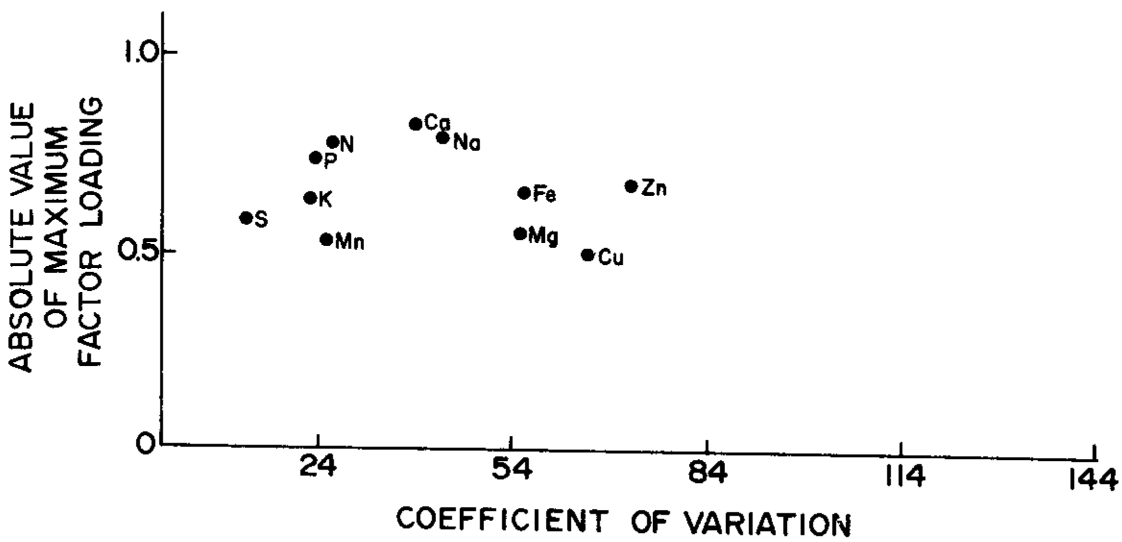

Fig. 10. Graph of coefficients of variation (reliability of analyses) and factor loadings (measure of heterogeneity of samples) for blue grama plant variables.

and zinc coefficients of variation were some higher than for other variables implying the analyses used were probably not quite as good as those used for the other variables. However, nitrogen, calcium, phosphorus, and sodium were the only variables with high factor loadings. This indicates a high enough degree of heterogeneity to possibly allow modeling. The other variables; sulfur, potassium, iron, magnesium, zinc, phosphorus, manganese, and copper had lower factor loadings and hence problems may occur in modeling attempts due to the high degree of homogeneity of the samples.

SUMMARY

The objectives of this study were to obtain a better understanding of soil nutrient-plant nutrient relationships of a shortgrass ecosystem and to illuminate areas of interest for future modeling efforts. A "shotgun" approach was used to sample many soil-plant situations and study the interrelationships between soil nutrients and plant nutrients through multivariant analysis techniques. The multivariate techniques included discriminant analysis, factor analysis, and canonical correlation. The multivariable technique of multiple regression was also used. The soil variables studied were pH, electrical conductivity, lime, organic matter, phosphorus, potassium, nitrate, zinc, iron, copper, manganese, sand, silt, clay, sulfate, and cation exchange capacity. Magnesium, calcium, potassium, sodium, zinc, manganese, iron, copper, nitrogen, phosphorus, and sulfur were the plant variables included in the study.

Discriminant analysis was used to determine whether there were two distinct groups of data, blue grama and wheat, or whether there might be some overlapping of these two data sets.

There was complete discrimination between the blue grama and wheat plant samples. For soil variables, only one wheat sample was concluded to be more like the blue grama samples than like the other wheat samples. The variables for this sample were closer to the mean of blue grama samples than the mean of wheat samples for seven variables. These variables were pH, organic matter, phosphorus, manganese, clay, sulfate, and cation exchange capacity.

One by-product of the discriminant program is a multivariate analysis of variance; this also showed a significant difference between blue grama and wheat groups.

Factor analysis was used to reduce the large number of correlated variables in the sets of soil variables and plant variables into smaller sets of uncorrelated variables.

The factor analysis results indicated four underlying factors in the blue grama soils data. The first factor included organic matter, potassium, silt, clay, and cation exchange capacity. The second factor included pH, conductivity, phosphorus, iron, and manganese. Nitrate, zinc, and copper were in the third factor. Sulfate was the only variable contained in factor four.

The wheat soils data when analyzed by factor analysis resulted in five factors. Included in the first factor were pH, iron, manganese, conductivity, and sulfate. Clay and cation exchange capacity were incorporated in the second factor. The third factor was comprised of phosphorus, potassium, zinc, copper, and lime. The fourth and fifth factor included organic matter and silt, and nitrate, respectively.

The factor analysis of blue grama plant variables resulted in five factors. The first included calcium and magnesium; the second factor included zinc and copper; the third factor included potassium and sodium; the fourth factor included manganese, phosphorus, and nitrogen; and iron and sulfur were included in the fifth factor.

Wheat plant variables resulted in four plant factors after factor analysis. The first of these was comprised of potassium, magnesium, and sulfur. Sodium, manganese, and copper were incorporated in factor two and zinc, nitrogen, and phosphorus was incorporated in factor three. The fourth factor contained plant variables calcium and iron.

The results of the factor analysis were used to screen the soil variables. The soil variable in each factor that was most highly correlated with each plant variable was then included as an "independent" variable in a multiple regression analysis.

Calcium, potassium, and iron were the only blue grama plant variables with significant correlations with any soil variables. Wheat plant variables that had significant correlations were calcium, potassium, manganese, copper, nitrogen, phosphorus, and sulfur.

The last multivariate analysis calculated for these data sets was canonical correlation. The canonical correlations were relatively low. The first set of canonical variables for blue grama had a canonical correlation of .779. Wheat also had a canonical correlation of .779 for the first set of canonical variables.

Canonical variable set one of blue grama related soil potassium and clay to plant potassium. Canonical variable set two correlated soil zinc to plant zinc and had a canonical correlation of .745. Canonical correlation for canonical variable set three was .709 and connected soil pH, zinc, and iron to plant calcium and manganese.

Canonical variable set one of wheat related soil pH, silt, clay, and cation exchange capacity to plant calcium and manganese. The canonical correlation of set two was .708 and related soil pH, manganese, and clay to plant magnesium, calcium, and potassium.

Canonical variable sets three and four were biologically uninterpretable although having canonical correlations of .653 and .627, respectively.

Comparisons were made between the absolute value of the maximum factor loadings of each variable and the coefficient of variation of the variables to help clarify whether the results were due to reliability of the measurement techniques or not and heterogeneity of the samples. Both plant and soil trace elements frequently showed sensitivity problems in measurement while soil nitrate and sulfate values may have been influenced by soil water and temperature differences.

CONCLUSIONS

Multiple regression analyses and factor analyses were the most helpful of the statistical techniques used in this study. Multiple regression was helpful in pointing out cases where plant nutrients were related to soil variables; factor analyses pointed out relationships between two or more plant variables or two or more soil variables but did not show plant nutrient-soil nutrient relationships. Discriminant analyses and canonical correlation were less helpful for these purposes.

The low coefficients of determination, in most cases, from the multiple regression analyses, indicate it would be very difficult to model plant nutrients as a function of soil variables in the two systems investigated. This is not meant to imply that such modeling is impossible, especially if careful planning and experimentation is done to consider other relevant control variables, such as water content, temperature, and plant phenological stage.

There are three major reasons for the low correlation coefficients and coefficients of determination results from the multiple regression analyses. First, the limited range of values for the soil variables; second, the situations sampled were severely moisture limited tending to mask the nutrient effects; and third, the questionable results obtained due to the analytical method being used at the lower limits of their reliability.

Nutrient relationships found in this study that may warrant further study and modeling efforts are blue grama plant nutrients calcium and potassium. Soil variables that would be of interest to study in relationship to plant calcium are clay and sulfate.

Potassium, pH, nitrate, and sulfate would be of interest in studying plant potassium.

Wheat plant nutrients that seem to be suggested for further research and modeling efforts by the multiple regression results are calcium, potassium, manganese, copper, nitrogen, phosphorus, and sulfur. Due to a high coefficient of variation for copper, a more sensitive analysis is probably needed before further modeling can be done with this wheat plant nutrient. The soil variables indicated for further study in their relationship to plant calcium are electrical conductivity and soil texture. Electrical conductivity, potassium, and organic matter are the soil variables relationships indicated for further study with wheat plant potassium. The relationships of soil manganese and potassium with plant manganese should be studied. Conductivity relationships with wheat nitrogen content should be studied and sulfate and phosphorus relationships with plant sulfur were indicated for further study.

The factor analyses indicated that promising areas for modeling include the soil potassium as influenced by cation exchange capacity, divalent anions ($SO_4^{=}$, $HPO_4^{=}$) as influenced by pH, and cation ratios in plant tissues.

Nitrogen and sulfur, which are commonly shown to be important in grassland soil-plant relationships, appear to be controlled by variables other than those included in this study.

The basic conclusion of this study is that the relationships between plant nutrient concentrations and soil nutrient concentrations are so complicated by dilution effects of increased growth and the complexity of the soil system and plant uptake that the relationships found were very weak.

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APPENDIX A

Description of Typical Ascalon Series Soil Profile

ASCALON SERIES

The Ascalon series is a member of a fine loamy, mixed, mesic family of Typic Argiustolls. Typically they have friable granular A horizons, B2t horizons having moderate grades of prismatic to subangular blocky structure, and distinct and continuous ca horizons. They have mollic epipedons less than 20 inches thick and argillic horizons.

Typifying Pedon:		Ascalon fine sandy loam
Ap	0-4"	Grayish-brown (10YR 5/2 dry) fine sandy loam, very dark grayish brown (10YR 3/2 moist); moderate very fine granular structure; soft dry, very friable moist; noncalcareous, pH 7.0; clear smooth boundary. 3 to 6 inches thick.
B1	4-7"	Grayish-brown (10YR 5/2 dry) light fine sandy clay loam or heavy fine sandy loam, very dark grayish-brown (10YR 3/2 moist); weak to moderate subangular blocky structure breaking to moderate medium granules; slightly hard dry, very friable moist; a few thin patchy clay films on both the horizontal and vertical faces of the soil aggregates; noncalcareous, pH 7.2; clear smooth boundary. 3 to 4 inches thick.
B21t	7-14"	Brown (10YR 5/3 dry) fine sandy clay loam, dark brown (10YR 3/3 moist); moderate medium prismatic structure breaking to moderate medium subangular blocks; hard dry, very friable moist;

		thin continuous clay films on the surfaces of the soil aggregates; noncalcareous, pH 7.2; gradual smooth boundary. 4 to 7 inches thick.
B22t	14-18"	Brown (10YR 5/3 dry) fine sandy clay loam, brown or dark brown (10YR 4/3 moist); weak medium prismatic structure breaking to moderate medium subangular blocks; hard dry, very friable moist; thin patchy clay films on both the horizontal and vertical faces of the soil aggregates; noncalcareous, pH 7.4; clear smooth boundary. 0 to 5 inches thick.
B3ca	18-25"	Light gray (2.5Y 7/2 dry) heavy fine sandy loam, light olive (2.5Y 5/3 moist); weak medium subangular blocky structure; slightly hard dry, very friable moist; a moderate ca horizon with visible calcium carbonate occurring as concretions, and in thin seams and streaks; a few thin patchy clay films on the faces of some of the soil aggregates; calcareous, pH 8.2; gradual smooth boundary. 4 to 8 inches thick.
Cca	25-60"	Pale yellow (2.5Y 7/3 dry) fine sandy loam, light olive brown (2.5Y 5/3 moist); massive, slightly hard dry, very friable moist; a moderate ca horizon with visible calcium carbonate occurring as concretions, and in thin seams and streaks; calcareous, pH 8.2. Several feet thick.

Type Location: Approximately 360 feet south and 100 feet east of the west quarter corner of sec. 8, T. 2 N., R. 52 W., Washington County, Colorado.

Range in Characteristics: Thickness of the mollic epipedon typically ranges from 7 to 20 inches, depth to calcareous material ranges from 8 to 30 inches, thickness of solum ranges from 15 to 40 inches, and there should be no bedrock or strongly contrasting substratums above 40 inches. When the solum is less than 20 inches thick they should not be calcareous above 15 inches. Content of organic carbon ranges from .6 to 2 percent in the mollic epipedon and decreases uniformly with depth. Conductivity is typically less than 1 millimho, and E. S. P. less than 1 percent in the solum, but both may increase slightly in the Cca horizon. The soil is typically base saturated, and soft powdery accumulation of secondary calcium carbonate usually occurs immediately below the B2t horizon. The soil is dry more than 90 cumulative days in some part but is dry in all parts less than 60 consecutive days. Content of coarse fragments may range from 0 to 50 percent but is usually less than 15 percent.

Color of the A horizon usually ranges in hue from 2.5Y to 10YR, in chroma from 2 to 3, and in value from 4 to 5 dry and 2 to 3 moist. Reaction ranges from pH 6.6 to pH 7.6. Typically the A horizon has a granular structure and dry consistence ranges from soft to slightly hard.

Color of the B2t horizon ranges in hue from 2.5Y to 7.5YR, in chroma from 2 to 4, and in value from 5 to 6 dry and 3 to 4 moist. When hue exceeds 10YR the color is usually not lithochromic.

Reaction of the B2t horizon ranges from pH 6.8 to pH 7.8. Typically the horizon is prismatic to subangular blocky, but structure may vary in grade and class. Texture of the B2t horizon is usually a sandy clay loam with clay ranging from 18 to 35 percent, silt from 5 to 30 percent, and sand from 45 to 75 percent with more than 35 percent being fine sand or coarser, but with only minor amounts of medium to coarse angular granitic sands.

Hue of the Cca horizon ranges from 2.5Y to 10YR. Reaction of the Cca horizon ranges from pH 8.0 to pH 8.6, and calcium carbonate equivalent ranges from 6 to 14 percent with some inconsistent areas in excess of 15 percent.

Competing Series and Their Differentiae: These include the Carnero, Salas, Satanta, Hyrum, Marcine, Wenatchee, Wages, and Wolf series. They differ from the Carnero series in lacking a lithic contact above 40 inches, in having sandy clay loam argillic horizons containing more than 35 percent fine or coarser sand, and in having sandy loam C horizons. They differ from the Salas series in lacking in lithic contact above 40 inches, in having lithochromic hues of 10YR or yellower, in having continuous ca horizons, in being calcareous within 30 inches, and in having sandy clay loam argillic horizons with more than 35 percent fine or coarser sand. They differ from the Satanta series in having sandy clay loam, argillic horizons with more than 35 percent fine or coarser sand, and in having sandy loam C horizons. They differ from the Hyrum series in lacking skeletal substratum above 40 inches, in having sandy clay loam argillic horizons with more than 35 percent fine or coarser sand, in having only minor amounts of limestone, gravel, cobble, or sand, and in lacking a salcic horizon. They differ from the Wenatchee series in having sandy clay loam argillic horizons with more than 35 percent fine or coarser sand, and in having coarser textured sandy loam C horizons. They differ from the Wages series in having sandy clay loam argillic horizons with more than 35 percent fine or coarser sand, and in having solums thicker than 20 inches or in being noncalcareous for 15 or more inches if solums are less than 20 inches thick. They differ from the Wolf series in having solums thicker than 15 inches, in having sandy clay loam argillic horizons with more than 35 percent fine or coarser sand, and in lacking a calcic horizon.

Setting: The Ascalon series occur on gently sloping to undulating uplands. Slope typically ranges from 1 to 10 percent. They are developing in Ogallala pedi-sediments which, in places, have been locally reworked by wind or water. At the type location the average annual precipitation is 17 inches, 12 inches of which falls during the months of April through September. The average annual soil temperature is 51°F., and the average summer soil temperature is 72°F.

Principal Associated Soils: These include the Platner, Manter, Wages, and Bresser series.

Drainage and Permeability: Well-drained. Runoff is medium to rapid depending upon slope gradient, and permeability is medium to rapid.

Use and Vegetation: These soils are used as dry and irrigated croplands or as native pastureland. Native vegetation is chiefly short grasses with blue grama predominating.

<u>Distribution and Extent</u>: Eastern Colorado and southeastern Wyoming. The series is of large extent.

<u>Series Established</u>: The Cheyenne Soil Conservation District, Cheyenne County, Colorado. Series name is taken from a local place name in Cheyenne County, Colorado.

National Cooperative Soil Survey

U.S.A.

APPENDIX B

List of Abbreviations and Symbols Used For

Plant and Soil Variables Throughout This Paper

	Symbol
Soil Variables	
Acidity	pH
Electrical Conductivity	Cond.
Lime	Lime
Organic Matter	OM
Phosphorus	P
Potassium	K
Nitrate	NO_3
Zinc	Zn
Iron	Fe
Copper	Cu
Manganese	Mn
Sand	Sand
Silt	Silt
Clay	Clay
Sulfate	SO_4
Cation Exchange Capacity	CEC
Plant Variables	
Magnesium	Mg
Calcium	Ca
Potassium	K
Sodium	Na
Zinc	Zn
Manganese	Mn
Iron	Fe
Copper	Cu
Nitrogen	N
Phosphorus	P
Sulfur	S

APPENDIX C

Results of Laboratory Analyses for Soil Variables of Blue Grama and Wheat Samples

BLUE GRAMA

pH	Cond. (mmhos/cm)	Lime	OM (%)	P (ppm)	K (ppm)	NO_3 (ppm)	Zn (ppm)	Fe (ppm)	Cu (ppm)	Mn (ppm)	Sand (%)	Silt (%)	Clay (%)	SO_4 (ppm)	CEC (meq/100g)
6.30	.20	1.00	1.00	12.80	195.00	0.00	.58	19.20	.72	10.60	67.80	18.20	14.00	2.25	7.44
6.30	.20	1.00	1.30	21.90	215.00	0.00	.56	23.40	.72	9.20	67.60	17.60	14.60	6.50	9.44
6.30	.20	1.00	1.30	19.50	254.00	0.00	.74	29.40	.92	13.60	65.20	18.20	15.60	2.00	8.40
5.80	.30	1.00	1.60	22.80	263.00	0.00	.92	38.50	.96	19.00	66.90	18.60	14.60	2.00	9.60
6.80	.20	1.00	1.60	10.80	375.00	0.00	.46	11.40	.60	9.40	68.80	17.40	13.80	2.25	10.36
6.30	.20	1.00	1.30	7.60	330.00	0.00	.36	13.20	.70	9.40	68.80	17.40	13.80	1.00	9.20
6.80	.20	1.00	1.30	7.30	320.00	0.00	.48	11.00	.36	4.80	74.40	12.20	13.40	1.00	8.88
6.30	.20	1.00	1.20	11.00	250.00	0.00	.76	15.25	.70	8.40	74.40	12.60	13.00	.50	6.80
6.30	.30	1.00	1.20	23.00	320.00	0.00	.55	13.40	.68	11.00	71.40	14.00	14.60	.50	8.08
6.20	.30	1.00	1.80	23.00	370.00	1.30	1.40	31.60	1.02	18.00	60.40	22.00	17.40	.50	8.96
5.90	.30	1.00	1.50	20.00	375.00	3.55	1.22	33.00	1.96	20.60	56.60	25.60	17.80	.25	9.60
6.50	.30	1.00	1.80	19.80	365.00	3.40	2.20	35.30	4.60	18.00	58.60	24.60	16.50	2.50	9.44
6.40	.20	1.00	1.10	23.50	258.00	0.00	1.92	30.50	.88	10.40	67.60	15.60	16.80	.50	7.60
7.30	.20	1.00	.90	15.80	290.00	0.20	.54	5.10	.40	4.40	78.60	7.60	13.50	.25	7.68
7.60	.30	1.00	1.00	2.30	230.00	0.00	.50	3.20	.34	3.20	78.60	16.60	12.80	.50	9.44
7.80	.40	1.00	2.00	9.50	360.00	0.00	.64	7.50	1.32	6.40	47.60	29.60	22.80	.25	14.20
7.20	.30	1.00	1.30	7.30	305.00	0.00	.48	4.80	.44	4.80	67.60	18.60	13.90	1.00	8.96
6.00	.20	1.00	1.30	25.30	380.00	0.00	.82	31.00	1.80	12.00	65.60	19.60	14.80	.50	7.28
6.10	.20	1.00	1.10	17.90	193.00	0.00	.65	22.70	.72	10.80	65.60	19.60	14.80	.50	5.36
6.00	.20	1.00	1.80	21.50	235.00	0.00	.88	40.00	1.20	22.00	60.40	20.20	19.40	.25	8.96
6.00	.20	1.00	1.20	21.50	243.00	0.00	1.76	25.20	1.26	11.20	58.00	22.60	19.40	.50	8.96
6.10	.20	1.00	2.00	19.50	373.00	0.00	.72	15.10	.84	17.20	58.40	23.20	18.40	3.00	11.20
6.10	.20	1.00	1.40	14.50	745.00	0.00	.70	20.40	.94	12.60	62.40	21.20	16.40	2.00	9.20
6.30	.20	1.00	1.70	23.50	315.00	0.00	.98	25.50	.64	14.20	60.80	23.20	16.00	2.00	10.00
4.90	.30	1.00	2.70	13.50	478.00	0.00	.98	12.20	.56	16.50	55.40	24.80	20.80	2.50	10.64
6.10	.30	1.00	2.00	20.50	360.00	.50	1.42	33.50	1.26	10.80	66.40	18.60	15.00	2.25	11.68
6.40	.20	1.00	.60	20.00	375.00	.30	.66	21.80	.70	10.20	70.80	12.80	16.40	.50	7.44
6.10	.30	1.00	1.10	24.50	250.00	1.50	.89	27.00	1.18	13.40	68.40	17.20	14.40	1.00	7.12
5.90	.30	1.00	1.30	23.50	243.00	1.50	.92	39.00	1.02	13.40	69.40	15.20	16.40	2.25	8.08
5.80	.20	1.00	1.20	22.80	253.00	1.40	.71	26.60	.84	15.00	66.40	18.20	15.40	.25	8.00
5.60	.20	1.00	1.20	23.00	243.00	1.10	.82	35.80	1.18	17.20	66.40	15.20	15.40	1.25	8.32
6.10	.10	1.00	1.20	10.30	350.00	0.00	.69	13.60	.84	11.40	62.40	19.80	17.80	2.25	10.80
5.70	.20	1.00	.90	23.30	233.00	1.30	.72	31.00	.80	12.80	71.40	15.00	13.60	1.00	8.32
5.80	.20	1.00	1.10	19.60	243.00	2.50	.68	23.40	.80	13.60	68.40	16.40	15.20	2.00	8.80
5.80	.30	1.00	1.00	24.00	233.00	.70	.83	24.30	.94	13.40	70.40	16.20	13.40	1.00	8.08
5.50	.20	1.00	1.10	28.50	275.00	.50	1.54	33.00	3.26	24.80	68.40	17.00	14.60	0.00	8.32
5.70	.20	1.00	1.40	17.50	295.00	.50	.84	31.00	1.12	21.60	57.40	23.00	19.60	2.00	10.08
5.70	.20	1.00	1.40	25.50	345.00	.70	1.04	33.80	1.96	27.60	61.00	22.00	17.00	1.75	10.48
5.70	.10	1.00	1.40	23.00	315.00	.30	.83	35.00	1.00	21.60	65.60	18.00	16.40	.50	10.08
6.10	.20	1.00	1.30	18.50	370.00	.50	1.00	15.60	1.14	17.60	69.20	14.20	16.60	.25	8.32
5.90	.10	1.00	1.10	19.50	273.00	.50	.85	15.90	.70	15.60	69.20	17.40	13.40	.50	8.32
6.40	.30	1.00	.90	6.30	225.00	.30	.41	11.60	.72	7.60	68.20	16.00	15.80	.25	10.32
5.80	.20	1.00	1.30	16.30	270.00	.80	.82	20.40	.60	10.60	78.60	10.60	10.80	.25	8.32
5.50	.20	1.00	1.10	24.00	270.00	1.40	.64	23.80	.60	13.60	71.20	17.60	11.20	.50	8.08
5.80	.20	1.00	.90	8.00	175.00	.50	.55	14.60	.64	10.20	80.20	8.00	11.90	.75	6.40
6.00	.30	1.00	2.10	23.30	500.00	1.23	1.10	22.40	1.22	25.80	58.20	22.60	19.20	.50	13.44
5.40	.10	1.00	1.80	20.30	335.00	.50	.77	29.40	1.16	26.40	61.20	19.80	19.30	.25	11.04
6.00	.20	1.00	1.20	19.50	245.00	.70	.89	27.60	.92	21.20	65.20	17.40	17.20	1.00	9.28
5.70	.20	1.00	1.10	14.50	280.00	0.00	.56	23.40	.84	19.40	69.40	16.00	14.60	1.00	8.40
6.10	.20	1.00	1.40	27.50	335.00	.33	1.05	34.60	2.08	27.20	64.40	18.00	17.60	1.00	10.40
6.20	.20	1.00	1.30	26.00	295.00	1.33	1.04	23.40	1.96	17.60	66.40	19.60	14.00	1.00	8.08
6.00	.20	1.00	2.50	19.80	500.00	.30	1.28	26.00	1.10	27.20	60.40	21.00	18.60	.50	13.76
6.30	.20	1.00	1.20	16.50	305.00	.50	.61	16.60	.64	13.00	78.40	10.00	11.60	1.00	6.96
6.60	.20	1.00	1.00	18.00	295.00	0.00	.75	24.20	.74	14.40	70.40	16.80	13.60	.50	8.40
6.10	.20	1.00	1.30	13.50	335.00	0.00	.77	26.70	.84	15.40	72.40	14.00	13.60	1.50	8.80
6.20	.20	1.00	1.30	15.50	310.00	2.10	.75	22.40	.70	17.60	69.40	15.20	15.40	.50	9.44

WHEAT

pH	Cond. (mmhos/cm)	Lime	OM (%)	P (ppm)	K (ppm)	NO_3 (ppm)	Zn (ppm)	Fe (ppm)	Cu (ppm)	Mn (ppm)	Sand (%)	Silt (%)	Clay (%)	SO_4 (ppm)	CEC (meq/100g)
7.50	.40	1.00	.80	7.00	360.00	.20	.21	3.00	.30	6.20	60.00	23.60	15.00	4.50	11.12
7.60	.40	1.00	1.10	8.40	460.00	.20	.43	3.90	.34	9.00	67.20	18.20	14.60	1.25	12.32
7.80	.40	1.00	1.00	5.50	500.00	1.30	.36	3.60	.34	8.60	65.20	19.60	15.20	8.25	11.76
7.30	.30	1.00	.60	7.50	365.00	.20	.28	6.00	.54	11.20	43.60	20.00	16.40	1.25	6.88
7.80	.30	3.00	1.00	4.30	370.00	.20	.20	4.00	.54	6.20	62.00	18.40	19.40	14.50	11.20
7.70	.30	3.00	.60	1.50	235.00	.70	.24	4.20	.54	4.40	58.00	13.60	20.40	13.75	15.20
6.20	.20	1.00	.50	16.50	413.00	.20	.52	25.20	.74	25.30	57.00	20.20	16.00	1.00	8.00
6.30	.20	1.00	.60	9.00	280.00	0.00	.42	16.00	.64	10.20	60.00	21.60	18.40	2.00	8.16
6.30	.20	1.00	.60	12.80	340.00	0.00	.28	16.40	.70	23.60	56.00	23.60	20.40	1.50	13.20
7.60	.30	2.00	1.20	6.00	500.00	.30	.26	6.00	.70	7.20	43.00	20.40	20.60	15.00	17.60
7.70	.30	2.00	.90	5.50	330.00	.20	.26	5.00	.54	6.00	54.00	21.60	24.40	16.50	13.20
7.80	.30	3.00	1.10	4.80	285.00	.70	.20	4.60	.58	6.20	51.00	24.70	24.80	16.50	13.20
7.40	.20	1.00	1.00	13.40	500.00	.30	.36	4.80	.74	10.60	56.00	19.60	24.40	2.50	13.20
7.40	.30	1.00	.90	13.80	500.00	.40	.88	7.60	3.30	16.00	48.00	24.40	27.60	2.50	15.20
7.70	.30	2.00	1.00	9.50	325.00	0.00	.30	5.00	.60	7.20	55.60	22.80	21.60	7.00	12.00
7.80	.30	2.00	.90	5.30	300.00	.50	.26	4.00	.58	5.40	57.00	20.80	22.20	8.50	13.20
8.00	.30	3.00	.90	4.00	185.00	0.00	.20	4.60	.54	4.80	59.60	17.60	23.00	13.00	11.20
8.00	.20	3.00	1.00	4.00	168.00	.30	.20	4.40	.54	4.20	55.60	19.60	24.80	13.75	12.00
7.60	.20	1.00	.50	13.00	375.00	0.00	.30	5.40	.40	8.00	71.20	9.80	19.00	.75	10.40
7.50	.20	1.00	.60	8.50	320.00	.20	.48	5.60	1.50	7.40	65.60	19.90	14.50	2.50	11.76
7.60	.20	1.00	.50	11.30	290.00	0.00	.26	4.60	.60	6.00	75.40	7.60	17.00	1.25	9.60
7.80	.20	1.00	.40	9.00	335.00	.30	.46	4.00	.40	6.40	65.60	15.20	19.20	7.75	10.80
7.80	.20	1.00	.90	7.50	370.00	0.00	.28	5.80	.48	6.20	65.60	15.20	19.20	3.00	10.00
7.90	.20	1.00	1.10	5.50	290.00	.40	.34	6.20	.70	5.60	51.60	21.20	27.20	8.50	15.40
7.80	.20	1.00	.90	12.50	413.00	1.30	.34	7.40	.46	7.00	64.60	14.20	21.20	2.25	10.16
7.90	.20	2.00	.90	10.00	400.00	0.00	.42	5.60	.46	9.40	61.80	16.00	22.20	5.25	10.00
8.20	.20	1.00	.70	12.50	445.00	.40	.34	5.20	.40	7.60	67.80	13.00	19.20	9.50	8.88
7.90	.20	1.00	.60	10.30	258.00	.20	.30	5.20	.66	7.20	78.80	12.00	17.20	2.50	8.00
7.90	.30	2.00	.70	5.50	225.00	1.50	.20	5.20	.52	5.20	63.80	13.00	23.20	11.50	12.32
7.90	.30	2.00	.60	15.00	413.00	.70	.30	4.60	.52	6.00	70.60	9.80	19.40	11.00	9.28
7.90	.30	2.00	1.20	6.80	300.00	.50	.60	6.40	.84	6.60	54.80	20.80	24.40	7.00	13.60
7.80	.30	1.00	1.10	9.00	390.00	.20	.68	5.80	1.24	7.20	61.00	18.80	19.40	8.75	10.24
7.00	.30	1.00	.90	12.00	485.00	.30	.48	11.20	.60	12.40	64.80	18.00	17.20	5.00	8.00
6.60	.20	1.00	1.20	13.00	455.00	1.30	.54	12.20	.98	14.60	52.80	20.80	27.20	2.00	13.20
6.80	.20	1.00	1.00	10.50	418.00	0.00	.42	13.80	.98	16.60	53.20	20.40	26.40	1.00	13.04
7.00	.20	1.00	1.10	12.00	455.00	0.00	.52	8.60	.96	12.20	54.80	19.40	25.80	.50	12.72
7.70	.30	1.00	.90	16.50	470.00	0.00	.54	5.20	.42	9.00	66.80	16.00	17.20	.25	7.76
7.20	.30	1.00	.90	17.00	455.00	0.00	.40	9.40	.48	15.60	66.40	16.60	17.00	.25	8.32
7.50	.30	1.00	.80	12.50	350.00	.80	.42	6.20	.56	7.40	64.40	17.80	17.80	3.00	9.28
6.30	.20	1.00	1.70	14.00	370.00	.50	.48	14.20	.54	14.60	69.40	15.00	15.60	.25	7.44
7.40	.20	2.00	1.00	5.00	380.00	.80	.42	6.20	.40	7.20	68.40	18.40	21.20	7.00	12.40
6.70	.20	1.00	.70	11.30	315.00	.50	.42	11.40	.60	12.60	68.40	12.40	19.20	.50	10.00
7.70	.30	1.00	1.00	6.50	230.00	.80	.32	4.00	.34	5.00	66.40	14.40	19.20	11.50	10.80
7.80	.30	2.00	1.50	7.50	340.00	.80	.29	3.80	.50	6.20	80.40	20.20	19.40	5.75	10.80
7.70	.30	2.00	1.10	5.50	300.00	1.50	.24	5.80	.66	5.80	61.40	15.80	22.80	5.50	12.00
7.20	.20	1.00	1.20	7.50	285.00	.40	.34	6.00	.66	9.60	59.40	19.40	21.20	7.00	10.40
7.50	.30	1.00	1.00	14.50	360.00	1.40	.40	5.20	.56	8.00	69.40	14.40	16.20	3.75	8.32
7.40	.30	1.00	1.10	14.30	395.00	1.30	.38	5.60	.58	7.80	63.40	17.40	19.20	.75	11.60
6.90	.20	1.00	1.00	13.00	380.00	.80	.36	7.80	.54	10.80	68.00	12.60	18.60	.50	9.12
7.20	.30	1.00	.70	7.30	270.00	.30	.26	4.80	.66	8.40	66.80	12.20	21.00	1.00	10.40
7.10	.30	1.00	1.00	7.00	280.00	.30	.28	7.00	.56	10.00	68.50	13.00	18.20	1.25	9.68
7.50	.40	1.00	.90	10.00	370.00	.50	.66	5.60	.54	7.00	69.80	13.80	16.40	2.75	8.32
7.60	.30	2.00	1.00	6.50	325.00	.80	.32	5.60	.58	7.40	66.80	15.80	17.40	2.75	9.64
7.50	.30	2.00	.50	18.50	380.00	.80	.36	5.40	.44	6.60	76.80	7.80	15.40	.75	7.60
7.70	.30	2.00	.80	4.00	445.00	.50	.22	5.00	.44	5.00	66.80	12.00	21.20	1.25	11.76
7.60	.20	1.00	1.00	4.00	245.00	.50	.30	6.00	.64	6.40	64.80	14.00	21.20	2.75	12.40
7.30	.20	1.00	.70	8.50	290.00	.80	.34	5.80	.56	7.40	69.80	12.80	17.40	0.00	8.56
7.30	.20	1.00	.60	7.00	745.00	.80	.24	4.00	.56	7.00	65.80	13.00	21.20	3.00	10.72
7.20	.20	1.00	.80	7.00	300.00	1.70	.29	8.20	.60	8.40	56.90	16.00	27.20	2.75	12.40
7.70	.30	3.00	1.00	7.50	235.00	.80	.30	3.60	.50	5.20	64.60	17.80	17.60	7.75	9.60
7.90	.30	1.00	.50	13.00	295.00	.80	.28	4.20	.46	4.20	77.40	5.40	17.00	11.75	8.00
7.80	.30	1.00	.60	11.50	345.00	1.10	.32	4.20	.44	6.00	76.60	7.00	16.40	12.75	8.00
7.70	.30	1.00	.70	11.80	340.00	.80	.32	4.40	.58	6.00	71.60	11.00	17.40	8.50	8.80
7.70	.30	1.00	.50	9.00	768.00	.80	.26	4.80	.48	5.20	76.60	6.20	17.20	7.50	8.08
7.70	.30	1.00	.60	18.50	355.00	.50	.30	5.00	.48	6.40	70.60	11.40	17.80	7.50	9.52
7.50	.30	1.00	.90	8.30	305.00	.80	.32	5.80	.66	8.00	66.60	13.00	20.40	2.50	11.20
7.50	.30	1.00	1.10	8.30	340.00	.80	.34	6.00	.78	7.20	56.60	18.00	25.40	5.00	15.00
7.80	.30	2.00	1.00	6.50	320.00	.50	.32	5.80	.76	6.80	60.60	17.80	21.60	5.50	12.00

APPENDIX D

Results of Laboratory Analyses for Plant Variables of Blue Grama and Wheat Samples

BLUE GRAMA

Mg (%)	Ca (%)	K (%)	Na (%)	Zn (%)	Mn (%)	Fe (%)	Cu (%)	N (%)	P (%)	SO_4 (%)
.061635	.353968	.556232	.006539	.001044	.002749	.007154	.000251	1.82	.151318	.14
.074790	.329608	.614440	.008439	.000515	.001726	.018769	.000247	1.77	.099675	.15
.057465	.283345	.432797	.005771	.000595	.002244	.033367	.000250	1.46	.198830	.15
.054423	.268310	.504750	.006404	.001607	.002937	.024128	.000491	1.70	.139645	.14
.072840	.310056	.634965	.008692	.000516	.002468	.005551	.000248	1.60	.119351	.14
.065693	.265864	.564524	.010982	.000796	.001940	.011405	.000243	1.58	.144839	.12
.060966	.300182	.650084	.008692	.000589	.002221	.008578	.000248	1.59	.137714	.12
.045271	.262834	.508097	.013021	.000594	.000498	.004579	.000250	1.43	.114412	.17
.059189	.232313	.405336	.005743	.000444	.001240	.015728	0.000000	1.39	.158638	.14
.050756	.210766	.588085	.010404	.000721	.001969	.018970	.000494	1.11	.190483	.17
.060781	.211018	.704533	.011408	.001030	.001971	.007055	.000494	1.86	.116546	.14
.066746	.260269	.573577	.007439	.001912	.001725	.013509	.000494	2.06	.120533	.12
.061325	.222854	.487430	.011260	.004453	.000994	.005593	0.000000	1.12	.184861	.16
.055182	.272052	.542192	.014734	.005037	.003226	.021224	.000249	1.23	.192376	.14
.032997	.300812	.575699	.007715	.002510	.002226	.006574	.000496	1.60	.153872	.13
.067067	.192177	.682499	.005232	.000813	.001733	.011643	.000248	1.46	.088775	.17
.067047	.320859	.616592	.009714	.001182	.003465	.007591	.000248	1.60	.120360	.14
.079332	.289561	.692058	.009488	.000913	.002548	.005731	.000256	1.80	.114205	.14
.075120	.251764	.495741	.007230	.002366	.001486	.024521	.000249	2.11	.225042	.14
.061296	.254193	.452080	.004601	.001149	.002887	.019698	0.000000	1.16	.189197	.14
.063200	.248900	.510700	.008900	.000891	.001990	.002544	0.000000	1.65	.175351	.14
.054677	.230211	.517150	.008413	.002642	.001721	.009552	.001233	1.47	.207587	.12
.060715	.338835	.487606	.011991	.001029	.002461	.004530	0.000000	1.08	.115418	.11
.071594	.323318	.616223	.008533	.000596	.002992	.005609	0.000000	1.59	.128188	.15
.057762	.274780	.793296	.012107	.001197	.002506	.016187	0.000000	1.33	.205618	.13
.072378	.308089	.550818	.013326	.000878	.001471	.011031	.000492	1.73	.099102	.11
.053245	.238604	.471866	.013753	.006921	.002484	.014331	.000499	1.67	.120832	.14
.071378	.282547	.553436	.007257	.000445	.000746	.005593	0.000000	1.35	.093308	.13
.063107	.261703	.490732	.008726	.001627	.004211	.005572	.000249	1.65	.165009	.14
.057177	.301778	.410362	.007490	.008146	.002233	.011160	.000996	1.50	.107783	.12
.051241	.252548	.613995	.007752	.000742	.001739	.003557	0.000000	1.61	.154614	.12
.049256	.242727	.472150	.008507	.001336	.000994	.003559	0.000000	1.85	.144526	.11
.068952	.310521	.550119	.009203	.002213	.000989	.007580	0.000000	1.55	.114884	.18
.088206	.415854	.515562	.006660	.004244	.002451	.004511	.000492	1.18	.133100	.16
.049791	.235310	.420830	.009611	.002701	.000754	.022316	.000252	1.40	.139871	.13
.058197	.252371	.485379	.009996	.001631	.001490	.040081	.000249	1.50	.136693	.13
.046761	.181165	.396965	.004458	.000735	.000492	.017000	0.000000	1.42	.104904	.14
.046841	.270235	.397637	.009674	.000441	.002218	.004536	.000247	1.41	.147238	.13
.065790	.275913	.500885	.008065	.000507	.003157	.002383	.000244	1.42	.149067	.13
.066178	.346595	.421644	.006082	.000401	.001511	.005664	.000253	1.85	.157474	.17
.055460	.293381	.412513	.004769	.001042	.003242	.002040	0.000000	1.34	.117944	.14
.062321	.328589	.376670	.004323	.001810	.001011	.004650	0.000000	1.40	.101660	.13
.060289	.258212	.534102	.009102	.000876	.001467	.007497	0.000000	1.78	.142098	.18
.057120	.281641	.440317	.010226	.004291	.001993	.004561	0.000000	2.04	.146050	.11
.091329	.381384	.461255	.004247	.000593	.001489	.003553	0.000000	1.47	.138516	.11
.040715	.279097	.611878	.006179	.003226	.003929	.005524	0.000000	1.49	.216616	.13
.044563	.268523	.445132	.004437	.001316	.001959	.003005	0.000000	1.40	.125890	.12
.079984	.287298	.618409	.009585	.000437	.002442	.014981	.000245	1.55	.120430	.14
.066986	.261206	.449404	.007714	.000738	.001978	.003034	0.000000	1.24	.147709	.12
.058689	.259881	.462196	.006685	.001763	.001722	.017549	.000247	1.49	.118767	.12
.074649	.289585	.542902	.005202	.001176	.001969	.007047	0.000000	1.40	.166212	.17
.060672	.299227	.472197	.011140	.001322	.002460	.004527	0.000000	1.98	.143002	.15
.055077	.212074	.571506	.014457	.000591	.001486	.006584	.000248	1.32	.147945	.12
.042991	.221629	.469602	.008710	.003691	.000989	.013194	.000249	1.47	.109986	.12
.073450	.265552	.677622	.008775	.001012	.001938	.008915	.000486	1.72	.103732	.14
.049971	.217200	.564137	.011218	.000579	.001454	.003469	.000243	1.47	.117849	.13

WHEAT

Mg (%)	Ca (%)	K (%)	Na (%)	Zn (%)	Mn (%)	Fe (%)	Cu (%)	N (%)	P (%)	SO4 (%)
.085608	.113622	.595132	.005014	.000818	.005230	.007131	.000250	2.23	.079211	.09
.116173	.173949	.801016	.007543	.001492	.005996	.003576	.000251	1.49	.080286	.19
.131349	.157908	.687948	.007749	.002011	.007700	.004428	.000483	1.77	.112218	.12
.076846	.102714	.655254	.004720	.000884	.003949	.003533	0.000000	1.12	.111908	.12
.068694	.083975	.494895	.012823	.000298	.005496	.003576	.000251	1.17	.090968	.11
.085127	.142718	.531098	.004986	.001109	.003467	.008104	.000248	.75	.097203	.11
.059959	.054308	.569718	.003035	.000600	.003519	.005653	0.000000	1.05	.088756	.15
.067479	.053821	.595132	.003008	.001190	.002989	.008149	0.000000	1.12	.112934	.12
.069107	.071279	.525993	.003876	.000719	.001926	.004430	.000483	.72	.141857	.08
.124564	.033530	.483157	.005457	.000294	.005422	.004536	.000495	1.07	.113329	.12
.099969	.053962	.484495	.009300	.000149	.003996	.002553	.000501	1.08	.149185	.12
.088400	.080100	.360900	.009900	.000761	.005809	.004949	.000243	1.01	.138805	.10
.114553	.092662	.674137	.013141	.000883	.004680	.007556	.000494	.98	.089700	.09
.100569	.055406	.675489	.005935	.000612	.004359	.006292	.000515	1.40	.123320	.14
.078280	.062758	.380339	.004933	.000366	.003431	.007149	.000246	.84	.136486	.06
.095900	.065200	.462100	.010000	.000522	.003494	.003573	.000250	.94	.147081	.09
.117517	.073555	.532645	.006250	.001112	.003478	.006095	.000997	1.21	.104867	.13
.086091	.070838	.454342	.006501	.000786	.003110	.004403	.000240	1.35	.105431	.10
.075301	.083461	.461440	.010996	.000074	.003476	.005585	.000249	.70	.098894	.08
.088938	.083069	.464320	.003731	.000812	.002966	.006570	.000248	.77	.061408	.09
.077340	.093435	.594591	.002750	.000964	.002484	.005080	.000499	.95	.091547	.11
.085841	.053968	.387635	.003519	.002535	.003247	.006129	.000251	.91	.081556	.09
.075597	.083789	.381803	.004265	.000372	.003739	.004588	.000250	.83	.078827	.07
.082284	.043167	.375521	.003208	.000439	.003432	.007019	.000246	.78	.138705	.07
.079282	.051046	.405239	.003091	.000705	.004252	.009178	.000474	.89	.063092	.09
.074512	.080441	.425194	.004095	.000572	.002872	.003915	.000960	1.11	.098146	.10
.087472	.053729	.396077	.006757	.000668	.003481	.006102	.000249	.97	.109586	.11
.119329	.179575	.642520	.012519	.001019	.005366	.000499	.000489	.76	.071011	.11
.114416	.131935	.688407	.005200	.000588	.003937	.006541	.000247	1.34	.076803	.12
.103134	.182326	.622019	.010717	.001626	.006933	.005064	.000248	1.18	.095754	.15
.114291	.102286	.557151	.008163	.000807	.004916	.004021	.000473	1.10	.105267	.13
.087763	.123789	.601187	.006779	.000968	.003742	.004591	.000250	1.21	.130016	.12
.092030	.084069	.679322	.010572	.000597	.004252	.006137	.000502	1.23	.101086	.17
.117286	.064595	.618110	.005092	.000678	.004288	.003095	0.000000	1.05	.081055	.10
.101477	.083520	.679961	.005002	.000568	.003479	.005081	.000249	1.86	.066362	.11
.501761	.069796	.432535	.005771	.000446	.005482	.015796	.000250	1.24	.114585	.10
.093366	.091424	.481474	.007094	.001088	.005833	.003976	.000488	1.17	.099679	.10
.095907	.101760	.714082	.005660	.000584	.005135	.021444	.000245	1.20	.083835	.13
.108336	.095979	.495041	.008732	.000457	.005358	.005740	.000512	1.07	.101628	.08
.083199	.093247	.612579	.003493	.000740	.003966	.006590	0.000000	.88	.090266	.14
.054710	.059064	.386838	.004209	.001175	.002952	.014588	.000247	1.14	.101835	.09
.087633	.072107	.556968	.006617	.002108	.003409	.004980	.000244	1.40	.110410	.13
.094603	.112344	.518025	.006444	.000956	.002463	.004532	.000247	1.22	.102477	.12
.030864	.043352	.221248	.002230	0.000000	.001477	.014053	0.000000	1.35	.106172	.12
.102517	.084376	.487003	.005558	.001199	.004016	.004106	.000252	1.50	.105974	.12
.104229	.104148	.730843	.005793	.000598	.004254	.011259	.000251	1.64	.143915	.18
.096514	.081867	.472521	.010295	.000582	.003897	.005479	.000244	1.12	.085191	.12
.091503	.043784	.406273	.004255	.000891	.004227	.003560	.000499	1.48	.156856	.14
.088190	.044139	.547796	.006055	.000599	.003510	.003588	.000503	1.08	.139906	.18
.084401	.054341	.415994	.004050	.000676	.004527	.004114	.000505	1.36	.101641	.10
.071558	.053859	.381764	.007275	.000298	.002991	.003058	.000250	.94	.105227	.10
.091191	.063468	.602273	.005737	.001702	.004461	.006081	0.000000	1.09	.086178	.09
.080589	.102398	.592935	.004210	.000588	.004183	.005375	.000247	.88	.086521	.08
.085513	.123453	.655445	.013522	.000446	.004478	.005596	.000499	1.26	.096206	.13
.095295	.113167	.486355	.005493	.000296	.002481	.002536	.000249	.78	.060510	.07
.116848	.102786	.534657	.009197	.003687	.004940	.004040	.000248	1.10	.078103	.11
.110190	.104043	.643308	.002768	.000672	.004250	.004601	0.000000	.74	.069150	.09
.078654	.043352	.457582	.007187	.001470	.002955	.006546	.000247	1.20	.143145	.11
.073389	.073621	.497585	.004504	.000520	.003232	.006101	.000249	1.25	.091912	.09
.077286	.093369	.441024	.004997	.000815	.003972	.006091	.000498	1.02	.097417	.12
.096066	.134096	.679254	.007299	.000672	.004251	.006137	.000502	1.50	.123328	.16
.079111	.122884	.703002	.004736	.000665	.004953	.002532	.000248	1.46	.152022	.21
.083670	.111051	.735776	.005145	.000872	.003651	.007965	0.000000	1.37	.111946	.12
.109580	.123366	.715913	.005755	.000594	.004724	.009234	.000499	1.09	.117588	.12
.092030	.084069	.794799	.003776	.001344	.003752	.010229	.000251	1.29	.120290	.16
.091027	.093052	.671917	.007718	.000591	.004700	.009612	0.000000	.82	.080781	.10
.103154	.108030	.596853	.006232	.000298	.003963	.003039	.000248	1.05	.145962	.12
.105021	.073246	.676901	.004232	.002141	.004947	.009611	.000248	1.20	.084607	.14

APPENDIX E

Correlation Matrix for Blue Grama Soil and Plant Variables

BLUE GRAMA

CORRELATION MATRIX

VARIABLE NUMBER	pH*	Cond.	OM	P	K	NO_3	Zn	Fe	Cu	Mn
pH	1.000	.388	.058	-.614	.155	-.293	-.196	-.673	-.211	-.604
Cond.		1.000	.273	-.105	.164	.211	.137	-.104	.133	-.228
OM			1.000	.038	.700	.023	.325	.134	.220	.423
P				1.000	.017	.347	.525	.769	.427	.571
K					1.000	.103	.281	-.057	.209	.391
NO_3						1.000	.364	.372	.421	.317
Zn							1.000	.553	.699	.369
Fe								1.000	.474	.651
Cu									1.000	.395
Mn										1.000

VARIABLE NUMBER	Silt	Clay	SO_4	CEC	Mg**	Ca	K	Na	Zn	Mn
pH	-.040	-.016	.059	.179	-.098	.014	.417	.224	.061	.135
Cond.	.289	.180	.007	.271	-.012	-.148	.326	.023	-.022	.007
OM	.648	.606	.213	.816	-.079	-.150	.391	.023	-.256	.252
P	.151	.134	-.012	-.140	-.007	-.198	-.270	-.029	.172	.036
K	.391	.481	-.032	.704	-.258	-.261	.324	.257	-.034	.177
NO_3	.173	.035	-.061	-.054	.093	-.012	.099	-.005	.144	-.018
Zn	.383	.368	-.045	.144	-.029	-.250	.027	.123	-.002	-.063
Fe	.240	.214	.065	-.091	.049	-.195	-.166	-.095	-.035	.038
Cu	.376	.277	.052	.113	.031	-.152	-.053	-.136	-.079	-.097
Mn	.371	.451	-.053	.319	-.165	-.187	-.194	-.211	-.093	.113
Silt	1.000	.743	.193	.597	-.087	-.235	.256	-.211	-.157	.130
Clay		1.000	.047	.667	-.144	-.314	.105	-.179	-.051	.131
SO_4			1.000	.207	.205	.237	.208	.005	-.201	.054
CEC				1.000	-.187	-.082	.342	-.000	-.140	.193
Mg					1.000	.519	.238	-.129	-.187	.069
Ca						1.000	-.018	-.196	.008	.293
K							1.000	.317	-.242	.234
Na								1.000	.184	-.002
Zn									1.000	.096
Mn										1.000

VARIABLE NUMBER	Fe	Cu	N	P	S
pH	.063	.131	-.061	.060	.046
Cond.	.203	.162	.013	-.043	.109
OM	.016	.062	.027	.200	-.057
P	.248	.004	-.046	.113	.100
K	-.099	.096	.120	.111	-.089
NO_3	-.142	.180	.139	-.163	.041
Zn	.122	.010	.094	.136	.086
Fe	.192	.016	.055	-.037	-.036
Cu	.276	.066	.152	-.068	-.121
Mn	-.032	-.025	-.054	.083	-.138
Silt	.031	.087	.114	.044	-.039
Clay	.048	.003	-.128	.168	-.013
SO_4	.096	.175	.141	-.073	-.107
CEC	-.055	-.041	-.042	.063	-.126
Mg	-.070	-.044	.141	-.186	.226
Ca	-.252	-.059	.067	-.130	.094
K	-.067	.107	.158	-.032	.093
Na	.015	.177	.018	.008	-.059
Zn	.108	.388	-.027	.100	-.082
Mn	-.083	.073	.001	.288	-.039
Fe	1.000	.208	-.016	.224	.026
Cu		1.000	.123	-.028	-.158
N			1.000	-.100	-.057
P				1.000	.038
S					1.000

* Variables 1-14 are soil variables.

** Variables 15-25 are plant variables.

APPENDIX F

Correlation Matrix for Wheat

Soil and Plant Variables

WHEAT

CORRELATION MATRIX

VARIABLE NUMBER	pH*	Cond.	Lime	OM	P	K	NO_3	Zn	Fe	Cu
pH	1.000	.361	.399	-.022	-.337	-.166	.112	-.295	-.867	-.153
Cond.		1.000	.200	.086	-.132	.130	.154	-.030	-.429	-.092
Lime			1.000	.166	-.505	-.342	.010	-.390	-.304	-.117
OM				1.000	-.219	.166	.093	.194	-.028	.085
P					1.000	.519	-.051	.444	.360	.106
K						1.000	-.132	.491	.214	.225
NO_3							1.000	-.126	-.179	-.106
Zn								1.000	.347	.629
Fe									1.000	.187
Cu										1.000

VARIABLE NUMBER	Mn	Silt	Clay	SO_4	CEC	Mg	Ca	K	Na	Zn
pH	-.851	-.240	.062	.563	.146	-.054	.297	-.142	.219	.046
Cond.	-.328	.027	-.243	.278	.017	-.050	.360	.258	.177	-.002
Lime	-.390	.190	.333	.579	.314	-.093	.014	-.294	.153	-.126
OM	-.018	.458	.285	.026	.347	.131	-.233	-.247	-.059	-.088
P	.456	-.223	-.368	-.442	-.501	.058	.005	.298	.097	-.092
K	.395	.236	-.060	-.265	.011	.203	-.016	.177	.142	-.122
NO_3	-.271	-.274	.056	.089	.016	-.098	.102	.041	-.023	.059
Zn	.452	.230	-.029	-.367	-.062	.181	-.120	.171	-.055	.120
Fe	.912	.345	.041	-.401	-.102	-.004	-.302	.114	-.231	-.049
Cu	.314	.348	.355	-.121	.363	.134	-.188	.109	-.053	-.067
Mn	1.000	.403	-.023	-.498	-.090	.044	-.246	.186	-.180	-.060
Silt		1.000	.392	.094	.558	.068	-.386	-.232	-.112	-.149
Clay			1.000	.316	.814	.228	-.329	-.250	-.024	-.161
SO_4				1.000	.324	-.077	.096	-.105	.171	-.057
CEC					1.000	.176	-.205	-.213	-.020	-.063
Mg						1.000	.076	.054	.140	.016
Ca							1.000	.586	.339	.185
K								1.000	.136	.202
Na									1.000	-.015
Zn										1.000

VARIABLE NUMBER	Mn	Fe	Cu	N	P	S
pH	.209	-.107	.293	.001	-.013	-.095
Cond.	.444	-.067	.051	.395	.090	.212
Lime	-.006	-.041	.214	-.090	.025	-.100
OM	.078	.112	-.098	.108	.073	.015
P	.113	.167	.032	.029	.003	.292
K	.368	.061	.037	.126	-.103	.119
NO_3	.097	-.067	-.142	.172	.033	.142
Zn	.112	.092	-.058	.030	-.062	.143
Fe	-.202	.072	-.226	-.070	-.057	.091
Cu	-.029	.017	.043	.022	.071	.036
Mn	-.106	.122	-.164	-.002	-.015	.114
Silt	.032	.053	-.053	.088	.153	-.180
Clay	-.114	.010	.125	-.075	.192	-.243
SO_4	.115	-.112	.148	.077	.316	.103
CEC	-.015	-.059	.096	-.008	.191	-.251
Mg	.344	.252	.061	.090	.015	-.001
Ca	.477	-.145	.024	.164	-.248	.265
K	.378	.035	-.081	.327	-.104	.548
Na	.451	-.248	.212	-.013	.025	.067
Zn	.216	-.043	-.050	.161	-.184	.136
Mn	1.000	-.047	.111	.289	-.070	.244
Fe		1.000	-.190	.095	-.069	.006
Cu			1.000	.072	.159	.075
N				1.000	.128	.452
P					1.000	.283
S						1.000

* Variables 1-15 are soil variables.

** Variables 16-25 are plant variables.

APPENDIX G

Summary of Blue Grama and Wheat Regression Analysis

Dependent Variable	Independent Variable	RSQ	F-Value to Enter or Remove
	BOGR		
Ca	Clay	.099	5.91
	SO_4	.162	4.01
K	pH	.174	11.4
	K	.243	4.81
	SO_4	.281	2.74
	NO_3	.321	3.02
Fe	Cu	.076	4.44
	TRAE		
Ca	Silt	.149	11.5
	Cond.	.286	12.5
K	Cond.	.066	4.69
	OM	.139	5.50
	K	.175	2.77
Mn	K	.135	10.3
	Mn	.210	6.18
Cu	pH	.086	6.19
N	Cond.	.156	12.2
P	SO_4	.100	7.33
S	P	.085	6.15
	SO_4	.152	5.13