IRRIGATED CORN YIELD AS RELATED TO SPATIAL VARIABILITY OF SELECTED SOIL PROPERTIES IN A SILTY CLAY LOAM AND SANDY SOILS

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2000

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by

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A DISSERTATION

Presented to the Faculty of

The Graduate College at the University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Doctoral of Philosophy

Major: Agronomy

(Soil and Water Science)

Under the Supervision of Professors:

John W. Doran and Darrell G. Watts

Lincoln, Nebraska

June, 2000

DISSERTATION TITLE

Irrigated Corn Yield as Related to Spatial Variability

of Selected Soil Properties in Silty Clay

Loam and Sandy Soils

BY

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GRADUATE COLLEGE
UNIVERSITY OF NEBRASKA

IRRIGATED CORN YIELD AS RELATED TO SPATIAL VARIABILTIY OF SELECTED SOIL PROPERTIES IN SILTY CLAY LOAM AND SANDY SOILS

Antonio Marcos Coelho, Ph.D.

University of Nebraska, 2000

Advisors: John W. Doran and Darrell G. Watts

Precision farming is important to development agricultural production systems and has created a need for spatial data on crop yield and soil characteristics. The objectives of this research were to identify: (i) the spatial and structural variation of soil properties across the landscape; (ii) how yields are related to these soil properties; and (iii) how information of spatial variability within soil physical, chemical, and biological properties can be used to assess in field soil degradation.

On farm research was conducted on center-pivot-irrigated fields in Adams and Buffalo Counties, Nebraska, during 1997 and 1998. Samples were taken and analyzed soil physical, chemical, and biological properties, plant population, leaf tissue analysis for nutrients, and grain yields. Factor analysis, multivariate linear regressions, and geostatistics were used to explore soil and crop variability, and classify and map soil properties in the fields.

On the farm field with a finer textured silty clay loam soil, soil variation was decomposed into five factors, which accounted for 75% of the total variance. Regression models based on these factors showed that soil fertility as related to available phosphorus and manganese, as associated with organic matter, was associated with 73% of corn yield variability. However, the application of Mn and P fertilizers did not improve significantly

the corn grain yield. These indicated that yields were limited by constraints other than P and Mn. The results suggest the need for careful interpretation when using statistical models to seek cause and effect relationships related to yield variability in fields.

On the farm field characterized by sandy soils, most of the soil variation related to crop growth was described by five factors, which collectively explained 85% of the total soil variability. Regression models based on these factors were associated with 50% of the corn yield variation. Soil physical-chemical factor, as related to organic matter, texture, bulk density, and pH had the largest effect on the variation of corn yield.

Loss of organic matter due to erosion, intensive tillage and input of nitrogen fertilizer, acidification and compaction were some indicators of soil and environmental degradation under current management practices.

ACKNOWLEDGMENTS

As expected, words will never really express my gratitude to the people and institutions mentioned herein, nor do justice to their efforts in assisting and encouraging me from the beginning until the completion of this work.

I would like to express my sincere gratitude to Empresa Brasileira de Pesquisa Agropecuària – EMBRAPA-Brazil, by the opportunity and financial support.

I would specially like to thanks Dr. John W. Doran and Dr. Darrell G. Watts my advisors, for this research and my degree, for simply weathering the storms with me, even though sometimes the turbulence was actually myself. I am grateful that both of you allowed me to "earn my wings" on my own, both inside and outside the university, even though the journey took longer than expected.

Dr James S. Schepers for always smiling and staying upbeat despite any gloom and doom that came our way during the completion of this research and for being like a adviser to me, and by the opportunities to attend the conferences.

Dr. David T. Lewis for graciously serving on my graduate committee and sharing his expertise.

Thanks also for the much needed assistance given by USDA-ARS-Lincoln, especially Denis Francis, Wallace Wilhelm, Mike Schlemmer, Tim Kettler and Spencer Arnold, for providing the research facilities and equipment.

Finally, I specially thank my wife, Jussara, my sons Igor and Andrei, and my daughter Kenia for enduring this period of graduate school with me. Their love, faith and support enable me to complete my studies with joy. I dedicate this work to them.

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INTRODUCTION

In Nebraska, over 2.5 million hectares of dry pasture and prairies have been converted into highly productive irrigated cropland since the dust storms and long periods without rain of the 1930s (drought-filled "Dust Bowl"). This expansion of agricultural production can be largely attributed to the development of local ground water resources through the introduction of improved irrigation technology during periods of drought. Other contributing factors include the expanded use of fertilizers, mainly nitrogen and other agricultural chemicals, historical increases in both crop prices and credit availability, and the establishment of tax incentives for development of agricultural land (Supalla et al., 1986).

The most recent agricultural census show that corn is the main crop cultivated in Nebraska, achieving 2.0 million hectares harvested in 1998, of which 1.6 million hectares (78%) were irrigated for grain or seed production. The average grain yield was 10.35 Mg ha^{-1}, which is 40% higher than the average grain yield obtained under dryland conditions (7.35 Mg ha^{-1}) (U.S. Department of Agriculture, 1998).

Although systems of corn production vary across Nebraska, there are some physical attributes that can be compared or contrasted regardless of farm operation type, such as area of crop harvested. Observing the comparison of area (Figure 1) shows that more than 40% of the irrigated producers grow corn on areas of 100 hectares or more. The largest and smallest areas recorded were >100 and <10 hectares, respectively.

Advances in technology, as well as other factors such as farm policy, have contributed to increases in the size of individual farms and fields within a farm. With this larger scale of operation, the potential for the individual farmer to effectively manage variability by observation and experience, has declined precipitously (National Research Council, 1997). In addition, as individual farm fields increase in size, variability within field has generally increased.

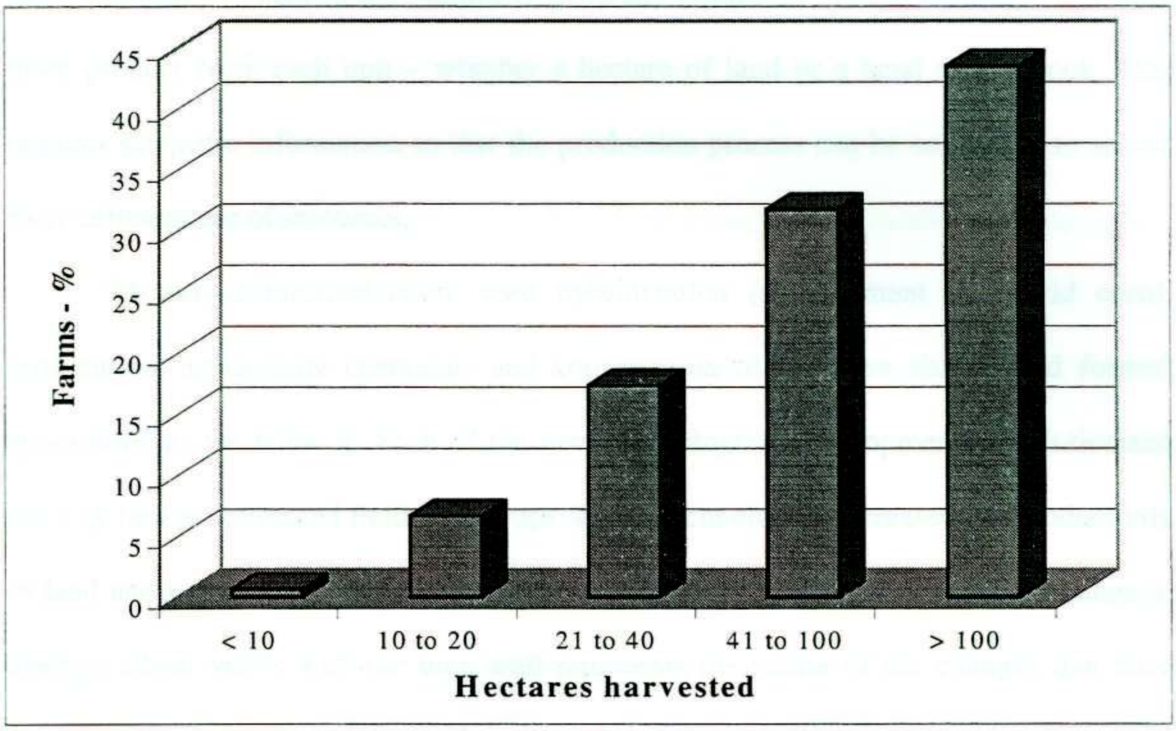

Figure 1. Area of corn for grain or seed harvest from irrigated farms in Nebraska, in 1998. (Modified from U.S. Department of Agriculture, 1998)

All agricultural production results from the capture of solar radiation by the process of photosynthesis by plants. The overall efficiency of the photosynthetic process is low. Spedding et al. (1981) presented data for the conversion of energy in solar radiation to energy in the agriculture products from crops (energy produced per MJ solar radiation received). The data range from 0.12% for field beans yielding 2.5 Mg ha^{-1}, to 0.20% conversion by wheat and corn yielding 4.5 Mg ha^{-1} of grain, and 0.70% conversion by a crop of grass yielding 12 Mg ha^{-1} of dry matter.

The task of agricultural scientists is to make this process more efficient. This is done by identifying constraints in agricultural systems, then by improved soil and crop management, such as tillage, controlling plant populations, input of fertilizers, and pest and disease control, we plan to overcome these constraints. At the same time other scientists endeavour to increase the genetic potential of our plants by selection and breeding. Improvement in agriculture is generally related to intensification. We require more product from each unit – whether a hectare of land or a head of livestock. This requires scientific information so that the production process can be controlled to secure more efficient use of resources.

Motorized mechanization, seed hybridization (development of hybrid corn), fertilization, agricultural chemicals and conservation tillage have shaped and formed agriculture, as we know it. Each of the new technological developments revolutionized the way farmers managed fields and crops. These technologies increased the productivity of land and indirectly the efficiency of the solar radiation captured by plants. Change in average wheat yields with the time well represents the nature of the changes that have occurred in agriculture. At the beginning of this century in Western Europe, wheat grain yields were on the order of 1.5 Mg ha^{-1}. Today, yields are commonly 5 to 6 fold higher, 7 – 9 Mg ha^{-1} (Rabbinge, 1997).

Today, new revolutions, in philosophy and technology are reshaping agriculture and crop management and there is greater emphasis on soil and environmental quality and precision agriculture. In the past, most emphasis had been placed on production of agricultural crops. In 1960, more than 80% of private research funding was to improve farm machinery, while public research focused on increasing crop yields. By 1992, 60% of private research was also devoted to increasing crop yields through improvement in crop varieties and increased use of agricultural chemicals (National Research Council, 1997).

Increasingly, however, attention is being paid to the environmental side effects of agricultural production and to product quality (Bouma, 1997). For example, leaching of agrochemicals to ground water should be limited to quantities that do not exceed certain quality standards. Protection of water quality has long been a high priority of the general public. Legislation defining and regulating "clean water" is well established throughout the world.

Interest in the concept of soil quality has recently been renewed. Soil quality was defined by an ad hoc committee of the Soil Science of Society of America (SSSA, 1995) as, "the capacity of a specific kind of soil to function within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water quality, and support human health and habitation". Soil quality was conceptualized as, "a three-legged stool, the function and balance of which require an integration of three major components – sustained biological productivity, environmental quality, and plant and animal health" (Karlen et al., 1997; Doran et al., 1999). Several attributes have been suggested as being useful for assessing changes in soil quality, reflecting changes over space and time (Doran et al., 1994). Evaluation of pH, electrical conductivity, organic carbon and nitrogen content of soils are essential for assessing chemical aspects of soil quality (Doran and Parkin, 1996). Assessment of chemical aspects of soil quality is important, because they provide an indication of the ability of soil to supply plant nutrients and the capacity for buffering against chemical additives or amendments. Soil organic matter content is often used to assess the impact of management practices on soil degradation, because it can be directly related to soil structural stability and the nutrient supplying power of soil.

The other revolution related to precision agriculture is spatial and temporal variability in crop production systems. Since the mid -1980s, a host of terms have been used to describe the concept of precision agriculture: farming by foot (Reichenberger and Russnogle, 1989); farming by soil (Carr et al., 1991; Larson and Robert, 1991); variable rate technology (VRT) (Sawyer, 1994); site-specific crop production (Schueller, 1991); and site-specific crop management (SSM) (Pierce and Sadler, 1997). Soil – specific crop management (SSM) is a holistic attempt to identify and analyze soil characteristics, cropping history, climate and other crop production variables at multiple locations within fields. Production techniques including input application are then customized for these specific locations.

Precision farming is a new technology with a long history (Figure 2). Farmers have long tried to maximize crop yields and profits by spatially varying input applications (Lowenberg-Deboer, 1998). Farmers of ancient times were keen observers of crop performance and recognized benefits from spreading different amounts of manure and liming materials on different kinds of soils (Kellogg, 1957). In the 1620s, colonists observed the site-specific fertilizer practice of Indian farmers who placed fish directly at the roots of each plant. In 1929, researchers Bauer and Linsley as cited by Goering (1993) suggested marking a field in 100 meter space intervals in the north-south and east-west directions to determine field position for variable application of limestone material.

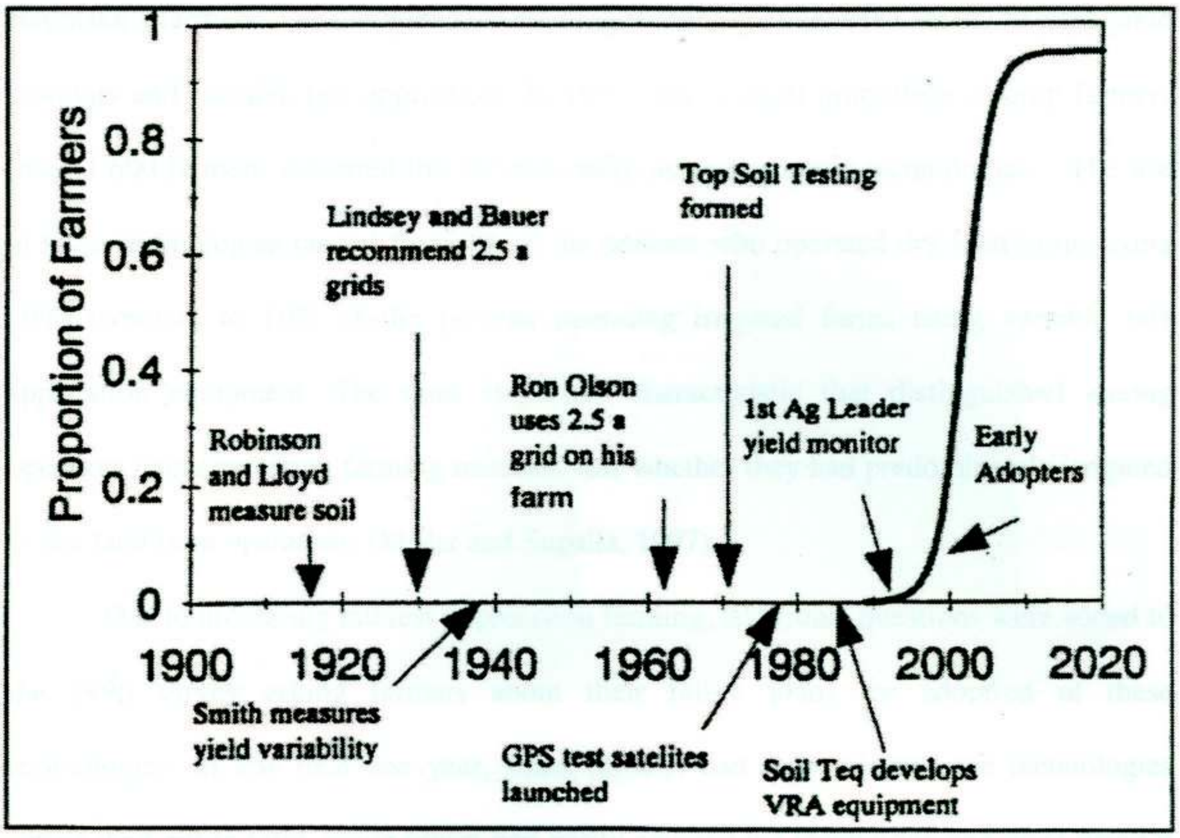

Figure 2. History of site-specific management and potential for adoption of new technologies in precision farming. (after Lowenberg-Deboer, 1998)

Mechanization made it profitable to treat large areas with uniform inputs. Inputs tend to be supplied on a maximum response, whole field basis. Global positioning system (GPS) and other precision farming technologies, promise to reverse that trend to make it economically feasible to manage crops on a more site-specific basis and to standardize crop receipts. Today's information technologies have the potential to generate more sophisticated assessments and responses to within-field heterogeneity and variation in soil fertility.

The initial interest about precision farming operations has resulted in the adoption of a variety of technologies that are potentially useful for making site-specific management decisions. During the years of 1995 and 1996, Miller and Suppala (1997), conducted a representative survey of the adoption of precision farming technologies by

Nebraska's farmers. The two precision farming technologies selected for study were yield monitors and variable rate applicators. In 1995 only a small proportion of crop farmers (over 1,600 farmers answered the surveys) were using these two technologies. The use of these technologies ranged from 2% of the persons who operated dry land farms using yield monitors to 10% of the persons operating irrigated farms using variable rate application equipment. The most important characteristic that distinguished among operators using precision farming methods was whether they had predominately irrigated or dry land farm operations (Miller and Supalla, 1997).

Due to increasing interest in precision farming, additional questions were added to the 1996 survey asking farmers about their future plans for adoption of these technologies. In less than one year, some farmers had fully adopted the technologies across their entire farm, while others had partly adopted the technology and were using it on a few fields. The proportion of farmers with irrigation systems who used yield monitors on their farm operation increased from 6% in 1995 to 9% in 1996. Similarly the use of variable rate applicator by farmers with irrigated operations doubled to 18%. Producers with dry land farms increased their use of yield monitors to 4% of the farm operations and their use of variable rate application to 18% in 1996. In addition to the increase in use that occurred between 1995 and 1996, a large number of farmers in 1996 indicated that they would adopt these technologies by the year of 2001 (Miller and Supalla, 1997), (Figure 3).

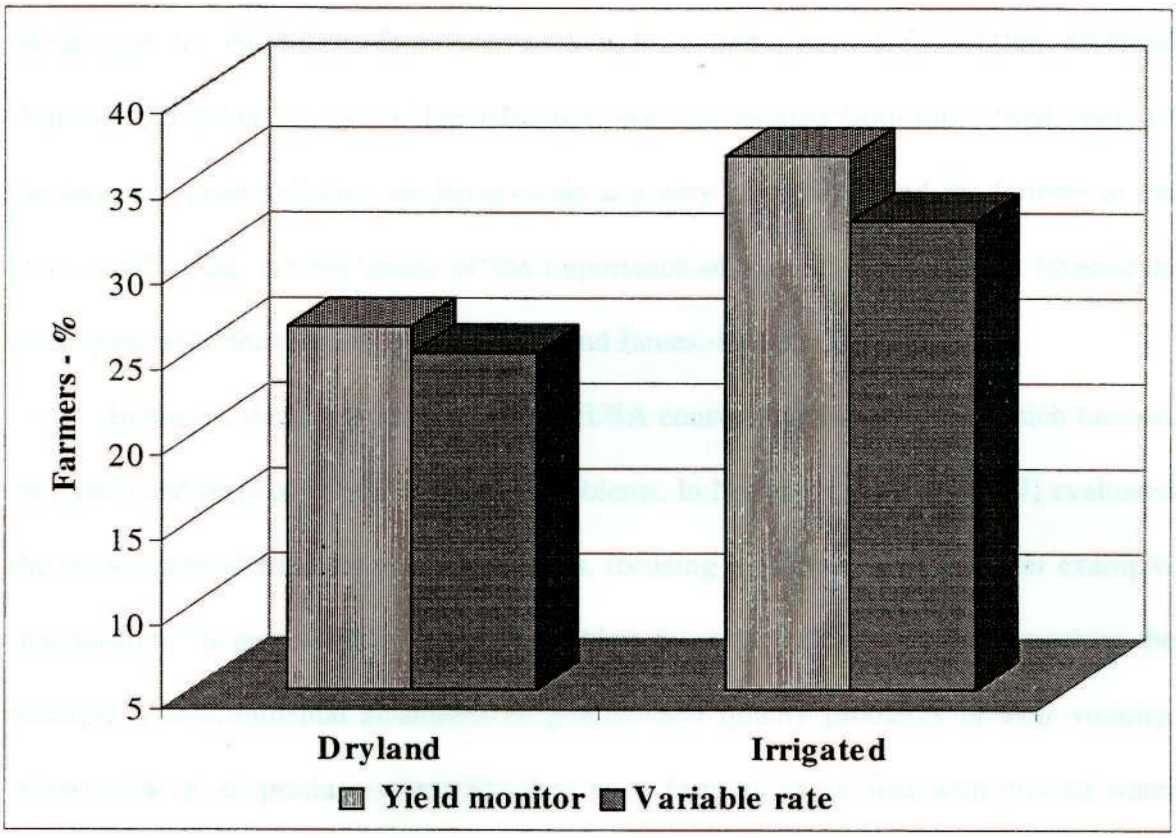

Figure 3. Estimative of potential for adoption of precision agriculture technologies by farmers in Nebraska from 1996 to 2001. (modified from Miller and Supalla, 1997)

The main aim of precision agriculture is to manage all parts of an individual cropped area in an optimal way such that farm profits are maximized and the impact of farming on the environment is minimized. It is incorrect to say that the goal of precision agriculture is to result in uniform yields across the whole field. Precision agriculture seeks to realize the potential crop yield, crop quality and gross margin of all parts of a field, with minimum impact on the environment. Principal environmental problems of agriculture include water, air and food quality, and natural resources depletion.

Frequently, environmental problems are first noticed at a very large scale, such as the ones in the Gulf of Mexico, which receives water from large catchment systems feeding into the Mississippi river. In the Gulf of Mexico there is a large zone of hypoxia (a zone of low oxygen), which is thought to be the result of nitrogen that is being transported by the Mississippi river system from agriculture areas of the Midwest (Randall and Schepers, 1997). The paradigm that has resulted from this is that many of the decision about pollution are being made at a very large scale, and the farmers at the local, small-scale, are not aware of the importance of what they do and its large-scale consequences to the environment (Burkart and James, 1999).

However, there is some work in the USA concerning the extent to which farmers recognize and respond to environmental problems. In Nebraska, Juliano (1997) evaluated the environmental attitudes of the producers, focusing on different aspects. For example, one question "is ground water quality a problem in my area?" was asked to measure the producer's environmental awareness of groundwater quality problems in their vicinity. About 50% of all producers believed they were farming in an area with ground water quality problems, with at least 10% remaining neutral or undecided, and, almost 75% of producers were willing to protect ground water, while 85% were aware that ground water quality could impact human health. The positive response was due mainly the prevalence of ground water quality issues in Nebraska agriculture and local mass media, as well as the emphasis on environmental education since the early 1970s (Juliano, 1977).

PURPOSE AND OBJECTIVES OF THE STUDY

The purpose of this study was to evaluate the spatial variability of soil properties and corn yield in different soil types, under irrigated agricultural conditions in the Platte River Valley of South-Central Nebraska.

The results will contribute to understanding the relationships between the variations in crop yields and soil properties that can lead to the development of better criteria for diagnosing soil constraints to crop growth and advance our ability to predict and increase yield.

Hypothesis

Unlike dry-land crops, under irrigated conditions the soil physical – chemical properties are the main factors affecting yield variability. Through the use of modern sampling and analysis techniques it is possible to accurately and reliably identify and interpret cause and effect relationships, a prerequisite for the success of site-specific soil and crop management.

The identification of cause and effect in the crop yield variability may not necessarily imply recommended precision agriculture technologies. However, it could be an important tool to identify the effect of management in degrading soil properties and to suggest options of management practices for the enhancing sustainability of the system.

Objectives

The specific questions addressed by this research are: (i) to identify the spatial and structural variation of soil properties across the landscape, (ii) to show how crop growth and yields are related to these spatially distributed soil properties and how soil differences can have a significant effect on corn productivity, (iii) to show the implication of site-specific or whole field management, and (iv) to use the information of spatial variability of soil physical-chemical properties to assess within field soil degradation.

REVIEW OF RELATED LITERATURE

Precision agriculture or site-specific crop management is concerned with the management of variability in the dimensions of both space and time. Without variability, the concept of precision agriculture has little meaning (Mulla and Schepers, 1997) and would never have evolved. Therefore, aspects of precision agriculture encompass a broad array of topics, including variability of the soil resource base, weather, plant genetics, crop diversity, machinery performance, and physical, chemical, and biologic inputs used in the production of a crop, whether natural or synthetic (Pierce and Nowak, 1999).

Although studies of soil variability are usually linked to the concept of precision agriculture, the identification of soil variability could also be used as an important tool to evaluate the effect of management on soil properties and as an indicator for procedures related to sustainable strategies in crop production.

SPATIAL AND TEMPORAL VARIABILITY OF FIELD SOILS

As discussed by Dahiya et al., (1984) and Burrough (1993), the spatial variability of field soils is an important feature in the identification of soil properties relative to: (i) describing, classification and mapping soils (ii) crop production; (iii) irrigation scheduling; (iv) land drainage; (v) land reclamation; (vi) runoff pollution; (vii) ground water contamination; (viii) pesticide management; and (ix) liquid waste disposal from municipalities, industries and nuclear power.

In realization of the importance of the spatial and temporal variability of soils in many fields of agriculture, some reviews have been written: Beckett and Webster (1971) mainly concerned with spatial variation of usual soil survey parameters of mapped soil units; Biggar (1978) focused on the spatial variability of nitrogen in soils; Warrick and Nielsen (1980) indicated the features of some methods of evaluating variability of soil physical properties; Upchurch et al. (1988) discussed the theoretical basis in application of selected statistical tools to summarize spatial variability of soils; and Dahiya et al. (1984) review the available, but widely scattered information on soil variability ad its significance in different areas of research, sources and magnitude of lateral and vertical spatial variability in natural and cultivated landscape, and classical statistical and geostatistical methods of evaluating soil variability.

The first meeting of the working group on spatial and temporal variability on field soils was held in Las Vegas, NV, in 1984, and was sponsored by the International Society of Soil Science, Soil Science Society of America and the U.S. Department of Agriculture. The meeting entitled "Workshop on Soil Spatial Variability", and its objectives were to explore and discuss alternative statistical concepts and procedure for: (i) enhancing the understanding and development of pedology, and (ii) improving technology of soil survey, soil science, and hydrology applied to management of field soils. (Nielsen and Bouma, 1985)

More recently, Burrough (1993) reviews the progress that has been made in the last twenty years in our ability to record, analyze and use of information about the spatial variation of soil. From this review he concluded: "In spite of a huge literature, knowledge about soil variability is still dispersed and not well organized. There is a need to organize and systematize our knowledge on soil variability in such a way that the user of soil information unskilled in geostatistic or chaos theory can make the best possible use under conditions of uncertainty"

Although these literature reviews very well documented the affects of geologic origin, climatic and chemical process, and the effect of human management in modifying and complicating soil variability, the effect soil management and crop growth had not been explored. Only recently has research attempted to define management zones based on common soil and landscape characteristics. Recognition of the degree of soil variability and its effect production is encouraging change in soil management. The holistic approach to managing the relationship between soils, plant growth, climate, pests and other variables is evolving. This extensive effort in soil inventory has laid the foundation for soil specific and crop management.

Typical Magnitudes of Variability

Farmers, soil scientists, agronomists, etc, have long recognized the spatial variability of soil properties. The relationship between parent material, topography, elevation, time and the resultant soil's physical-chemical properties have led to appreciation of the variable nature of soils in the landscape. The degree of spatial variation in a soil depends on soil forming process and their balance in space and time. Considerable short-range differences in parent material, drainage and biological activity (including human) can cause large differences in soils over short distances (Beckett and Webster, 1971; Burrough, 1993).

According to Wilding (1985), a few generalities that should be considered about spatial variability are: (i) soil spatial variability is a function of the nature of parent material. From least to most variable are loess < till < fluvial deposits, < tectonic rocks < drastically disturbed soil materials; (ii) reliability in accurately predicting many soil properties decreases with depth (iii) static soil properties (O.M., texture, mineralogy, solum depth, soil color) are less variable than dynamic ones (moisture content, hydraulic properties, salt content, microorganisms, exchangeable cations and redox conditions); (iv) properties which can be closely calibrated to a standard, or quantified in the field (texture, color, pH), are less variable than those which are qualitative (structure, consistence, porosity, etc).

Some differences between soil properties commonly sampled for site-specific farming applications are illustrated in Table 1. Some of the most extensively characterized soil properties involve soil fertility. Soil pH exhibits little spatial variation with coefficients of variation (CV) values that are typically 10 % (Pierce et al., 1995). Soils are generally well buffered against pH changes, unless subsurface soils are exposed. However, the pH is measured at logarithmic scale and its CV is not directly comparable to other soil properties. Nitrate, organic matter content and plant available potassium have all been found to exhibit high CV values (Ferguson et al., 1995; Gotway et al., 1996; Wollenhaupt et al., 1994). Plant available soil phosphorus often exhibit extremely high CV values, particularly where animal manure's were applied preferentially to one part of the field (Ferguson et al., 1995; Wollenhaupt et al., 1994). Extractable micronutrients (Zn, Mn, Cu, Fe, and Co) have showed high spatial variability and their distribution largely dependent on soil texture, organic carbon, cation exchange capacity and pH (Paz et al., 1996).

Sampled properties also can be classified according to the extent of their variability in time (temporal). Static properties that do not change appreciably within a time frame of several seasons include organic matter content, cation exchange capacity, and texture. Dynamic properties that exhibit seasonal and annual variations include for example soil inorganic nitrogen (NO_3 and NH_4), and moisture.

Table 1. Relative ranking of variability of soil properties that occurs in natural and cultivated landscape (modified from Wilding, 1985; Dahiya et al., 1984).

Variability of Property	Property
Least (CV's < 15 %) Relatively less affected or unaffected by management	Soil color (hue and value) Soil pH Thickness of A – horizon Bulk density Available water capacity Total silt content
Moderate (CV's 15 to 35 %)	Total sand content Total clay content Cation exchange capacity Base saturation Soil structure (grade and class) Calcium carbonate equivalent
Most (CV's > 35 %) Relatively more affected by management	Exchangeable hydrogen, calcium, magnesium and potassium Electrical conductivity Organic matter content Soluble salt content Hydraulic conductivity Water content Micronutrient (Zn, Mn, Cu, Fe) Inorganic – N (NO_3 and NH_4) Available - Phosphorus

Although, the amplitude of variation, as measured by the coefficients of variation (CV's defined as the ratio of the standard deviation to the mean) have been used as the primary objective to assess the relative variability of a soil properties, its importance for site-specific crop management or variable rate of inputs application may not have practical significance. As observed by Wright et al., (1990), Pierce et al., (1995), and Timlin et al., (1998) the soil fertility factors had little relationship with corn yields, mainly due to high sufficiency levels of measured nutrients in the fields. Thus, a parameter can vary spatially but not deviate sufficiently from the mean field-value or values do not fall within a range manageable by current applications of precision agriculture (Pierce and Nowak, 1999).

Precision agriculture is based on the availability of intensive data about important agronomic indices. The process of obtaining these data involves a cost and the greater the data requirement the greater the cost. As a result, producers and their advisors must decide how detailed the required data should be. The practicality of the data often depends on how long information has value in management decisions. Indices such as soil type and topography have long-term usefulness. The investment in obtaining this information will have returns for many growing seasons. Factors such as nutrient availability, except inorganic nitrogen, may exhibit intermediate usefulness because they change slowly. Available soil moisture and inorganic nitrogen are components of a short-term dynamic index of soil condition for plant growth.

SPATIAL AND TEMPORAL VARIABILITY OF CROP YIELDS

A successful implementation of precision agriculture will depend on the ability of individual growers to manage their crops differentially to achieve the multiple goals of maximizing yield or profit while minimizing environmental impact. Assessing crop yield variability is the critical first steps in precision agriculture since it is clear that one cannot manage that which can't be measured or identified. Adequately quantifying the spatial and temporal variation in crop yield and the process responsible for it is the challenge facing precision agriculture (Mulla and Schepers, 1997).

Quantifying Spatial and Temporal Variability

Farmers and researchers have known in a relative sense that crop yields are not uniform across fields. Some locations will consistently produce higher or lower yields than the field average, while others locations produce higher or lower yields in some years but not in others (Jaynes and Colvin, 1997). This is particularly true for rainfed crops, but also applies to irrigated production. Such variations decrease the effectiveness of uniformly applied soil management practices on a field scale, reducing the productive potential of a given area.

Uniformity trials have been used to study soil heterogeneity by simply planting a crop that was uniformly managed throughout the growing season. Fields are divided into small segments and crop yields are measured on each segment. Crop yields variability among segments are the measure of varying levels of soil fertility in the field (National Research Council, 1997). Crop yields obtained from uniformity trials were plotted on a map, and field segments having similar yields, were connected by smooth lines. These yield maps were interpreted as soil fertility contour maps.

One of the early works on spatial variability of crop yields, using blank experiment (sometimes called uniformity trials in which the yield from a field is determined by harvesting a number of small plots), was reported by Smith (1938). In fact, he presented one the earliest yield maps, derived from data collected in Australia (Figure 4). It is typical of modern maps in that it shows approximately 100 % variation in yield from lowest to highest across the area of study. However, the objective of Smith was not to use the concept of site-specific crop management, but to determine the best size of experimental plots to improve the efficiency of field experiments.

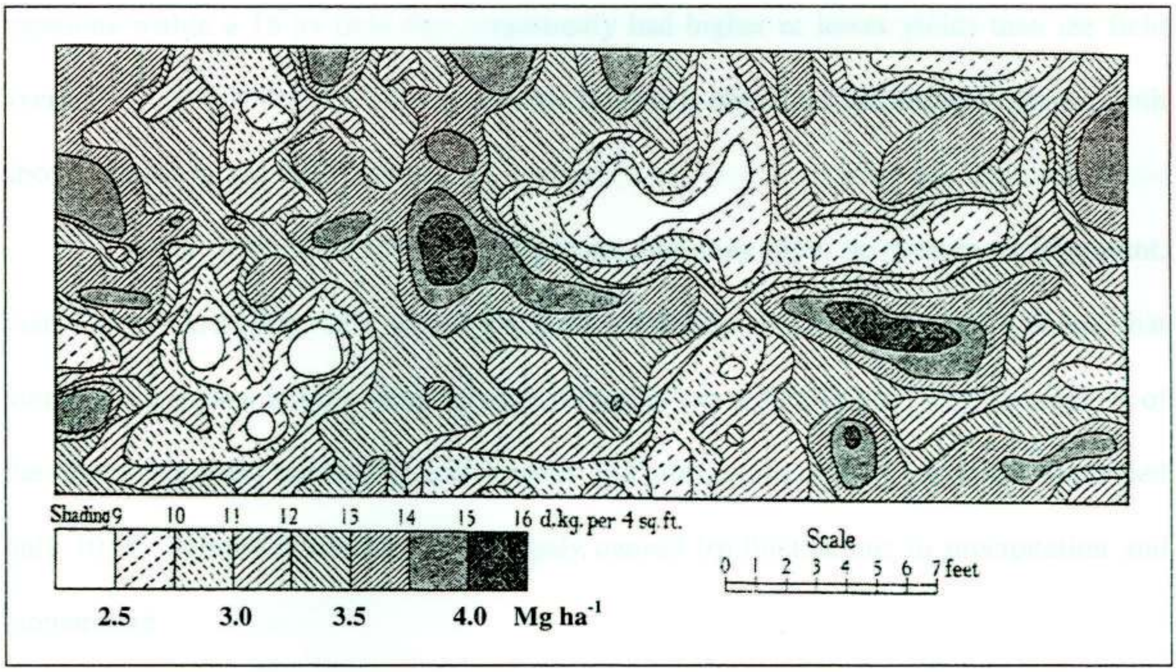

Figure 4. Wheat yield contour map derived from data collected in Canberra, Australia. (Smith, 1938).

With the recent evolution of yield monitors, quantitative measurement of within field yields variations is now simple and inexpensive. It will become routine, allowing for more systematic study of yield, both the spatial and temporal components (Borgelt, 1992, and Colvin et al., 1995). It is estimated that yield monitors were used in roughly eight percent of grain and oilseed acreage in North America in 1997 (Lowenberg-Deboer, 1998).

The spatial variation in crop yield at regional scales is often considered to be the consequence of variability in the interaction between crop genetics and environmental factors (Bresler et al., 1981). However, at the field scale, site-specific variation in soil type, nutrient levels, soil moisture content and structural integrity will significantly contribute to the spatial variability in crop yield (McBratney et al., 1997).

In a recent paper, Colvin et al., (1995), for example, documented the great variability in corn and soybean yield across space and among years. They found several locations within a 16-ha field that consistently had higher or lower yields than the field average for a 6-yr period. Most locations, however, exhibited inconsistent yields, both above and below the field average.

Climatic variability is no less important, and may often be even more important, than spatial variability. In a long-term study, Huggins and Alderfer (1995) found that temporal variations in corn grain yield (< 4 Mg ha^{-1} to > 10 Mg ha^{-1}) explained 67 % of the total grain yield variability across years and sites, while spatial variations explained only 10 %. Temporal variations are largely caused by fluctuations in precipitation and temperature.

Crop yield exhibits moderated spatial variability with CV values raging from 8 to 29 % (Ferguson et al., 1995; Pierce et al., 1995). Even with moderate values for CV, the differences between maximum and minimum crop yield within a field can range from 1.0 Mg ha^{-1} to 8.0 Mg ha^{-i} (Mulla et al., 1992). Thus, CV is not necessarily a good indicator of the possibility for extremely high or low data values.

RELATIONSHIP BETWEEN SPATIAL VARIABILITY IN SOIL PROPERTIES AND CROP PRODUCTION

Information on the spatial variability and distribution of crop yield can be used to tailor management practice for specific locations within field. Yields can be mapped in detail, and techniques are needed to interpret yield maps in terms of soil variability and to develope site-specific management practices based on that variability.

Many approaches have been used to identify spatial variability within a field, including yield monitors, soil survey, grid soil sampling, electronic sensors and remote sensing (Yang et al., 1999). Obtaining a clear understanding of the nature and causes of variation in the crop yields is critically important. A yield map defines the spatial distribution of crop yield but does not explain the observed variability. Thus, data in crop performance must be integrated with other information to understand the causes of variation (Figure 5). The more information you have about a problem, the more able you are to make a decision.

If site-specific management is to be successful it must be based on techniques that encompass the simultaneous effect of the most important factors influencing yield, rather than individual factors taken in isolation. According to Dampney and Moore (1999), there are three main categories of factors that can cause spatial variation in crop yields: fixed site characteristics, not easily altered (e.g., soil texture and depth of rock); persistent site characteristics, which may be altered (e.g., soil pH, soil nutrients); and short-term seasonal factors (e.g., weather, foliar diseases and pests).

In many crop production areas, landscape factors can cause dramatic variations in yield. Landscape elements affect many properties relevant to plant growth, including soil texture, soil organic matter, and temperature. Landscape morphology affects soil moisture available to crops by its influence on soil depth, drainage, and catchment area.

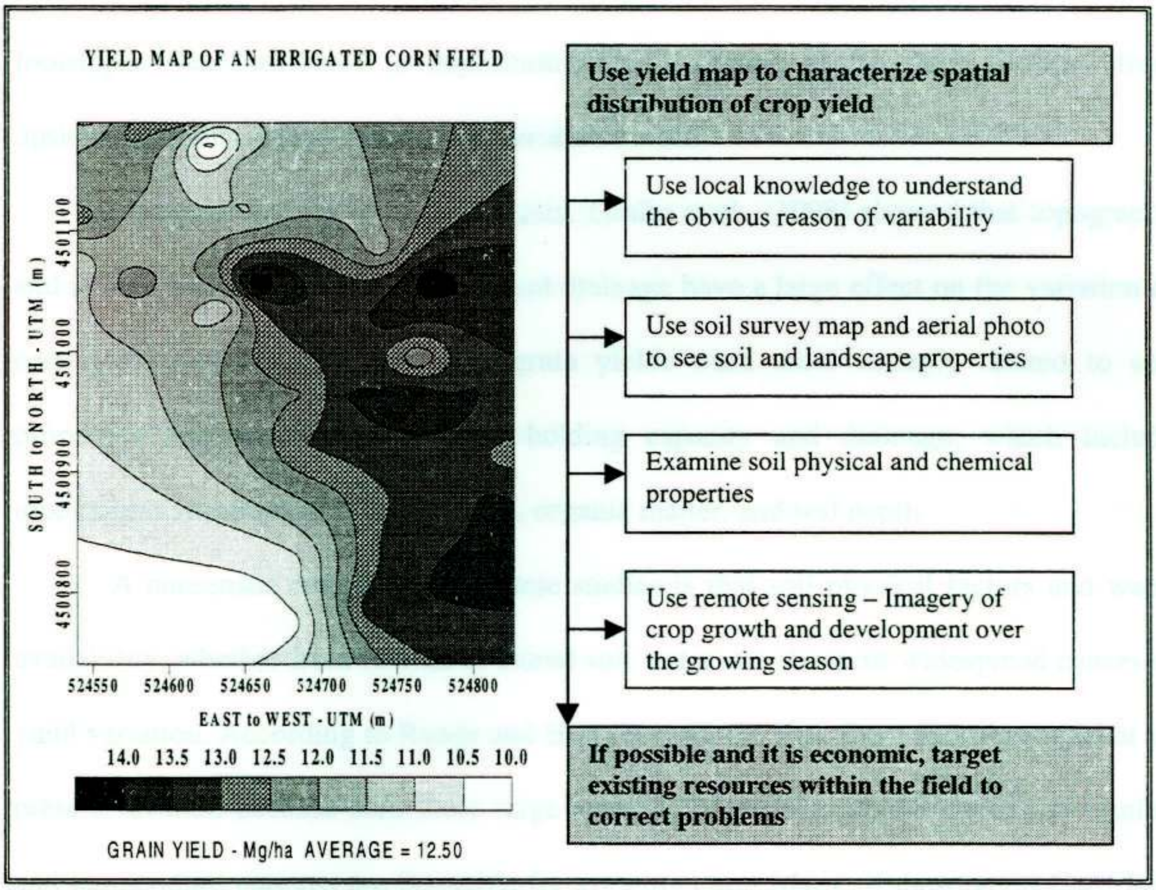

Figure 5. A practical scheme for identifying the reasons for yield variations

Several studies have shown that landscape positions, which vary in several soil properties, greatly affect crop productivity (Ciha, 1984; Stone et al., 1985 Miller et al., 1988; Peterson et al., 1993; Vetsh et al., 1995). In Nebraska, increased corn yields were reported on the upper and lower interfluve and footslope positions while decreased yields were seen on the upper and lower linear slopes (Jones et al., 1989). In Colorado, Ortega (1997) observed that higher corn yields were associated with depositional areas that had higher SOM content and available N, and lower pH values and lower $CaCO_3$ contents. Winter wheat yields and P levels were strongly correlated with landscape positions in northeast Colorado (Ortega et al., 1997). Greater crop yields were obtained in footslope positions compared to the backslope and sideslope positions in western Iowa (Spomer and Piest, 1982) and west central Minnesota (Khakural et al., 1999). Increase yields on footslopes were attributed to deposition of soil, organic matter, and nutrients from upslope positions and additional plant available water.

Using methods of spectral analysis, Timlin et al., (1998) showed that topography and related factors such as soil depth and drainage have a large effect on the variation of corn yields. In this research, corn grain yields were most strongly related to soil properties that are related to water-holding capacity and drainage, which include topographic location, surface curvature, organic matter, and soil depth.

A consensus emerging from these studies is that soil physical factors and water availability, whether from rainfall or stored soil water, are the most widespread causes of yield variation. According to Runge and Hons (1999), the U.S. Corn belt developed at its present location because soils store large amounts of plant available water and rainfall and temperature patterns are favorable for growing corn. Many of these good Corn Belt soils, however, are interspersed with poorer soils with lower water-holding capacities and potentials for growing corn. Yields on poorer soils varied from 6.5 to 67% less than yields for the better soils, depending on rainfall (Runge and Hons, 1999).

Although the recognition of substantial sub-field variation in expected yield, little research has been conducted on interactions between soil characteristics that affect fertility recommendations, such as relative field elevation, organic matter, nitrogen content, and soil moisture.

SAMPLING SCHEMES FOR MAPPING SPATIAL VARIABILITY OF SOIL

When the concept of precision agriculture was developed in the mid 1980's, it was called "farming by soil type". The intention was to use mapping units of the USDA-NRCS (US Department of Agriculture-National Resource Conservation Service) County Soil Survey's (1:20.000 scale) as management unit and soil sampling units. However, it was quickly evident that because of the impact of past nutrient management practices, a more intensive soil sampling protocol was needed (Robert, 1997).

Karlen at al. (1990) found that although soil map unit could explain part of yield variation, the variability within individual soil maps was extremely high. For all crops (corn, sorghum, and wheat) grown over a 4-yr period, variance in yield among plots within a single soil map unit was nearly as large as the variance among soil map units. This indicates that development of management systems for individual soil map units may not be feasible, especially until factors that cause yield variations are better understood. Soil Survey maps provides a sound soil resources inventory for making decisions, but they were not designed for site-specific management (Mausbach et al., 1993).

Sampling schemes can be split into two general categories, random and systematic. Systematic sampling of a site is the most appropriate method for the study of spatial variability. In a systematic sampling scheme care is taken to sample evenly all areas of the study site to allow observation of all variability that exists (Upchurch et al., 1988). Most systematic schemes are variations of grid sampling or transect sampling approaches.

Grid Soil Sampling Design

Grid sampling involves overlaying a grid on the boundaries of a field, and is one method commonly used for assessing variability in soil fertility and provides the basis for variable rate of fertilizer recommendations (Yang, 1999). Grid sampling is a design in which the sampling locations are determined by the intersection of two sets of orthogonal lines. The lines may be either evenly spaced in both directions or have uneven spacing within or between directions (Upchurch et al., 1988). There are other grid-sampling methods referred to as grid-cell and grid-point sampling that can be used for mapping location specific soil test data (Figures 6).

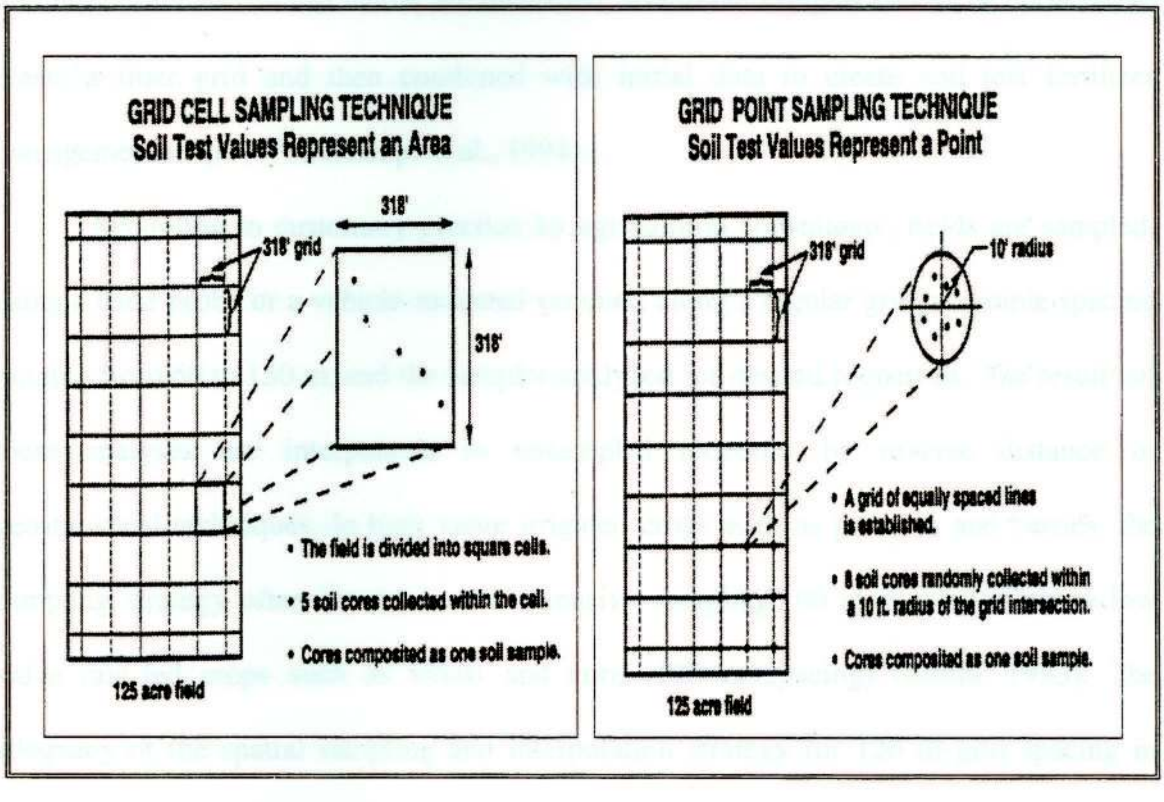

Figure 6. Schematic illustration of the layout of a 318-ft (97 m) grid and locations where soil cores would be collected for a 125-acre (50 ha) field, total of 54 samples. (modified from Wollenhaupt et al., 1994).

According to Wollenhaupt et al. (1994), compared with the grid-cell method the 318-ft (97 m) grid-point sampling technique (Figure 6) resulted in a substantial improvement in mapping accuracy for soil phosphorus and potassium, with a similar investment in soil sampling and testing. Grid-point soil sampling is more efficient than sampling to obtain a representative composite soil core within a cell. However, in order to avoid unnecessary soil sampling costs, a two-step approach to grid-point sampling is recommended. Fields that have shown soil test P and K levels in non-responsive categories and that have consistently received applications of nutrients meeting or exceeding crop removal, should be grid-point sampled on a 300-ft (97 m) grid. If areas of optimum or lower soil test values are identified, additional samples should be collected to create a finer grid and then combined with initial data to create soil test fertilizer management maps (Wollenhaupt et.al., 1994).

According to customary practice by agricultural consultants, fields are sampled, using a hand probe or a vehicle-mounted sampler, along a regular grid at sample spacing ranging from 60 to 150 m, and the samples analyzed for desired properties. The results of these analyses are interpolated to unsampled locations by inverse distance or geostatistical techniques. In high value irrigated crops such as potatoes and berries, the sampling strategy often involves more intensive sampling (60 m spacing) than in low value rain-fed crops such as wheat and corn (120 m spacing) (Mulla, 1993). The adequacy of the spatial sampling and interpolation strategy for 120 m grid spacing in wheat and corn crop systems is suspect, especially given that soil survey maps in such areas typically show changes in soil mapping units and landscape position that occur every 100 m or less (Mulla, 1997).

On the basis of extensive analysis of the spatial structure in rain-fed agriculture, it appears that the maximum sampling spacing for regular grid sampling is 60 m (Mulla, 1993; Wollenhautpt et al., 1994). At less intensive sampling spacing, the accurate delineation of management zones boundaries becomes difficult (Mulla, 1997). As this intensity of sampling is too expensive for many producers, new approaches are needed for targeted sampling. Targeted sampling may be guided by preliminary information about the site from remote sensing, soil maps, or terrain maps.

Transect Sampling Design

Transect sampling is a scheme in which samples are collected along a single line which traverses the study site (Upchurch et al., 1988). A very detailed description of the ramifications of the transect sampling is presented by Gruijter and Marsman (1985).

The simplest form of longitudinal transects, as used by Karlen et al. (1990) to measure soil chemical properties and corn yield variations across soil map units within, a field measuring 305 by 427 m (13 ha) is illustrated in Figure 7A. A set of radial transects was used by Trangmar et al. (1987) to characterize spatial variation of soil chemical properties and yield components of upland rice in a typical farm management unit on recently cleared land (Figure 7B).

Although the use of transects does not evenly sample the study site in all directions, it is appropriate when the systematic variation of the site follows a particular direction. The transect direction should be chosen such that samples are collected along the direction of greatest variability (Gruijter and Marsman, 1985). A set of two orthogonal transects can be used to reduce the number samples below that required by grid sampling while at the same time providing information concerning the variability in both directions. (Upchurch et al., 1988).

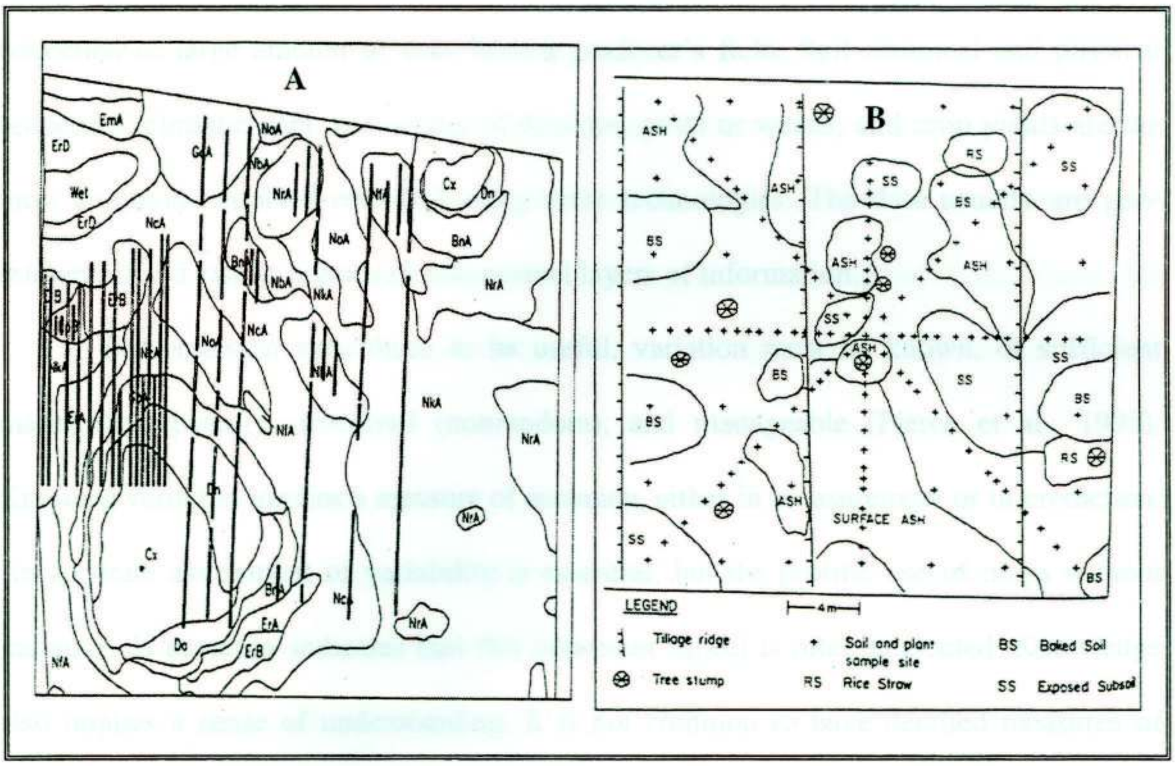

Figure 7. A variation in transects sampling design. (A) The simplest form with a set of longitudinal transects, (B) radial transects. (Modified from Karlen et al., 1990, and Trangmar et al., 1987)

Transects placed in representative parts of a field and covering a range of topographic position may be a better source of spatial information than grids with uniform but wider spacing. Timlin et al. (1998) reported that closely spaced data taken along the transects provided more information on the spatial structure of grain yield than did data from the more coarsely spaced grid.

STATISTICAL METHODS OF EVALUATING SOIL AND CROP VARIABILITY

Newly introduced precision farm technologies and related practices allow for collection of large amount of data from a producer's field. Soil chemical and physical properties, climatic data, incidences of diseases, pests or weeds, and crop yields are the most common variables recorded using these technologies. The data usually are geo-referenced and can be organized into several layers of information.

For precision agriculture to be useful, variation must be known, of sufficient magnitude, spatially structured (nonrandom), and manageable (Pierce et al., 1995). Knowing variation implies a measure of accuracy, either in measurement or in prediction. An accurate assessment of variability is essential, but the prolific use of maps without measures of accuracy indicates that this important aspect is often neglected. Knowledge also implies a sense of understanding. It is not common to have detailed measures of variation within a field with little understanding of the causes of the observed variability (Pierce and Nowak, 1999). Further analysis of these data is useful for understanding relationships among site variables and between these variables and crop yields. Various methods have been used to evaluate variability of soils and crops and their interactions across landscapes.

Classical Statistical

Traditionally investigations have used random sampling techniques and assumed independence between samples. Classical statistical analyses are then performed, such as analysis of variance (ANOVA) or regression analyses to describe the changes observed within and among plots. For most part, the variability of soil properties has been studied in conventional statistics terms (mean, standard deviation, variance, comparing means) (Dahiya et al., 1984).

According to Upchurch et al., (1988) CV's are useful if the primary objective is to assess the relative variability of a property and the probable number of observations necessary to estimate the mean of the population within a given confidence interval at a specified confidence level. However, the classical statistical analysis methods do not quantify the variability of soil parameters with regard to their spatial arrangement, but merely treat the values in terms of their relative magnitudes, independent of their coordinate position.

Geostatistical Techniques

The most common approach taken to study spatial variability is through the use of geostatiscal analyses (Vieira et al., 1981; Vauclin et al., 1983). Geostatistics, originally used in the mining industry (Matheron, 1963), has proven useful to soil science for characterizing and mapping spatial variation of soil properties. Geostatistical analysis of within-field variation of nutrient and plant growth parameters can help identify cause-effect relationships between these parameters (Tabor et al., 1984). Such analysis may also suggest management approaches for reducing the effects of soil variability on crop yield.

Central to the geostatistic theory are the variogram and kriging. Variogram uses semivariances to characterize and model the spatial variation of data, whereas kriging uses the modeled variance to estimate values between samples (Burgess and Webster, 1980). The semivariogram illustrates the relationship between the sample variance and lateral distance, known as the ***lag***, separating samples (Figure 8). From this relationship, a lateral distance between samples can be chosen that optimizes sample variance and number of samples. The ***lag*** distance where the variance approaches an asymptotic maximum, know as a ***sill***, is the range across which data are spatially correlated (Clark, 1979). The range defines the "zone of influence" of a sample and the region over which interpolation is possible. As the ***lag*** distance approaches zero, the variance usually approaches a finite value, called the ***nugget*** variance (Burgess and Webster, 1980). The ***nugget*** represents residual variation, not removed by closed sampling.

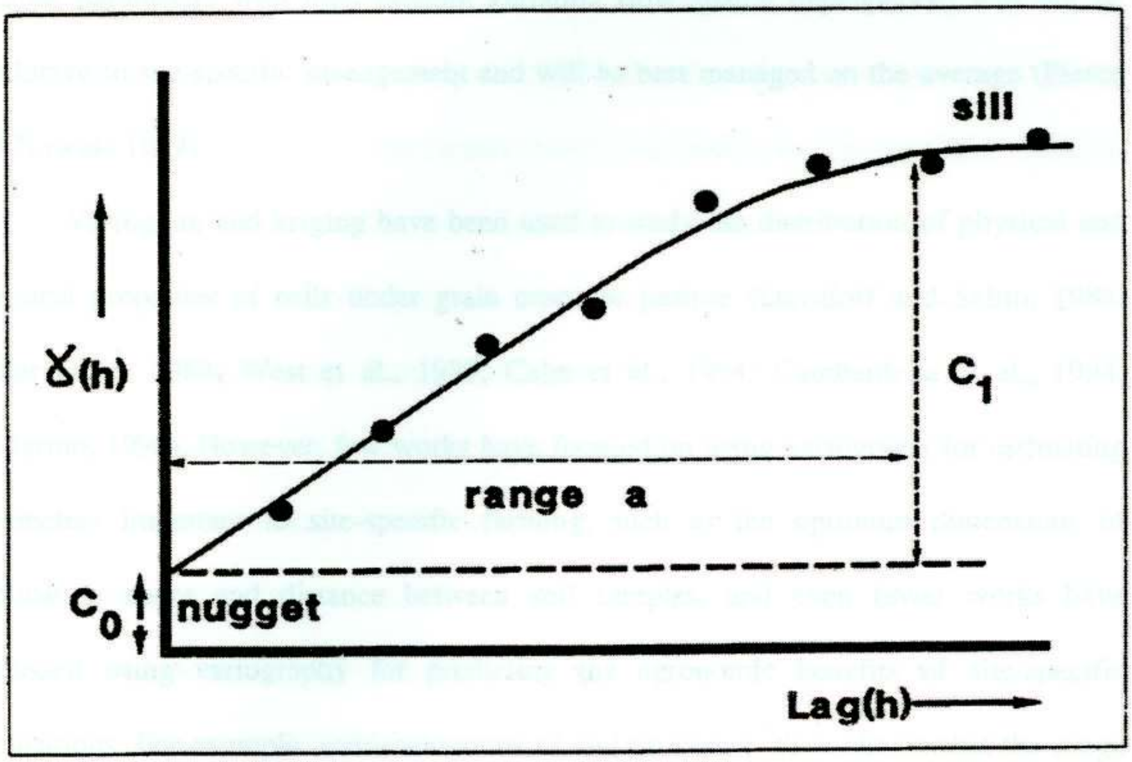

Figure 8. Variogram of a second order stationary regionalized variable: • experimental estimates of semivariance, —— fitted spherical model (Burrough, 1993)

Considering that the soil properties are affected by position of the soils on the landscape and relationship with their neighbors, the appropriate means for describing the spatial distribution of soil properties and their relationship to crop yield on erosional-depositional features is through the use of semivariogram and cross-semivariogram functions. Miller et al. (1988), in a study to determine the relationship between wheat yield and soil properties influenced by erosion, found that standard regression analyses showed no correlation between percent slope and yield or soil properties. Semivariograms and cross-semivariograms showed a strong spatial dependency between soil properties and wheat yield. A high degree of spatial dependence is needed for current applications of precision agriculture. Spatial dependence drives precision agriculture because parameters with high random variation (low spatial dependence) will not be conducive to site-specific management and will be best managed on the average (Pierce and Nowak, 1999).

Variogram and kriging have been used to study the distribution of physical and chemical properties of soils under grain crops or pasture (Davidoff and Selim, 1988; Miller et al., 1988; West et al., 1989; Cahn et al., 1994; Cambardella et al., 1994; Mallarino, 1996). However, few works have focused on using variograms for estimating parameters important to site-specific farming, such as the optimum dimensions of application zones and distance between soil samples, and even fewer works have discussed using variography for predicting the agronomic benefits of site-specific applications. For example, semivariograms of soil properties have shown that the range of spatial correlation for soil organic C to be > 180 m (Cahn et al., 1994), for P and K > 100 m (Yost et al., 1982; Mulla, 1989), in contrast to the 1 to 30 m range reported for NO_3-N (White et al., 1987).

Little is known about the spatial structure of yield across fields, nor of the temporal stability of this structure. In single-year studies, Mulla (1991) found wheat yields correlated to distances of 70 m in a field located in the Palouse region of eastern

Washington. Similarly, Miller et al. (1988) found grain yields correlated to distances of 80 m in a northern California wheat field. Jaynes and Colvin (1997) determined the spatial structures of grain yield of corn and soybean for 6 years of data and examined the stability of these structures over time. While they expect that the spatial structure of yield is controlled primarily by soil properties, other factors (e.g., weed, insect, disease, and management pressures) will also alter the structure. In addition, the influence of these will be modified by yearly weather, with one factor being more strongly expressed in one year and another in a subsequent year. The lack of stationary in the trend and/or variograms may indicate that the factors controlling yield are dynamic. For example, water extremes (either too little or too much) can vary considerably each year, due to the interaction among soil hydraulic properties and rainfall patterns. Conversely, the specific factor-controlling yield may change from year to year. For example, in a year with adequate rainfall it may be nitrate availability that is limiting yields, whereas in a dry year it may be soil water holding capacity that controls yield. The high correlation ($R^2 = 0.79$) observed between the range of spatial structure of yield with total rainfall, argues that it is the interaction among the soil hydraulic properties and rainfall that is controlling much of the spatial variation of yield (Jaynes and Colvin 1997).

Use of Factor Analysis and Multivariate Analysis for Interpreting Relationships Between Soil Properties and Crop Yields

The number of inter-related factors that affect yield complicates the process of understanding yield variability. Simple correlation and regression statistical analyses are usually applied to the data. Simple correlation analyses have shown that many soil properties often, but not always, are correlated with crop yields and that often some variables are correlated among themselves (Mallarino et al., 1996; Sudduth et al., 1996).

However, as reported by Sudduth et al. (1996) correlation analysis may not particularly useful in understanding yield variability, due to complex nonlinear relationships between yield-limiting factors.

Grouping variables so that the correlation of two variables from different groups is small and that for two variables from of the same group is large can minimize the problem caused by correlated variables. Each group can be represented by a new variable, which is created from the variables in the group. Groups of correlated variables can be defined by using factor analysis (Reyment and Joreskog, 1993). Factor analysis is a generic term used to describe a number of methods designed to analyze interrelationships within a set of variables. These new variables can be used as independent variables in a multiple regression equation.

On the other hand, if correlated site variables are used in a multiple regression analysis to explain crop yields, the correlations make it difficult to interpret the regression equation (Bowerman and O'Connel, 1990). The problem is that the value of the regression coefficient for one variable changes depending on what other variables are used in the equation. Moreover, tests of significance of the coefficients become unreliable when variables are highly correlated. When the variables are highly correlated, multivariate analysis techniques such as variable grouping, principal component analysis, and factor analysis may facilitate the analysis. Multivariate analysis techniques could partly circumvent the problem created by correlated variables and could facilitate the interpretation of potentially complex relationships.

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CHAPTER 1

IRRIGATED CORN YIELD AS RELATED TO SPATIAL VARIABILITY OF SELECTED SOIL PROPERTIES ON A SILTY CLAY LOAM SOIL

INTRODUCTION

A considerable portion of the time and energy invested in modern agriculture is spent in providing a soil environment suitable for plant growth and development. Residue management, plowing, seedbed preparation, fertilizer application, weed control, and crop plant populations are important components of the crop production system that must be optimized to assure a healthy environment conducive to crop growth and optimum grain yield production (Waisel et al., 1991). In addition, the spatial and temporal variability of soil chemical and physical properties are important factors that affect crop yields and should be considered in planning soil management.

Worldwide demand for agricultural cropland continues to escalate in response to increased population and loss of prime cropland to soil erosion and urbanization (Tester, 1990). As more prime agricultural land is taken for nonagricultural purposes, there is an increase in the intensity of land use on rolling, steeply sloping marginal lands, which are susceptible to accelerated erosion (Miller et al., 1988). Under these conditions the inherent spatial variability of soils will clearly be expressed in the variation of crop growth and yield. The emerging technology of precision farming provides a means for the producer to take soil variability into account as management plans for crop production are made and executed. However, before farmers can use intensive management practice such as differential fertilization, tillage practices, etc, within field units, yield variation within the field must be quantified and the factors responsible for that variation defined.

The continued evolution of precision farming depends on the availability of spatial data on crop yield and related soil characteristics. The information obtained from spatial analyses can be used to identify areas that need different management, to improve future sampling designs, and to gain a better understanding of the spatial distribution of soil properties. This will ultimately lead a to a sounder and more economical management of soil resources. However, data are not without cost. Accordingly, there is a growing need for practical guidelines for spatial resolution for soil and plant data collection.

MATERIALS AND METHODS

Evaluation Site

A 53 ha farm field in north-central Buffalo County (40° 53' 23''N 98° 51' 26''W) in the Platte River Valley of south-central Nebraska was selected for this study. The elevation is 640 m above mean sea level. The site has been cultivated at least twenty-five years under conventional tillage, using methods such as moldboard plow and recently with a transition to a ridge till system. It has been cropped principally to corn (*Zea mays* L.), with an occasional rotation with soybean [*Glycine max* Merr. (L.)], and irrigated with a center-pivot sprinkler irrigation system.

The climate is characterized by wide seasonal variations; winter temperatures below -17°C (0°F) and summer temperature above 38°C (100°F) are common. The average annual temperature is 10°C (50°F). The average annual precipitation is 595 mm (23.8 inches). Rainfall is heaviest in May, June, July and August, when most of it occurs during local thunderstorms (Soil Survey1974). During the growing seasons of 1997 and 1998 (May 1st to October 7th) the weather station located at Kearney-NE, registered precipitation of 334 mm (13 inches) and 496 mm (20 inches), respectively, with quite different patterns of distribution during the growing seasons (Figure 1.1). The potential evapotranspiration, based on a calculation using a modified Penman equation, was about 950 mm (38 inches) in both years. The average annual evapotranspiration (ET) for corn in Central Nebraska is approximately 600 mm (24 inches) from planting to maturity.

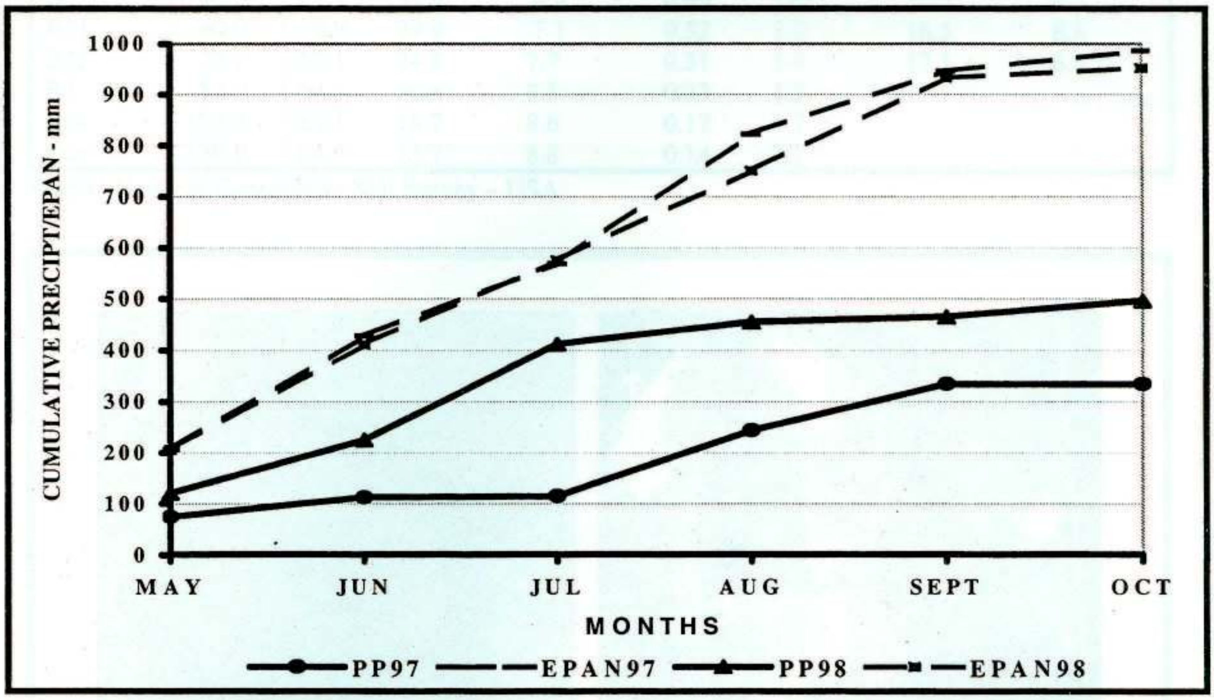

Figure 1.1 Cumulative precipitation (PP) and potential evapotranspiration (EPAN) at Kearney, NE, during the growing seasons of 1997 and 1998.

Soils within the experimental field were formed in calcareous, light-gray Peoria loess, and are predominantly of the Uly-Holdrege-Coly (UHC) soil association. This association, which covers 47% of the soils in Buffalo County, consists of deep, gently sloping to steep, well-drained silty soils located on upland with 5 to 11% slope (Figure 1.2). The soils that have been mapped are Uly silt loam (fine-silty, mixed, mesic Typic Haplustolls), Holdrege silt loam (fine-silty, mixed, mesic Typic Arguistolls), and Coly silt loam (fine-silty, mixed [calcareous] Typic Ustorthents). The Uly soil makes up 50% of total acreage, the Holdrege soil 30%, and the Coly soil the remaining 20%. These soils have profiles similar to the ones described as representative for their respective series (Table 1.1), (Soil Survey, 1974).

Table 1.1. Physical – chemical characteristics of a typical soil profile of a Holdrege silt loam

Horizon	Depth	Silt	Clay	pH	Org. C	Ext. Cations- cmol kg^{-1} soil		
	cm	%	%	water 1:5	%	K^+	Ca^{++}	Mg^{++}
A1p	17.5	61.4	22.0	6.6	1.68	1.8	11.7	3.9
A12	32.5	58.4	29.6	7.1	1.34	1.0	17.0	5.2
A3	40.0	55.3	31.4	6.8	0.89	1.0	17.3	6.2
B21	60.0	58.9	29.9	7.1	0.52	1.2	16.5	6.8
B22	75.0	62.1	24.8	7.7	0.31	1.4	17.1	6.6
B3	85.0	64.3	20.8	8.5	0.23	1.5		
Bca	105.0	65.1	18.7	8.6	0.17	1.7		
Cca	150.0	64.5	18.7	8.8	0.14	2.1		

Source: National Cooperative Soil Survey – USA.

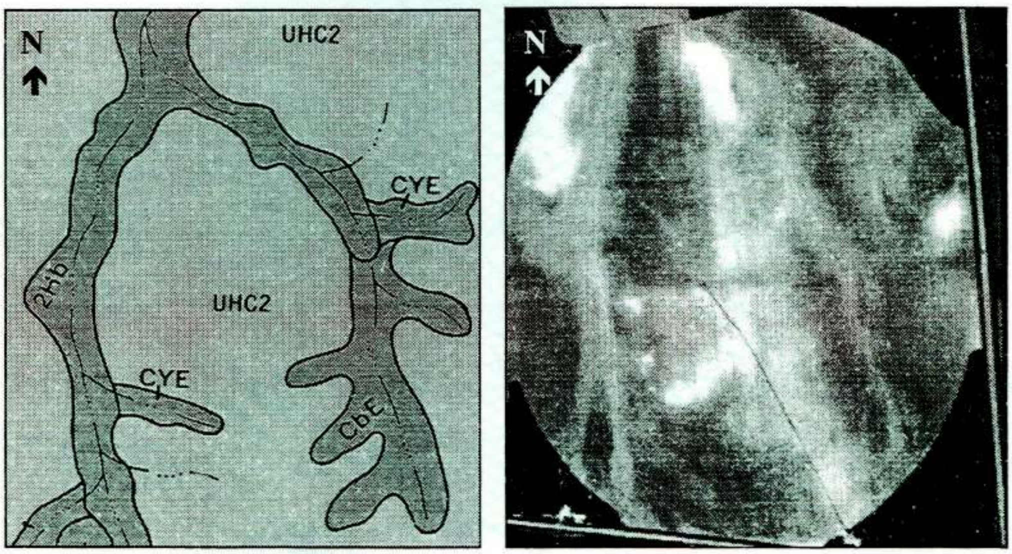

Figure 1.2. The left figure is a soil survey map made in 1967 and the right an aerial photograph taken of the experimental field in May 1997. SE1/4, sec.35, T11, R14W. Buffalo County, NE. (Soil Survey, 1974 and USDA-ARS-Lincoln, NE)

Experimental Design and Sampling Scheme

Replicated transects, spaced at 40 m from north to south, were established to represent a wide range in landscape position, soil organic matter content, nutrient content, texture and crop productivity. Forty-one plots (9.6 m wide x 12 m length), spaced at 10 m were placed continuously along transects, from west to east, for soil sampling and crop evaluation (Figure 1.3). In addition, one transect with 9 plots was established in an area planted to alfalfa to represent a benchmark in terms of effect of the soil management on soil properties. Global Positioning System (GPS) technology was used to permit the precise and repeatable location of plots within the field.

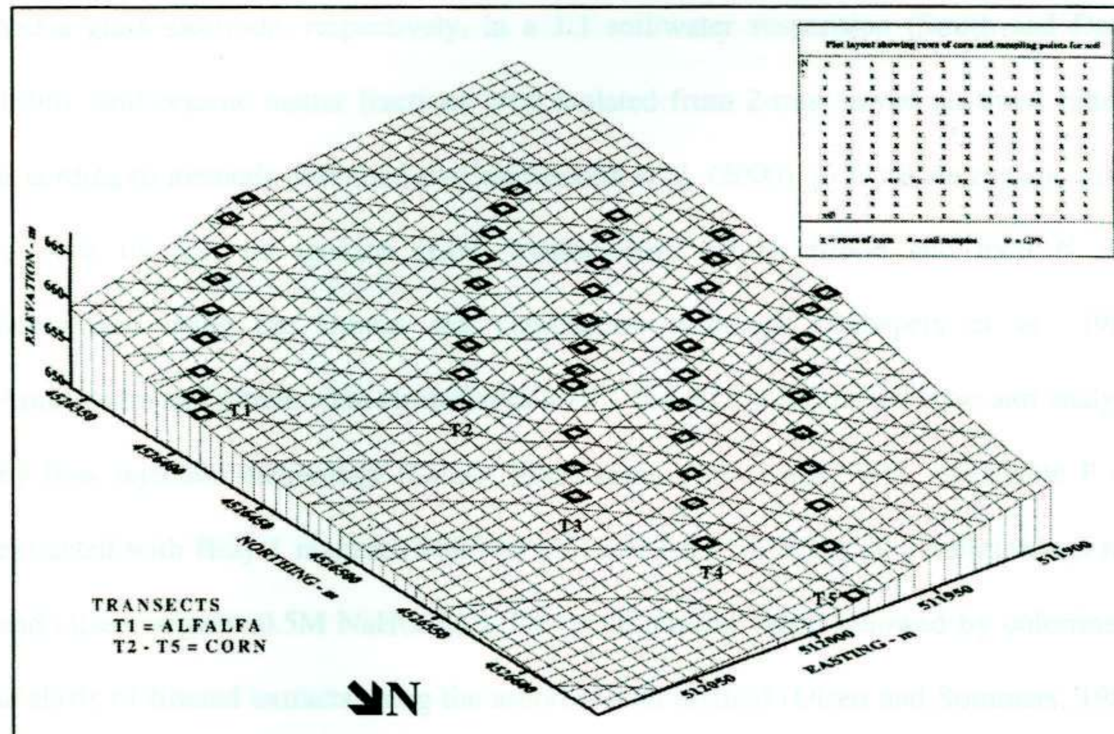

Figure 1.3. Three-dimensional surface contour map of the experimental field showing the transects, plot distribution, and plot layout, showing rows of corn and points for soil sampling.

Soil Sampling and Analysis

The field was sampled in June 1997 and 1998 when the corn was in the V3 to V4 vegetative stages. Soil samples were collected for analysis by using a 17.6 mm (inside diameter) hand probe. The samples were taken from between the rows (2nd to 10^{th} rows), 15 cm to the side of each row center, at 3 m from the beginning and end of plots (Figure 1.3). Eighteen cores per plot were collected from an area of 115.2 m^2 at 30 cm depth, and divided into two depth increments (0 to 15 and 15 to 30 cm). All soil samples were air-dried, and ground to pass a 2 mm screen.

Soil electrical conductivity (EC) and pH was measured with a conductivity meter and a glass electrode, respectively, in a 1:1 soil/water suspension (Smith and Doran, 1996). Soil organic matter fractions were isolated from 2-mm sieved air-dried samples according to methods described by Cambardella et al. (2000), to facilitate organic matter analysis by loss on ignition (LOI) methodology. Total carbon and total N were determined using the Dumas dry combustion technique (Schepers et al., 1989). Ammonium and nitrate were extracted in a 10:1 2M KCl solution/soil ratio and analyzed by flow injection technology (Lachat Instruments, Milwaukee, WI). Available P was extracted with Bray-1 reagent (0.025 M HCl and 0.03 NH_4F) at 10:1 solution/soil ratio and Olsen reagent (0.5M $NaHCO_3$) at 20:1 solution/soil ratio, followed by colorimetric analysis of filtered extracts using the ascorbic acid method (Olsen and Sommers, 1982). Exchangeable cations were extracted with neutral 1M NH_4OAc and determined by atomic absorption (Ca^{2+}, Mg^{2+}) and flame photometry (K^+, Na^+). Exchangeable Al^{3+} was determined by extraction with unbuffered 1M KCl and atomic absorption. Cation exchange capacity (CEC) was calculated as the sum of exchangeable cations plus

$H^+ + Al^{3+}$. Available micronutientes (Zn, Mn, Cu, and Fe) were extracted using DPTA and determined by inductively coupled plasma optical emission spectrometry (ICP-OES) (North Dakota Agricultural Experiment Station, 1988). Sand, silt and clay fractions were determined through sieve and pipette analysis (Gee and Bauder, 1986). Bulk density was measured according to Doran and Mielke (1984), based on the soil volume sampled in each plot, using the following expression: volume of probe ($V = \pi r^2 h$) times number of soil samples in each plot, divided by the dry soil weight at 105°C. Also, bulk density was estimated from particle size analysis and organic matter content according to the method described by Rawls (1983). Available water holding capacity (AWHC), defined as the difference between the water content at matric potential of –0.033 Mpa and –1.5 Mpa, was estimated from particle size distribution, organic matter, and bulk density, according to methods described by Gupta and Larson (1979).

Crop Evaluation and Analysis

Soil testing provides information on patterns in soil fertility and other soil conditions, but plant growth, development and vigor provides a more direct and integrative indication of plant response to soil properties and management. Plant performance across a landscape was determined by measurement of plant population, plant nutrient content, and grain yield. Ear leaf blades were selected at random from 20 corn plants in each plot at early silking. Leaf tissue was dried at 70°C, ground, and analyzed for nutrient content. Plant population counts were made before harvest in the center 6 m of each row, in 12 adjacent rows. Corn ears were hand-harvested from each of the central plots (4 rows x 3 m length), were dried and shelled, and the grain water content determined using a portable grain moisture tester. Grain yields were adjusted to 15.5% water content

Statistical Approach

Statistical analysis of data was done in five stages: (i) frequency distributions and background normality tests were conducted; (ii) the distributions were described using traditional summary statistics (minimum, maximum, mean, standard deviation, coefficient of variation, and median which is less influenced by skewed distributions; (iii) simple correlation analysis between soil properties and yield components; (iv) factor analysis was used to detect any underlying structure in relationships between soil properties and also to reduce the number of variables, while retaining the essence of all soil properties measurement; and (v) semi-variograms were defined and differences in nugget and total semi-variance and range examined for the variables. Semi-variograms were used to indicate the range for spatial correlation and the spatial structure of the observed variables and were used to interpolate between sampling points.

Summary statistics for the data sets were obtained from the univariate procedure in SAS. Each variable was tested for normality by adding the normal option (SAS Institute, 1995). The null hypothesis was that data sets were normally distributed and it was rejected when $P \leq 0.05$.

Groups of correlated variables (excluding plant population and yield) were defined using factor analysis. Before to applying factor analysis, each soil physical-chemical property and nutrient concentration in leaf dry matter were standardized using the following equation:

$$Z_i^* = \frac{X_i - X_m}{S_i} \qquad [1.1]$$

where Z_i^* is the standardized variable (zero mean, unit variance), and X_m and S_i are the mean and standard deviation of variable *i*. This transformation combines effects of column normalization and column centering. Each variable will have a mean of zero and will be expressed in units of standard deviation (Reyment and Joreskog, 1993). Factors were extracted with the factor procedure of the SAS package using the principal factor analysis method and promax oblique (non-orthogonal) rotation method (SAS Institute, 1995). Measurement of a soil property yields values that are represented by their coordinate along an axis. Principal factor analysis generates new axes that are related to the correlation between variables. As such, multiple correlated variables can be essentially represented by a single coordinate along this new axis (McCoy, 1998). This coordinate is called the "***Factor Variable Score (FV)***" and is calculated as a linear combination of the (standardized) variables using the equations (McCoy, 1998):

$$FV_1 = L_{11}X_1 + L_{12}X_2 + \ldots\ldots + L_{1j}X_j$$
$$FV_2 = L_{21}X_1 + L_{22}X_2 + \ldots\ldots + L_{2j}X_j$$
$$\ldots\ldots$$
$$FV_i = L_{i1}X_1 + L_{i2}X_2 + \ldots\ldots + L_{ij}X_j \qquad [1.2]$$

Where FV_i is ***Factor Variable*** on the ith coordinate axis, L_{ij} is the loading of component ***i*** for variable ***j*** and X_j is the standardized value of variable ***j***. In general, ***i*** and ***j*** are equal to the total number of observed variables. Based on these results, stepwise regression (backward) was performed to verify the relationships between factor scores (new variables) and corn yield. Grain yield was the dependent variable and the factor scores were the independent variables. The model is of the form:

$$Y = b_0 + b_1FV_1 + b_2FV_2 + b_3FV_3 + ... + b_jFV_j + \varepsilon \qquad [1.3]$$

Where Y represents estimated corn yields, b_0 to b_j are the coefficients, FV_1 to FV_j are the factor variable and ε represents the residual error. The factor variable scores were then used in geo-statistical mapping and as inputs for a simple soil quality classification. The sample set was classified in 3 classes (high, medium and low), based on the quartiles of the extracted soil factor. The inter-quartile ranges of the soil properties in each case were used for a final soil fertility evaluation.

Geostatistical software (GS^+ V3.1, Gamma Design Software, St. Plainwell, MI) was used to analyze the spatial structure of the standardized data of soil properties, nutrient concentrations in leaf dry matter, and non- transformed data of plant population and grain yield, to define the semi-variograms. Semi-variance calculations were based on an active lag distance, which ranged from 130 to 175 m, separated by an average distance of 19 m. Between 35 and 185 pairs of points were used in the semivariance calculations. Selection of models for semivariograms was made principally on visual fit, regression coefficient (R^2), and reduced sum of square (SSR), which provided an indication of how well the model fit the semivariogram data.

Surfer Software (Golden Software, Golden, CO) was used to make the maps. The elevation was interpolated by point-kriging using the default settings of a linear semivariogram. The contour maps were also interpolated by point-kriging, but using the modeled semi-variograms for each standardized soil property and plant parameter measured in the field.

RESULTS AND DISCUSSION

ASSESSING MAGNITUDES OF SPATIAL VARIABILITY

Grain Yield, Plant Population, and Nutritional Status of Corn

The grain yields, plant populations and nutrient concentrations in the leaf are summarized in Table 1.2. Field mean corn yield (11.3 Mg ha^{-1}) was higher than the average for irrigated corn in central Nebraska (10.4 Mg ha^{-1}). Although rainfall during growing season of 1998 was 48% (162 mm) higher than 1997 (Figure 1.1), the grain yields were similar in both years, with no significant differences in effect of year on the grain yields ($Pr > F = 0.79$). Correlation between years for grain yields values was positive and significant ($r = 0.75$), which means that the pattern of spatial variability was similar in both years. Working under dry-land conditions in a silt loam soil, Timlin et al., (1998) found that annual differences in weather had the largest effect on corn grain yields. Yield maps showed little temporal stability among 3 years of study.

The yield data for each year was normally distributed and the Wilks-Shapiro test for normality was not significant, indicating that the null hypothesis for normal distribution was not rejected. This was illustrated as well by the relatively low coefficients of variation and the small difference between the mean and the median, favoring the yields around the average (Table1.2). Although common management practices were used throughout the field, yield, is not uniform over the field. Corn yield varied spatially, ranging from 8.4 to13.8 Mg ha^{-1} in 1997 and 9.7 to 12.8 Mg ha^{-1} in 1998 (Table 1.2). Thus, its average does not exhaust all information about it, and the knowledge of the frequency distribution of the observations alone does not provide information about the spatial variability of the property of interest (Vieira et al., 1981).

Table 1.2. Descriptive statistics of grain yields, plant population and nutrient concentrations in the leaf below and opposite the first ear at early silking growth stage. Gibbon, NE, 1997/98.

Variable	Suffic. Range †	Statistical parameters						
		Min	Max	Median	Mean	Std. Dev.	CV (%)	Wilks-Shapiro
Yield, Mg ha^{-1} (97)	*****	8.44	13.82	11.32	11.29	1.37	12.2	0.97^{ns}
Yield, Mg ha^{-1} (98)	*****	9.73	12.82	11.35	11.33	0.83	7.3	0.96^{ns}
Stand, 1000 ha^{-1} (97)	*****	69.62	77.08	73.61	73.48	1.52	2.0	0.98^{ns}
Stand, 1000 ha^{-1} (98)	*****	71.88	88.56	78.13	78.91	3.65	4.6	0.97^{ns}
	Nutrient in leaf dry matter - g kg^{-1}							
Nitrogen	22 – 30	25	30.5	28.4	28.33	1.32	4.7	0.95^{ns}
Phosphorus	2 – 3	1.30	3.40	2.00	2.08	0.42	20.4	0.94^{ns}
Potassium	16 – 20	13.60	27.50	17.80	18.20	2.47	13.6	0.92*
Sulfur	2 – 3	1.50	2.80	1.80	1.87	0.25	13.5	0.89**
Calcium	2 – 6	3.70	8.10	4.90	4.98	0.74	14.8	0.85**
Magnesium	1.5 – 3	0.90	2.30	1.30	1.32	0.23	17.5	0.87**
Zinc	18 – 25	14.00	29.00	19.00	19.61	3.27	16.7	0.88**
Manganese	15 – 25	11.00	34.00	23.00	23.58	5.47	23.2	0.96^{ns}
Copper	2 – 5	8.00	18.00	10.00	10.58	2.10	19.9	0.89**
Iron	20 – 40	11.00	126.00	47.00	54.63	30.59	56.0	0.94^{ns}
Aluminum	20 – 300	48.00	104.00	69.00	70.34	12.69	18.0	0.96^{ns}

† Sufficiency range according to UNL Plant Test Analysis Laboratory. Wilks – Shapiro test for normality, significant at the $*P \leq 0.05$, $**P \leq 0.01$ probability levels. Significance indicates that the null hypothesis for normal distribution is rejected.

Plant population presented spatial and temporal variation, ranging from 69,920 to 77,080 plants ha^{-1} in 1997 and 71,880 to 88,560 plants ha^{-1} in 1998, with significant difference ($Pr > F = 0.0001$) within and between years (Table 1.2). However, it was not significantly correlated with grain yield ($r < 0.30$), probably due to the fact that the minimum number of plants measured in the field (~ 70,000/ha) was above the optimal minimum for maximum yield. Doerge (1997) summarized the results of several Pioneer Hi-Bred studies by saying that optimum seeding rates do not vary much across a wide range of soil and yield conditions in the U.S. Corn Belt. He also states that while seeding rates below the optimum can reduce yields, higher than optimum seeding carries little penalty. The optimal stand for corn generally ranges from 64,000 to 74,000 plants ha^{-1} at harvest (Doerge, 1997).

Nutrient concentrations in the leaf dry matter of corn, except iron, was characterized by low variability as indicated by coefficients of variation less than 25% (Table 1.2). The majority of nutrients were non-normally distributed. Nitrogen, P, Fe and Al where the only variables that were normally distributed. However, the similar values observed for mean and median indicate that the measures of central tendency are not dominated by the outliers in the distribution. Considering the mean values and comparing them with the sufficient range, defined as those levels found in high yielding fields or known to be adequate for healthy plants (Univ. of Nebraska, Plant Test Laboratory), all nutrients, except for sulfur, magnesium, copper and iron, fall into the sufficient range. Sulfur and magnesium were below the range, and copper and iron were above (Table 1.2). However, in some cases minimum concentrations of important nutrients for corn production such as phosphorus, potassium, zinc, and manganese, were below the sufficient range, indicating a deficiency of these nutrients in some parts of the field.

Because of the variability in plant population, nutrient concentrations in leaf dry matter, and yields (Table 1.2), it is important for the application of precision agriculture technologies to quantify the spatial structure of these variabilities and also to identify where low and high values are located in the field. If values appear to be randomly located (pure noise), the best estimator of the value taken by a variable at any point within the field remains the sample mean or median and the best way to manage the field is by applying a uniform soil and crop management (Nolin et al., 1996). Geo-statisticians normally define the spatial structure through the semi-variogram and consider kriging as the optimal method for interpolation because it gives the best linear unbiased estimate of the value of a variable at given point in minimizing the error of variance (Isaaks and Srivastava, 1989).

Semi-variograms were computed for each plant variable. The parameters for the best fitting theoretical models are presented on Table 1.3. Spherical, Exponential and Linear models were the most often selected (Figure 1.4). For spherical and exponential models, semivariance increases with distance between samples (lag distance) to a constant value (sill or total semivariance) at a given separation distance (range of influence). The range (a), which measures the maximum distance over which variables remain spatially correlated, is relatively short (< 130 m). The sill values from the fitted variogram matched the sample variance in some cases (Figure 1.4). For the linear model, as the distance between the two samples increases, the semi-variance also increases. The linear model where the slope (sill) does not equal zero describes variables that are spatially correlated at all lag distances.

Another useful parameter to analyze for evaluating geostatistical analysis efficiency is the ratio $C_1/(C_0 + C_1)$ (Table 1.3). It is a consistent indicator of the importance of the structured variance (C_1, Figure 7) in the spatial dependence of variables measured in the field. By using a similar ratio, Cambardella et al. (1994), defined distinct classes of spatial dependence. If the proportion was ≥ 0.75 the variable was considered strongly spatially dependent; between 0.25 and 0.75 moderately dependent; and < 0.25 the variable was considered weakly spatially dependent.

Table 1.3. Geostatistics for grain yields, plant populations (PP), and standardized plant nutrient concentration in the leaf below and opposite the first ear at early silking growth stage. Gibbon, NE, 1997/98.

Variable	Active † Lag (m)	Active † Step (m)	Nugget C_0	Sill † C_0+C_1	Range a (m)	R^2	Proportion $C_1/(C_0+C_1)$ ‡	Model
Yield-97	150	19	0.193	2.224	122	0.89	0.91	SPH
Yield-98	150	19	0.161	0.762	99	0.96	0.97	SPH
PP-97	150	19	1.999	2.668	124	0.17	0.25	LIN
PP-98	nd	nd	nd	nd	nd	nd	nd	nd
	Nutrients in leaf dry matter g kg^{-1}							
N	150	19	0.001	1.455	125	0.96	0.99	LIN
S	100	10	0.001	1.221	68	0.65	0.99	EXP
P	150	19	0.305	1.207	114	0.74	0.75	SPH
K	100	10	0.235	1.152	53	0.61	0.79	EXP
Ca	100	10	0.001	1.132	49	0.57	0.99	EXP
Mg	100	10	0.001	1.172	68	0.66	0.99	EXP
Zn	100	10	0.053	1.075	45	0.71	0.95	SPH
Mn	100	10	0.221	1.164	87	0.55	0.81	EXP
Cu	100	10	0.001	1.108	55	0.63	0.99	SPH
Fe	150	17	0.032	1.358	127	0.98	0.97	SPH

† Active lag, the distance to which variograms are computed. Active step, the lag increment used. Nugget, semi-variance at zero spacing. Sill, semi-variance at spacing > range. Range, distance after which values are not correlated. ‡ Proportion of spatial structure, measures the proportion of sample variance (C_0 +C_1) that is explained by spatially structured variance C_1. Model: SPH = spherical, EXP = exponential, and LIN = linear; nd = data not fit any model.

Semi-variograms indicated strong spatial dependence for variables such as yields and nutrient concentration in leaf dry matter, with a range from 45 to 127 m. This means that samples taken close together were more similar for most plant variables than samples taken further apart. For most variables, except P, the nugget was small (< 0.25), indicating low variability at short distances, and that the sampling distance was appropriate (Table 1.3).

This result suggests that appropriate grid size sampling for tissue analysis on this field should not be spaced more than 50 to 100 m apart. Plant population in 1997/9 was characterized by a variogram with weakly spatial structure (C_1/C_0+C_1 < 0.25). For 1998/99 the plant population does not fit any modeled variogram and consequently no spatial structure in the variability was observed. Since this variable was not correlated with any soil properties, extrinsic variation, such as planter and planting speed, may control the variability of this weakly spatially dependent parameter.

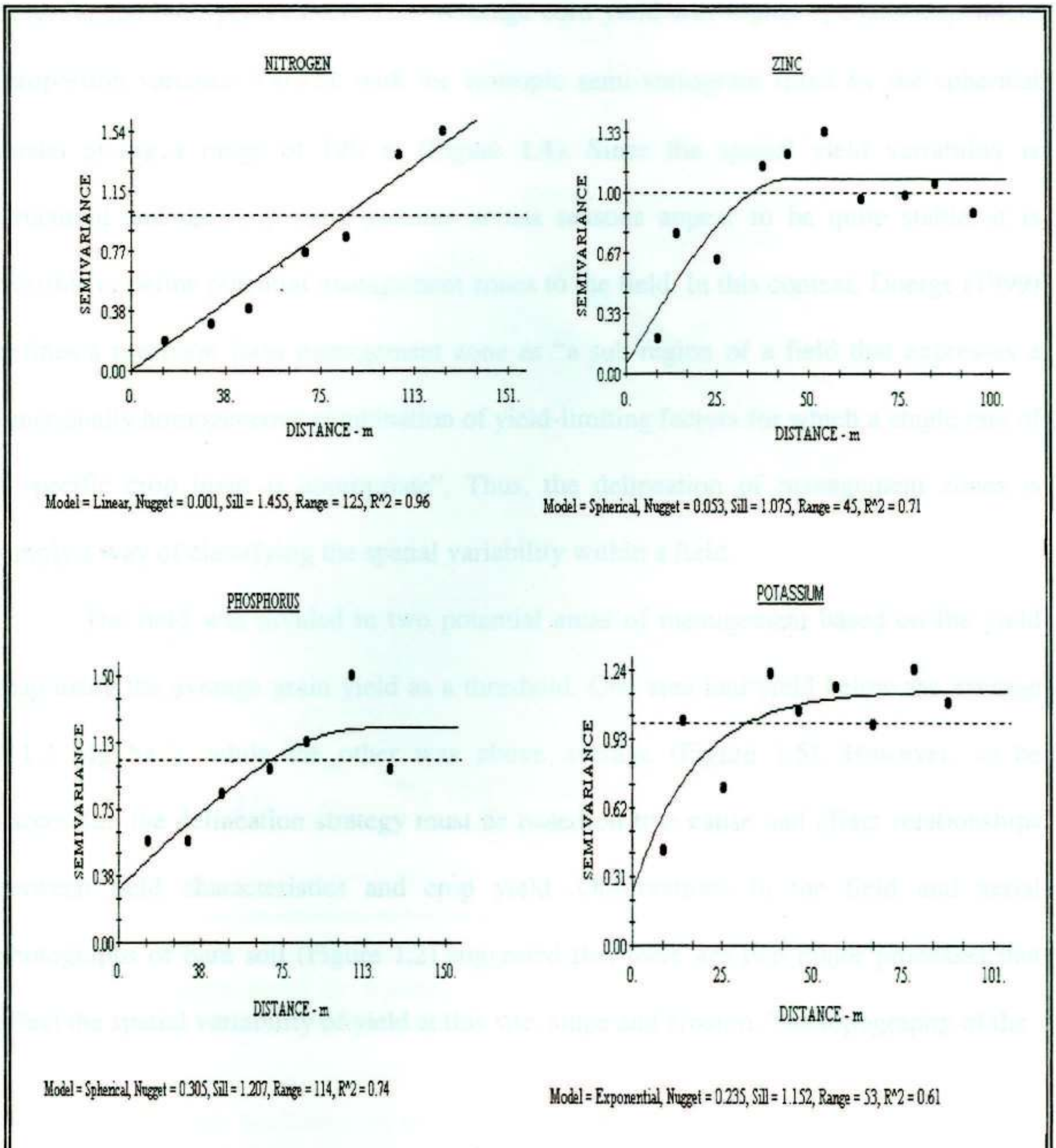

Figure 1.4. Experimental (•) and fitted isotropic variogram models (–) for some nutrients concentrations in the leaf dry matter of corn at early silking growth stage. The horizontal dashed line is the sample variance. Gibbon, NE, 1997/98.

A contour map was generated using geostatistical methods (semi-variograms and kriging) for average yield and overlaid on the topographic map (Figure 1.4). Geostatistical analysis revealed a range of spatial dependence for crop performance in the field, for the both years (Table 1.3). Average corn yield was highly spatially dependent (proportion variance > 0.75), with the isotropic semi-variogram fitted by the spherical model giving a range of 120 m (Figure 1.4). Since the spatial yield variability is structured and the crop yield patterns across seasons appear to be quite stable, it is possible to define potential management zones to the field. In this context, Doerge (1999) defines a precision farm management zone as "a sub-region of a field that expresses a functionally homogeneous combination of yield-limiting factors for which a single rate of a specific crop input is appropriate". Thus, the delineation of management zones is simply a way of classifying the spatial variability within a field.

The field was divided in two potential areas of management based on the yield map using the average grain yield as a threshold. One area had yield below the average (11.3 Mg ha^{-1}), while the other was above average (Figure 1.5). However, to be successful, the delineation strategy must be based on true cause and effect relationships between field characteristics and crop yield. Observations in the field and aerial photographs of bare soil (Figure 1.2) suggested that there are two major processes that affect the spatial variability of yield at this site, slope and erosion. The topography of the

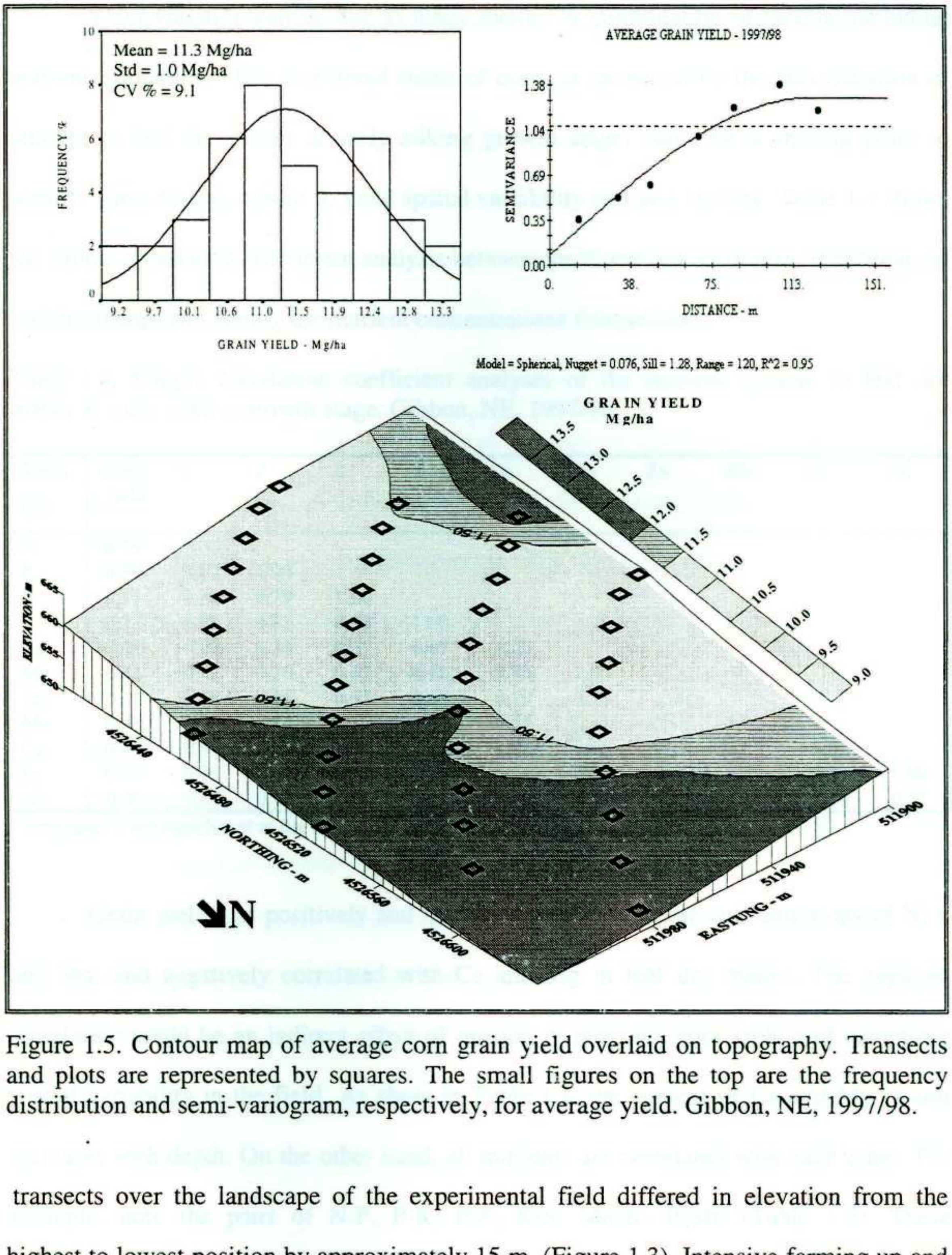

Figure 1.5. Contour map of average corn grain yield overlaid on topography. Transects and plots are represented by squares. The small figures on the top are the frequency distribution and semi-variogram, respectively, for average yield. Gibbon, NE, 1997/98.

transects over the landscape of the experimental field differed in elevation from the highest to lowest position by approximately 15 m. (Figure 1.3). Intensive farming up and down the slope with the heavy machinery and without management of crop residue or use of terraces has greatly increased water erosion.

Yield variation can be due to many factors or combination of factors, including nutrient availability. The nutritional status of corn, as measured by the concentration of nutrient in leaf dry matter at early silking growth stage, could be a starting point to identify some factors related to yield spatial variability and soil fertility. Table 1.4 shows the simple correlation coefficient analysis between yield and concentration of nutrients in leaf dry matter and among the nutrient concentrations themselves.

Table 1.4. Simple correlation coefficient analyses of the nutrient content in leaf dry matter at early silking growth stage. Gibbon, NE, 1997/98.

Variables	Grain yield	N	P	K	S	Ca	Mg	Zn	Mn	Cu	Fe
N	**0.75**	1.00									
P	**0.59**	**0.62**	1.00								
K	0.17	**0.31**	**0.79**	1.00							
S	0.27	**0.38**	**0.81**	**0.92**	1.00						
Ca	**-0.35**	**-0.32**	**0.33**	**0.67**	**0.67**	1.00					
Mg	**-0.46**	**-0.41**	0.20	**0.57**	**0.58**	**0.96**	1.00				
Zn	-0.11	-0.18	**0.36**	**0.57**	**0.65**	**0.78**	**0.76**	1.00			
Mn	**0.33**	**0.33**	**0.64**	**0.70**	**0.65**	**0.32**	0.21	0.18	1.00		
Cu	0.07	0.17	**0.59**	**0.71**	**0.78**	**0.70**	**0.65**	**0.73**	0.23	1.00	
Fe	0.17	0.26	0.17	**0.34**	0.27	-0.04	-0.07	-0.18	**0.72**	-0.14	1.00
Al	0.00	-0.05	0.15	0.18	0.26	0.15	0.21	0.25	0.11	**0.33**	-0.21

Correlation's are significant at the 5 % level if they are higher than + 0.30 or lower than – 0.30

Grain yield was positively and highly correlated with the concentrations of N, P and Mn, and negatively correlated with Ca and Mg in leaf dry matter. The negative correlation could be an indirect effect of erosion in reducing corn yield and increasing spatial variability in the field. As show in Table 1.1, the content of Ca and Mg in soil increases with depth. On the other hand, all nutrients are correlated with each other. For example, note the pairs of N-P, P-K, P-S, K-S, Mn-K, P-Mn (Table 1.5). These interactions are a limiting factor to the use of simple correlation analysis in interpretation of data, making it difficult to identify cause and effect relationships. Such inter-correlation between variables illustrates the need for analysis techniques that are based on grouping of variables.

Groups of correlated variables were defined using factor analysis performed by an oblique rotation using the principal-factor method and promax criterion. It was used to detect the most important sources of variation and co-variation in the observed data. Table 1.5 shows the eigenvalues, the proportion of the total variance and the loadings of each of three first factors derived from factor analysis.

The original set of 11 variables was reduced to three factor variables having eigenvalues greater than 1 (Figure 1.6). The first three principal factors (FV_1 to FV_3) accounted for 84.4% of the overall variation. The factor loadings can be used for a functional interpretation (Table 1.5). As rule of thumb, absolute loadings of 0.30 were considered significant, loadings of 0.40 were considered more important, and loadings of 0.50 were considered very significant (Hair et al., 1992). The remaining factors became less meaningful and were considered as error, which include the random component of nutrient variations and various types of error produced in every stage of leaf sampling and analysis. The first factor variable (FV_1) represented 49% of the total variation, and high positive coefficients occurred for S, K, Ca, Mg, Zn, and Cu. The second factor (FV_2) explained 23% of the variability and high positive coefficients occurred for N, S, P, and K. The third factor (FV_3) explained 12% and is highly related to Fe and Mn (Table 1.5).

Table 1.5 Factor analysis after promax method of oblique rotation, for nutrients content in leaf dry matter. Gibbon, NE, 1997/98.

Variance component	Factor Variable		
	FV_1	FV_2	FV_3
Eigenvalues	5.41	2.58	1.30
Proportion (%)	49.21	23.43	11.81
Cumulated Proportion (%)	49.21	72.64	84.45
Variable	Factor loadings		
Nitrogen	-0.291	**0.758**	0.152
Sulfur	**0.728** †	**0.849**	0.278
Phosphorus	0.384	**0.936**	0.195
Potassium	**0.716**	**0.808**	0.378
Calcium	**0.975**	0.269	0.059
Magnesium	**0.952**	0.124	0.043
Zinc	**0.868**	0.320	-0.155
Manganese	0.346	**0.667**	**0.757**
Copper	**0.774**	**0.618**	-0.192
Iron	-0.031	0.304	**0.935**
Aluminum	0.285	0.237	-0.396

† Numbers in bold indicates the variables with large factor loading were selected from each factor to create new variables.

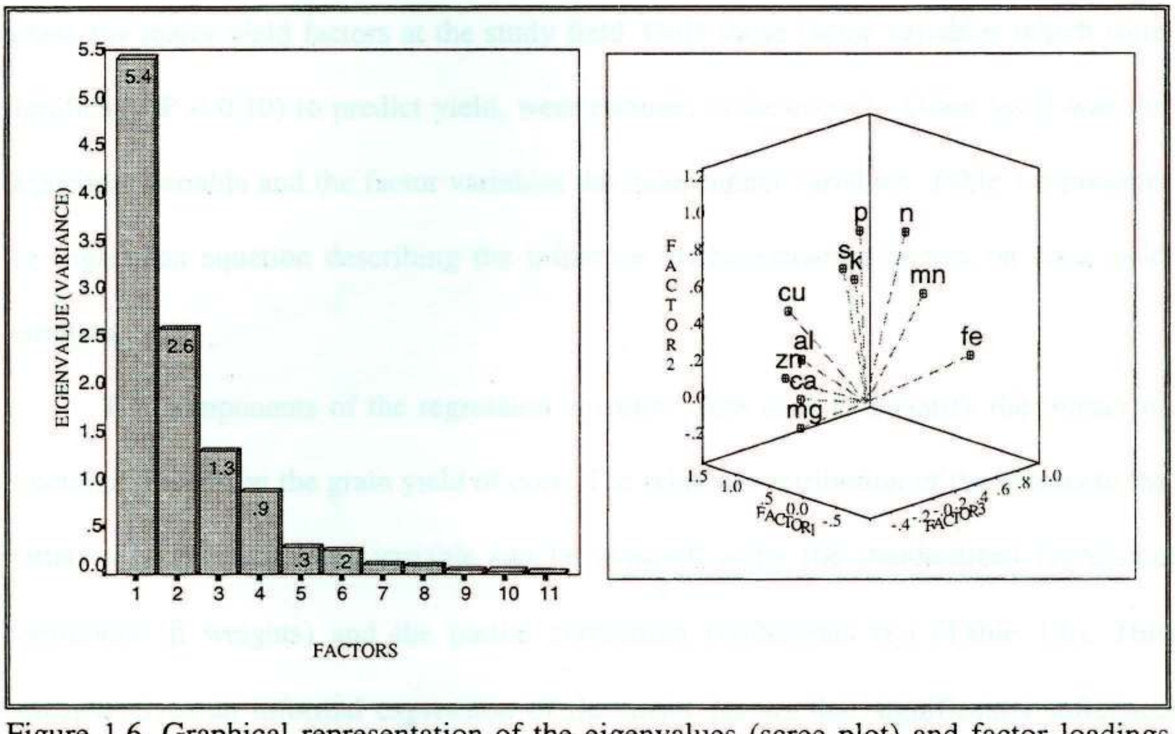

Figure 1.6. Graphical representation of the eigenvalues (scree plot) and factor loadings resulting from the factor analysis.

The interpretation of each factor variable is an important aspect of factor analysis. Agronomic knowledge of potential reasons for the observed covariation and subjective judgement are involved. For soil and plant properties, terms such as acidity, inherent soil fertility, salinization, land preparation, conditions for early growth, weed control, and seeding rate, have been used when interpreting groups of correlated variables defined by factor analysis (Kosaki and Juo, 1989; Dobermman, 1994; Mallarino et al., 1999). For this study, since the tissue analysis may suggest an optimum nutrient level, the factor variable could be interpreted as "***Nutritional Status of Corn***" and is directly related to soil fertility status when others factors, such as light, temperature, moisture, and the physical conditions of the soil are favorable.

To study the relationships between the factor variables and grain yield, multiple linear regression model (Stepwise regression – Backward), was used to identify and assess the major yield factors at the study field. Only those factor variables which were significant ($P < 0.10$) to predict yield, were retained in the model. Grain yield was the dependent variable and the factor variables the independent variables. Table 1.6 presents the regression equation describing the influence of the extracted factors on corn yield variation.

The components of the regression equation were used to quantify the impact of functional factors on the grain yield of corn. The relative contribution of the factors to the variation of the dependent variable can be assessed using the standardized regression coefficient (β weights) and the partial correlation coefficients (r_p) (Table 1.6). This equation gives an informal expression of the major factors that significantly influence corn yield variation in the field.

Table 1.6 Regression model of the contribution of extracted factors of nutrient content in leaf dry matter to the grain yield variation of corn. Gibbon, NE 1997/98.

Model no		Factor Variables FV_1	FV_2	FV_3	Intercept	Adj. R^2	SE of estimate
01	**B**	**-0.290**[a]	**0.440**[a]	-0.154	11.30	**0.58**	0.89
	β	-0.688	0.993	-0.176			
	r_p	-0.684	0.740	-0.229			
02	B	**-0.272**[a]	**0.388**[a]	****	11.30	**0.57**	0.90
	β	-0.646	0.824	****			
	r_p	-0.662	0.748	****			

B = regression coefficient; β = standardized regression coefficient; r_p = partial correlation coefficient; SE = standard error of estimate. Significance level: [a]$P < 0.001$.

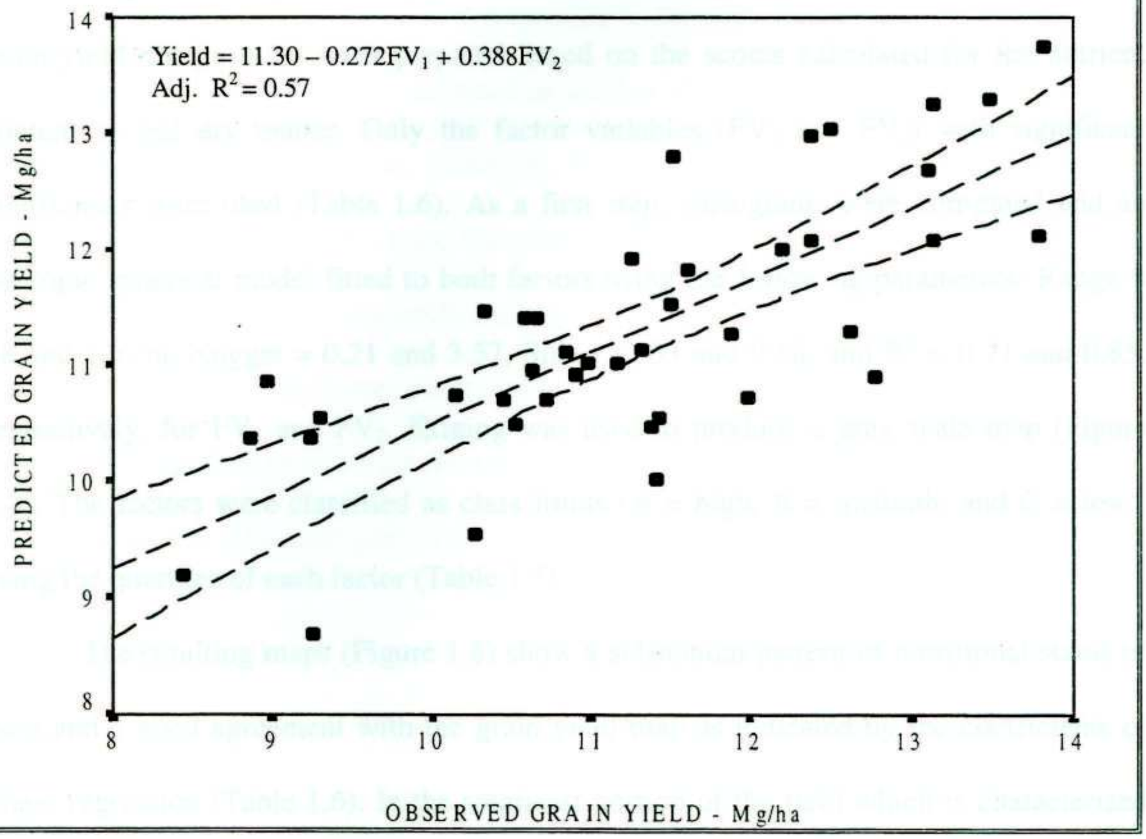

Figure 1.7 Observed and predicted grain yields with 95% confidence interval for the extracted factors of nutritional status of corn. Models are given in Table 1.6. Gibbon, NE, 1997/98.

The factor variables (FV_1 to FV_3) are composed of different groups of correlated nutrients in leaf dry matter, which define the nutritional status of corn in the field. These factor variables explain 57% of the grain yield variability (Table 1.6) with a linear relationship (Figure 1.7). The FV_3, represented by concentration of Mn and Fe in leaf dry matter, was not significant ($P > 0.10$) and was removed from the model. Thus, FV_1 which includes S, K, Ca, Mg, Zn and Cu ($r_p = -0.66$) and FV_2 ($r_p = 0.74$) represented by N, S, K, and P, were the main factors to explain yield variability in the field. Since the nutritional status of corn is an indirect measured of the soil fertility in the field we can presume that soil fertility is an important factor affecting corn yield variability.

To provide a spatial comparison of the nutritional status of corn in the field with grain yield, image maps were prepared based on the scores calculated for the nutrient content in leaf dry matter. Only the factor variables (FV_1 and FV_2) with significant coefficients were used (Table 1.6). As a first step, variograms were computed and an isotropic spherical model fitted to both factors using the following parameters: Range = 48 and 116 m, Nugget = 0.21 and 3.57, Sill = 12.03 and 9.58, and R^2 = 0.71 and 0.85, respectively, for FV_1 and FV_2. Kriging was used to produce a gray scale map (Figure 1.8). The factors were classified as class limits (A = high, B = medium, and C = low), using the quartiles of each factor (Table 1.7).

The resulting maps (Figure 1.8) show a substantial pattern of nutritional status of corn and a good agreement with the grain yield map as indicated by the coefficients of linear regression (Table 1.6). In the southeast portion of the field which is characterized by low yields (Figure 1.8A, light gray shaded), plants had higher concentrations of S, K, Ca, Mg, Cu, and Zn in the leaf dry matter, as determined by tissue analysis (Table 1.7).

Higher slope and soil erosion characterize that part of the field, exposing subsoil which is rich in exchangeable bases and consequently has a pH > 7.0 (Table 1.2). The influence of the soil pH level on the availability of essential nutrients is very well documented in the literature. Because the availability of the indicated group of nutrients is relatively less affected by soil pH in the range of 7.0 to 7.5, this could be explained by their higher content in leaf tissue in that part of the field (Figure 1.8B). The higher concentration of nutrients in plants located in parts of the field with low grain yield could be a problem when using reflectance based crop indices as a means for evaluating crop stress.

The most fertile part of the field, as indicated by the yield map (Figure 1.8 A) and nutrient concentrations in leaf dry matter (Figure 1.8 C), was located on the northeast corner of the area (dark shaded). It corresponds to the area situated in the concave slope or the depression, which is less, exposed to erosion. On this part of the field the nutrient concentrations in the leaf tissue, mainly N, S, P, K, and Mn (Table 1.7) fall within the sufficiency range, indicating a more balanced nutritional status of the plants. In the south part of the field, also characterized by low yield (Figure 1.8A), the nutrient concentrations in the leaf tissue, particularly, S, P and Mn, are very low (Table 1.7). Most values were equal to or less than the minimum critical level used to diagnose nutritional problems in corn. Also, this part of the field is located in a landform with linear slope and is highly eroded.

Table 1.7. Descriptive statistics of nutrient content in leaf dry matter according the class established for the nutrients within each factor variable. Gibbon, NE, 1997/98

Variable	Class	Min	25%	Median	75%	Max	Mean	S.D
		FACTOR-FV_1						
Sulfur	A	1.9	1.9	2.1	2.3	2.8	2.2	0.28
g kg^{-1} †	B	1.6	1.7	1.8	1.9	2.0	1.8	0.13
(2 – 3) ‡	C	1.5	1.6	1.7	1.8	1.9	1.7	0.14
Potassium	A	18.4	19.3	20.5	21.8	27.5	21.0	2.66
g kg^{-1}	B	15.5	16.9	17.6	18.4	20.0	17.7	1.13
(16 – 20)	C	13.6	15.5	15.6	17.1	20.6	16.5	2.12
Calcium	A	5.2	5.3	5.5	6.1	8.1	5.8	0.90
g kg^{-1}	B	4.2	4.7	4.9	5.1	5.4	4.8	0.30
(2 – 6)	C	3.7	4.2	4.3	4.5	5.2	4.4	0.40
Magnesium	A	1.3	1.4	1.5	1.6	2.3	1.6	0.29
g kg^{-1}	B	1.1	1.2	1.3	1.4	1.5	1.3	0.10
(1.5 – 3)	C	0.9	1.0	1.1	1.3	1.4	1.13	0.16
Zinc	A	20.0	21.0	22.5	26.0	29.0	23.8	3.30
g kg^{-1}	B	16.0	17.0	18.0	20.0	22.0	18.7	1.68
(18 – 25)	C	14.0	17.0	17.0	18.0	21.0	17.4	1.84
Copper	A	11.0	11.0	13.0	14.0	18.0	13.2	2.10
g kg^{-1}	B	8.0	9.0	10.0	11.0	12.0	9.8	1.36
(2 –5)	C	8.0	9.0	9.0	11.0	11.0	9.6	1.07
Variable	Class	FACTOR - FV_2						
Nitrogen	A	27.6	29.0	29.7	30.1	30.5	29.4	0.88
g kg^{-1}	B	26.7	27.6	28.3	29.3	30.4	28.3	1.08
(22 – 30)	C	25.0	26.2	27.2	28.4	29.2	27.3	1.32
Sulfur	A	1.9	2.0	2.1	2.3	2.8	2.2	0.27
g kg^{-1}	B	1.6	1.8	1.8	1.9	2.1	1.8	0.12
(2 – 3)	C	1.5	1.6	1.7	1.7	1.7	1.6	0.08
Phosphorus	A	2.2	2.4	2.55	2.7	3.4	2.6	0.36
g kg^{-1}	B	1.7	1.8	2.0	2.0	2.5	2.0	0.23
(2 – 3)	C	1.3	1.5	1.7	1.9	1.9	1.7	0.21
Potassium	A	19.6	20	20.6	21.8	27.5	21.4	2.35
g kg^{-1}	B	16.0	16.8	17.7	18.6	19.4	17.7	1.04
(16 – 20)	C	13.6	15.5	15.9	17.2	18.3	16.0	1.30
Manganese	A	22.0	28.0	30.0	34.0	34.0	30.0	3.83
g kg^{-1}	B	15.0	21.0	23.0	24.0	28.0	22.6	3.13
(15 – 25)	C	11.0	15.0	20.0	22.0	26.0	19.0	4.58
Iron	A	45.0	48.0	68.0	93.0	126.0	76.3	27.6
g kg^{-1}	B	11.0	27.0	41.0	80.0	100.0	51.4	28.7
(20 – 40)	C	11.0	13.0	36.0	47.0	74.0	37.2	22.6

† Grams of nutrient per kilogram of dry matter. ‡ Numbers in parentheses are the sufficiency range, according to Univ. of Nebraska Test Analysis Laboratory

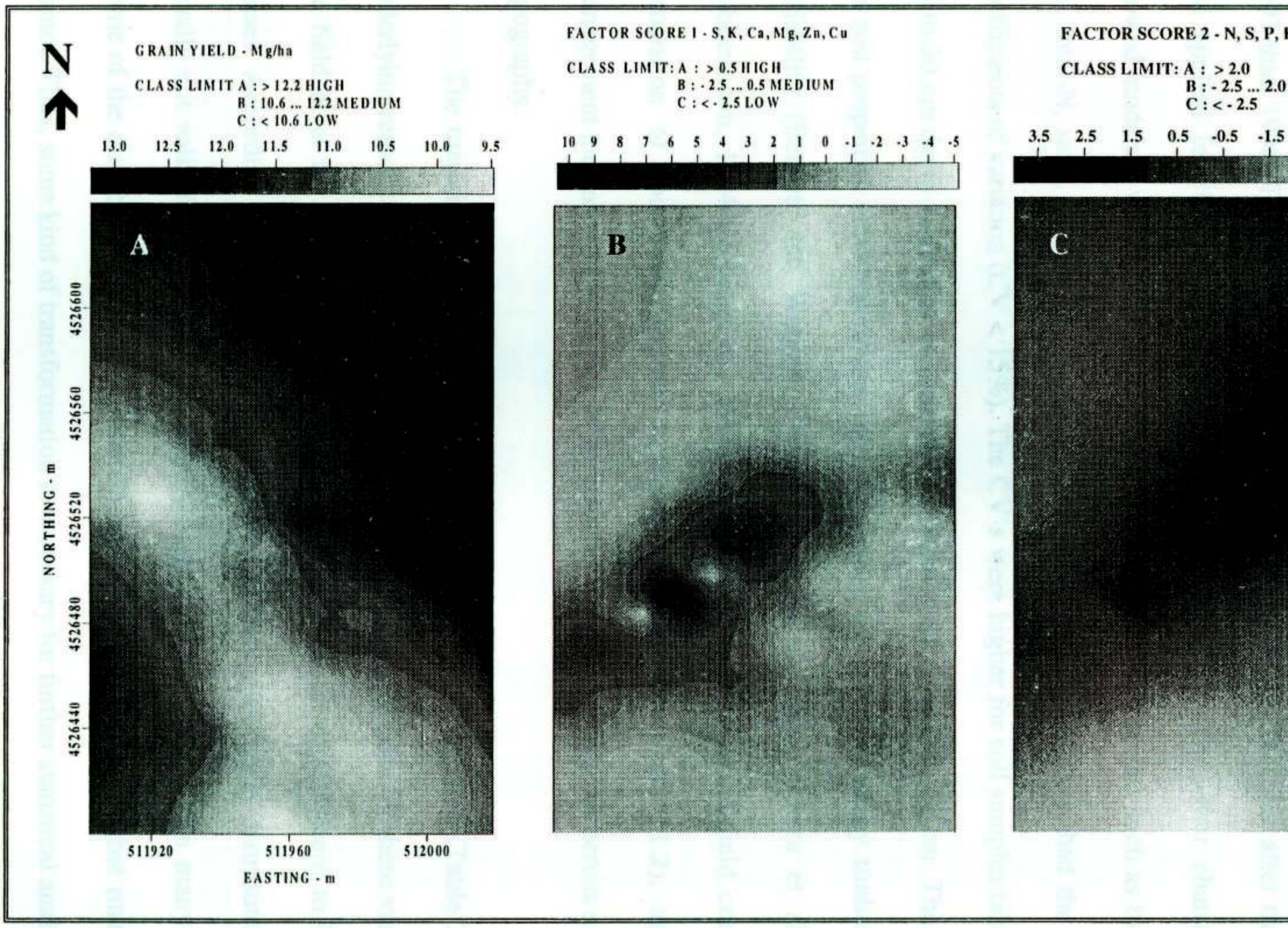

Figure 1.8. Image maps of average grain yield (A) and nutritional status of corn, based on the factors (FV_1-
Gibbon, NE, 1997/98

Soil Physical and Chemical Properties

At the scale of a single field of 53 ha, soil properties such as NO_3-N, NH_4-N, P, Zn, Mn and Fe, are strongly influenced by variable distribution of nutrients and soil management as indicated by CVs values of 35% - 60%. Inorganic-N and P were higher in 1997 than 1998 (Table 1.8) because the soil was sampled in 1997 just after the farmer had applied fertilizer containing these nutrients (10-30-0). The other characteristics showed moderate variability (CV < 35%) (Table 1.8). Soil properties such as the pH, K, Cu, total-N, sand, silt, clay, bulk density and water holding capacity, had the smallest coefficients of variation (CV < 15%). The CV's were higher for soil samples taken in the 15 to 30 cm depth increment as compared as those were from 0 to 15 cm. The CVs for the soil properties measured in this field agree with the results of many studies on soil variability (Beckett and Webster, 1971; Dahiya et al., 1984; Samra et al., 1988; Dobbermann, 1994; Nolin et al., 1996). Although the experimental field contains an association of soils with similar chemical characteristics (Table 1.2), agronomic management increases the within-field variation of many soil properties across a complex topography.

The majority of soil parameters were non-normally distributed (Table 1.8). The underlying reasons for normal and non-normal distributions of some of these variables at the field level are unknown, but management and temporal effects seem to be likely causes. According to Tevis et al. (1991) the assumption of normally distributed data is usually not valid for soils. Data are usually highly skewed and contain many outliers. Some of the distribution can be transformed into a normal distribution, but many others cannot. Thus, some kind of transformation is necessary for further statistical analysis.

Table 1.8 Descriptive statistics of soil physical–chemical properties. Gibbon, NE, 1997/98

Variable	Depth (cm)	Statistical parameters						
		Min	Max	Median	Mean	Std. Dev.	CV (%)	Wilks-Shapiro†
$pH_{1:1\text{-water}}$ (97)	0 – 15	5.84	7.41	6.41	6.49	0.44	6.8	0.91**
	15 – 30	5.54	7.63	6.41	6.60	0.63	9.5	0.90**
$pH_{1:1\text{-water}}$ (98)	0 – 15	5.89	7.55	6.44	6.55	0.41	6.3	0.92**
	15 – 30	5.82	7.76	6.35	6.64	0.62	9.3	0.88**
$EC_{1:1\text{-water}}$ dS m^{-1} (97)	0 – 15	0.31	0.76	0.49	0.51	0.12	24.6	0.94^{ns}
	15 – 30	0.21	0.71	0.28	0.35	0.13	38.3	0.83**
$EC_{1:1\text{-water}}$ dS m^{-1}) (98)	0 – 15	0.20	0.59	0.29	0.32	0.08	26.5	0.83**
	15 – 30	0.22	0.57	0.29	0.34	0.11	32.0	0.84**
$N0_3$-N, kg ha^{-1} (97)	0 – 15	13.81	56.35	27.13	30.03	9.72	32.3	0.92**
	15 – 30	4.65	16.68	8.29	8.82	2.50	28.3	0.96^{ns}
$N0_3$-N, kg ha^{-1} (98)	0 – 15	4.29	26.26	7.79	8.67	4.25	49.0	0.81**
	15 – 30	2.74	13.88	6.37	6.61	2.22	33.5	0.96^{ns}
NH_4-N, kg ha^{-1} (97)	0 – 15	16.87	121.18	46.12	53.84	26.37	48.9	0.91**
	15 – 30	5.09	20.16	8.69	9.37	3.28	35.0	0.87**
NH_4-N, kg ha^{-1} (98)	0 – 15	2.03	7.80	4.02	4.06	1.13	27.9	0.96^{ns}
	15 – 30	2.15	7.25	4.19	4.05	1.31	32.5	0.94*
P-Bray1, kg ha^{-1} (97)	0 – 15	15.67	62.27	26.40	27.53	9.30	33.8	0.86**
	15 – 30	7.09	46.13	12.36	16.11	9.26	57.5	0.79**
P-Bray1, kg ha^{-1} (98)	0 – 15	7.04	33.05	11.70	14.48	6.56	45.3	0.81**
	15 – 30	5.29	30.19	8.96	11.09	5.87	53.0	0.83**
P-Olsen, kg ha^{-1} (98)	0 – 15	1.82	10.81	3.99	4.61	2.32	50.4	0.88**
	15 – 30	0.88	5.56	2.32	2.34	1.09	46.8	0.92**
K, kg ha^{-1}	0 – 15	547	1027	743	749	111	14.8	0.97^{ns}
	15 – 30	401	844	584	588	101	17.2	0.97^{ns}
Ca, kg ha^{-1}	0 – 15	3625	8599	5226	5393	1171	21.7	0.95^{ns}
	15 – 30	4158	10547	6429	6705	1662	24.8	0.92*
Mg, kg ha^{-1}	0 – 15	589	1231	923	889	179	20.0	0.95^{ns}
	15 – 30	681	1589	11.04	1118	202	18.0	0.98^{ns}
Na, kg ha^{-1}	0 – 15	21.78	47.85	31.50	31.96	6.01	18.8	0.95^{ns}
	15 – 30	23.43	60.00	44.28	45.12	7.58	16.8	0.97^{ns}
Zn, kg ha^{-1}	0 – 15	1.28	3.02	1.97	1.99	0.40	20.3	0.96^{ns}
	15 – 30	0.64	3.89	0.89	0.94	0.51	53.9	0.43**
Mn, kg ha^{-1}	0 – 15	17.39	93.96	54.59	53.59	17.28	32.2	0.98^{ns}
	15 – 30	6.53	66.10	24.35	26.50	15.86	59.8	0.92*
Cu, kg ha^{-1}	0 – 15	1.47	2.94	2.19	2.18	0.42	19.2	0.95^{ns}
	15 – 30	1.98	3.65	2.83	2.75	0.41	14.7	0.97^{ns}

† Wilk-Shapiro test for normality, significant at the $^*P \leq 0.05$ and $^{**}P \leq 0.01$ probability levels. Significance indicates that the null hypothesis of normal distribution is rejected.

Table 1.8. Continuation

Variable	Depth (cm)	Min	Max	Median	Mean	Std. Dev.	CV (%)	Wilks-Shapiro †
Fe, kg ha^{-1}	0 – 15	8.86	66.53	21.45	25.19	12.17	48.3	0.87**
	15 – 30	9.14	57.11	17.08	20.63	10.48	50.8	0.86**
B, kg ha^{-1}	0 – 15	0.79	1.14	0.86	0.88	0.07	8.3	0.73**
	15 – 30	0.70	1.22	0.92	0.92	0.08	9.14	0.83**
CEC, meq 100g^{-1}	0 – 15	13.42	25.13	17.85	18.19	2.87	15.8	0.96^{ns}
	15 – 30	14.83	27.92	19.96	20.19	3.47	17.2	0.95^{ns}
SOM, Mg ha^{-1} (97)	0 – 15	25.65	50.21	33.30	36.22	6.85	18.9	0.92**
	15 – 30	12.87	45.20	26.32	26.05	8.06	30.9	0.96^{ns}
SOM, Mg ha^{-1} (98)	0 – 15	39.83	93.88	56.81	58.24	11.68	20.0	0.84**
POM, Mg ha^{-1} (98)	0 – 15	4.28	12.21	8.85	8.87	1.43	16.0	0.97^{ns}
Total-N, kg ha^{-1}	0 – 15	1656	2854	2183	2235	286	12.8	0.96^{ns}
	15 – 30	1022	2552	1479	1569	384	24.4	0.91**
Sand, %	0 – 15	10	16	12	13	1.40	10.9	0.82**
	15 – 30	10	16	12	12	1.64	13.6	0.84**
Silt, %	0 – 15	52	62	58	58	2.72	4.7	0.92*
	15 – 30	52	64	58	58	3.23	5.6	0.93*
Clay, %	0 – 15	24	36	30	30	3.17	10.7	0.93*
	15 – 30	26	36	30	30	2.75	9.0	0.92*
BD_m, g cm^{-3} ‡	0 – 15	1.32	1.58	1.43	1.43	0.05	3.5	0.97^{ns}
	15 – 30	1.42	1.66	1.55	1.55	0.06	3.9	0.96^{ns}
BD_e, g cm^{-3}	0 – 15	1.17	1.23	1.21	1.20	0.02	1.4	0.91**
	15 – 30	1.19	1.27	1.23	1.23	0.02	1.6	0.94^{ns}
AWHC, cm^3 cm^{-3}	0 – 15	0.100	0.166	0.135	0.136	0.01	9.4	0.98^{ns}
	15 – 30	0.089	0.148	0.116	0.116	0.01	12.0	0.98^{ns}

† Wilk-Shapiro test for normality, significant at the $*P \leq 0.05$ and $**P \leq 0.01$ probability levels. Significance indicates that the null hypothesis of normal distribution is rejected. ‡ BD_m is measured bulk density and Bd_e is bulk density estimated from SOM and particle size analysis.

From of data of Table 1.8, we can see substantial variation in most soil properties. For example the maximum P content, 62 kg ha^{-1} (31 mg kg^{-1}) is more than four times that of the minimum, 15 kg ha^{-1} (7 mg kg^{-1}). For Mn concentration, there is a fivefold difference between the minimum, 17 kg ha^{-1} (8 mg kg^{-1}) and the maximum 94 kg ha^{-1} (43mg kg^{-1}). The minimum values are below the deficiency threshold for both nutrients, 16 and 15 mg kg^{-1} for P and Mn, respectively. Thus, conventional approaches to soil testing based on an average are inadequate for characterizing spatial variation of soil properties.

The conventional statistical approaches discussed and presented in Table 1.8 for soil properties provide an incomplete description of the variability because there is no link between the calculated variance and the distance between observations. Thus, knowledge of the distributions as described by minimum, maximum, mean, median, and standard deviation of the observation alone, provides no information about the variability of the observations with respect to the coordinates of the area being sampled (Dahiya et al., 1984).

Because soil properties are spatially correlated (Burrough, 1993), i.e., points in close proximity in a field are more likely to have similar soil parameters than those more widely separated. Spatial analysis should be used when quantifying variability. Geostatistics provide an efficient means of describing the spatial dependence of soil properties. Soil scientists are applying geostatistical theory and semi-variograms with increased frequency (Han et al., 1992). Semi-variance provides a quantitative measurement of spatial variation of soil properties, which is called dissimilarity. The greater the semi-variance, the more dissimilar are the properties of soil at two locations.

Geostatiscal analyses were performed using all standardized (zero mean and unit variance) soil physical – chemical properties measured in the field at 0 to 15 cm and 15 to 30 cm depths. After calculating the semi-variances, semi-variograms were constructed by plotting semi-variance versus lag distance (h). Several models were fitted to the semi-variogram. Spherical, Exponential and Linear models were the most often selected (Tables 1.9 and 1.10). These models were used to estimate the semi-variances between sampled and non-sampled locations. For example, Figure 1.9 shows the pattern of the different models of the variogram selected.

Table 1.9. Geostatistical analysis of standardized soil properties measured at 0 to 15 cm depth. Gibbon, NE, 1997/98.

Variable	Active †		Nugget †	Sill †	Range †	R^2	Proportion	Model †
	Lag (m)	Step (m)	C_0	C_0+C_1	a (m)		$C_1/(C_0+C_1)$	
$pH_{1:1}$-97	142	19	0.001	1.216	115	0.95	0.99	SPH
$pH_{1:1}$- 98	142	19	0.121	1.148	117	0.96	0.89	SPH
$EC_{1:1}$-97	142	19	0.062	1.418	137	0.88	0.95	SPH
$EC_{1:1}$-98	160	19	0.221	1.631	163	0.87	0.86	SPH
NO_3-N-97	130	19	0.136	0.872	43	0.73	0.74	EXP
NO_3-N-98	160	19	0.326	1.202	134	0.68	0.73	SPH
NH_4-N-97	160	19	0.833	1.127	144	0.26	0.21	LIN
NH_4-N-98	131	19	0.849	1.077	41	0.73	0.46	EXP
P-Bray-97	160	19	0.240	1.267	120	0.83	0.81	SPH
P-Bray-98	160	19	0.136	1.602	130	0.80	0.91	EXP
P-Olsen	138	19	0.347	1.066	132	0.84	0.67	SPH
K	175	19	0.732	1.220	145	0.66	0.40	LIN
Ca	175	19	0.128	1.658	145	0.97	0.92	LIN
Mg	175	19	0.293	1.402	199	0.92	0.79	EXP
Na	150	19	0.805	1.182	125	0.66	0.32	LIN
Zn	160	19	0.359	1.204	114	0.78	0.70	EXP
Mn	150	19	0.001	1.396	156	0.80	0.99	SPH
Cu	150	19	0.440	1.218	125	0.96	0.64	SPH
Fe	130	19	0.214	0.934	41	0.31	0.77	EXP
CEC	160	19	0.223	1.583	145	0.95	0.86	LIN
SOM-97	140	19	0.001	1.208	132	0.91	0.99	SPH
SOM-98	140	19	0.001	1.118	125	0.98	0.99	LIN
POM	140	19	0.389	1.210	125	0.83	0.68	LIN
Total-N	140	19	0.152	1.167	132	0.92	0.87	SPH
Sand	150	19	0.499	1.204	125	0.96	0.58	LIN
Silt	150	19	0.249	1.021	87	0.95	0.75	SPH
C	150	19	0.083	1.136	119	0.97	0.92	SPH
BD_m	150	19	0.674	1.123	124	0.74	0.40	LIN
BD_e	150	19	0.036	0.868	123	0.92	0.95	SPH
AWHC	150	19	0.733	1.878	85	0.93	0.61	SPH

† Active lag, the distance to which variograms are computed; active step, the lag increment used. Nugget, semivariance at zero spacing. Sill, semivariance at spacing > range. Range, distance after which values are not correlated. Model: SPH = spherical, EXP = exponential, and LIN = linear.

Table 1.10. Geostatistical analysis of standardized soil properties measured at 15 to 30 cm depth. Gibbon, NE, 1997/98.

Variable	Active †		Nugget †	Sill †	Range †	R^2	Proportion	Model †
	Lag (m)	Step (m)	C_0	C_0+C_1	a (m)		$C_1/(C_0+C_1)$	
$pH_{1:1}$-97	160	19	0.001	1.686	182	0.91	0.99	SPH
$pH_{1:1}$- 98	160	19	0.001	1.743	193	0.91	0.99	SPH
$EC_{1:1}$-97	160	19	0.072	1.347	118	0.97	0.94	SPH
$EC_{1:1}$-98	160	19	0.016	1.195	100	0.96	0.98	SPH
NO_3-N-97	142	19	0.414	1.104	128	0.87	0.62	EXP
NO_3-N-98	110	19	0.250	0.835	24	0.35	0.79	EXP
NH_4-N-97	140	19	0.751	1.047	122	0.47	0.28	LIN
NH_4-N-98	140	19	0.411	1.031	54	0.60	0.60	SPH
P-Bray-97	140	19	0.135	1.040	53	0.47	0.87	EXP
P-Bray-98	160	19	0.487	1.164	110	0.59	0.58	SPH
P-Olsen	160	19	0.373	1.163	109	0.78	0.67	SPH
K	140	19	0.095	1.207	94	0.51	0.92	EXP
Ca	142	19	0.180	1.397	153	0.89	0.87	SPH
Mg	150	19	0.278	1.185	105	0.89	0.76	EXP
Na	150	19	0.329	1.065	40	0.70	0.69	EXP
Zn	140	19	0.011	0.911	122	0.65	0.98	LIN
Mn	140	19	0.001	1.418	122	0.84	0.99	LIN
Cu	140	19	0.748	1.116	122	0.43	0.33	LIN
Fe	140	19	0.001	1.249	122	0.92	0.99	LIN
CEC	140	19	0.225	1.417	158	0.85	0.84	SPH
SOM-97	140	19	0.281	1.130	132	0.83	0.75	SPH
Total-N	110	19	0.096	0.808	111	0.86	0.88	SPH
Sand	150	19	0.097	1.017	30	0.44	0.90	SPH
Silt	150	19	0.101	1.042	35	0.62	0.90	SPH
Clay	150	19	0.131	1.058	38	0.63	0.87	SPH
BD_m	150	19	0.130	1.044	18	0.06	0.87	SPH
BD_e	150	19	0.295	1.153	121	0.82	0.74	SPH
AWHC	150	19	0.330	2.020	30	0.55	0.84	SPH

† Active lag, the distance to which variograms are computed; active step, the lag increment used. Nugget, semivariance at zero spacing. Sill, semivariance at spacing > range. Range, distance after which values are not correlated. Model: SPH = spherical, EXP = exponential, and LIN = linear.

Fitting models to the semi-variograms provided useful parameters for describing the spatial variation of soil properties (Tables 1.9 and 1.10). The magnitude of nugget variance (C_0) depends largely on the variation occurring at a lag distance smaller than the sampling distance. Generally, as sampling intensity increases, the nugget variance decreases. At some point, the nugget variance will no longer decrease with sampling spacing. In this case, the nugget variance represents the inherent variance or error present in measuring the soil property. For both sampling depths, most of the soil properties have a nugget variance close to zero and a few with values close to 1, indicating smaller variability at a short distance, and that errors of sampling and analysis were small (Tables 1.9 and 1.10).

Another useful parameter is the sill ($C_0 + C_1$), which represents the maximum semi-variance. It is a function of the nugget variance (C_0) and the spatially dependent variance (C_1). The proportion $\boldsymbol{C_1/(C_0 + C_1)}$ is a consistent indicator of the importance of the structured variance (C_1) in the spatial dependence of variables. By using the same concept of the classes of spatial dependence as described for plant parameters, the soil properties measured in the field are classified as having moderate (ratio = 0.25 to 0.75) to strong spatial dependency (ratio > 0.75). Most of the soil properties were classified as strongly spatially dependent (Tables 1.9 and 1.10).

The lag distance at which the sill is reached is called the range (a), and marks the separation distance at which the property ceases to be spatially dependent. The range is an important parameter when designing a sampling strategy, as samples acquired at greater spacing than the range will appear to vary randomly and exhibit no spatial dependence. Therefore, it is important to sample at a spacing smaller than the range. The range values showed considerable variability among soil properties measured in the field (Tables 1.9 and 1.10). Soil properties sampled at 0 to 15 cm depth had values raging from 41 to 199 m, averaging 122 m (Std. Dev.=34 m); soil properties at 15 to 30 cm depth had values ranging from 18 to 193 m and averaged 98 m (Std. Dev.=49 m). Most of the spatial dependent soil properties had range values exceeding 100 m, probably because

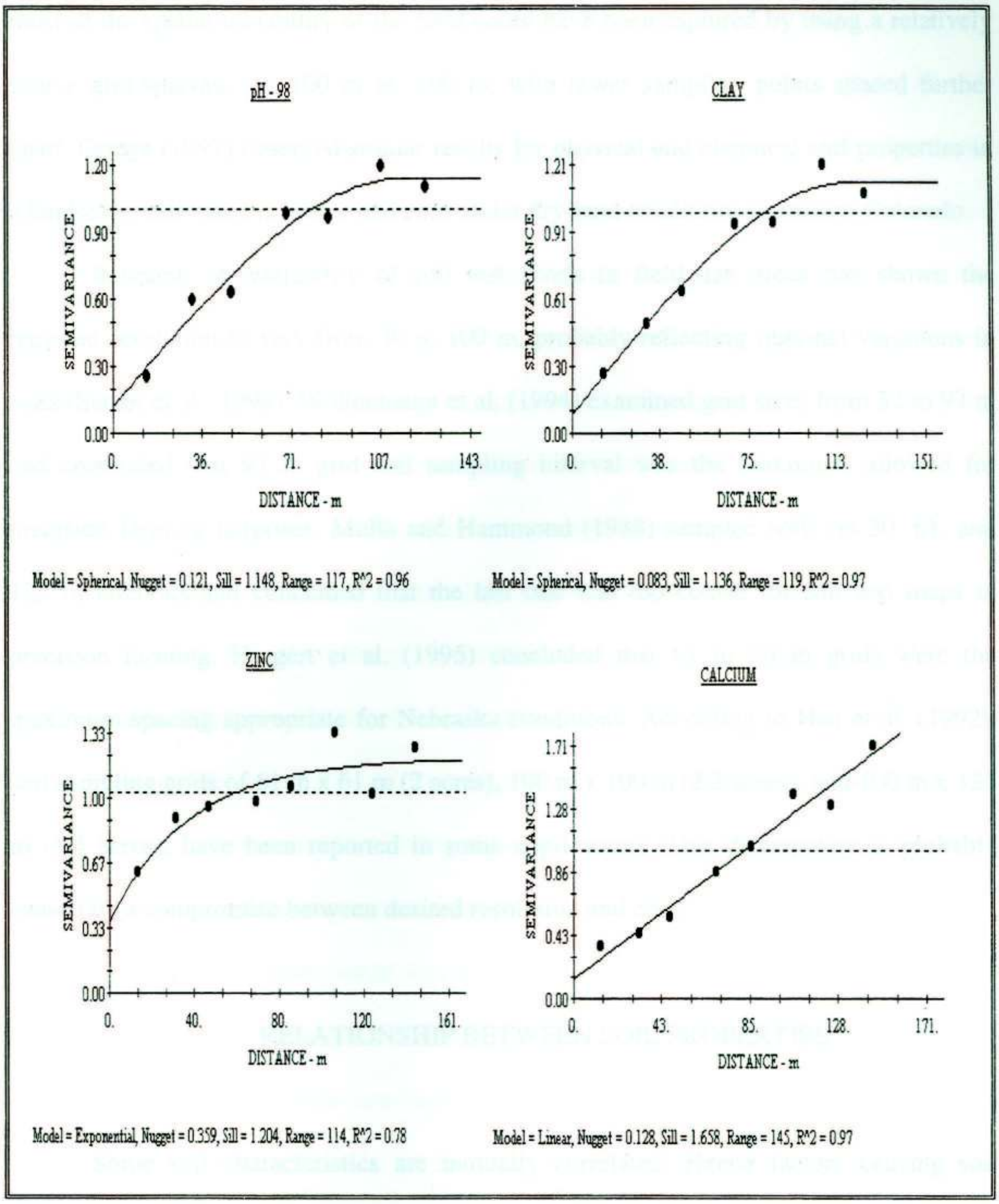

Figure 1.9. Experimental (•) and fitted variogram models (—) for some standardized soil properties measured at 0 to 15 cm depth. The horizontal dashed line is the sample variance. Gibbon, NE, 1997/87.

the soils in the field are related to one another by their position on the landscape. Thus, most of the spatial variability of the field could have been captured by using a relatively coarse grid-spacing, i.e. 100 m by 100 m, with fewer sampling points spaced further apart. Ortega (1997) observed similar results for physical and chemical soil properties in a landscape cultivated in wheat and corn under dry-land conditions in eastern Colorado.

Research on variability of soil test levels in field-size areas has shown the required resolution to vary from 30 to 100 m, probably reflecting regional variations in soils (Sadler et al., 1998). Wollenhaupt et al. (1994) examined grid sizes from 32 to 97 m and concluded that 97 m grid soil sampling interval was the maximum allowed for precision farming purposes. Mulla and Hammond (1988) sampled soils on 30, 61, and 122 m intervals and concluded that the last one was too coarse for soil test maps in precision farming. Hergert et al. (1995) concluded that 61 to 90 m grids were the maximum spacing appropriate for Nebraska conditions. According to Han et al. (1992), soil sampling grids of 61 m x 61 m (2 acres), 100 m x 100 m (2.5 acres), and 100 m x 135 m (3.4 acres), have been reported in some applications. This discrepancy is probably caused by a compromise between desired resolution and cost.

RELATIONSHIP BETWEEN SOIL PROPERTIES

Some soil characteristics are mutually correlated. Hence factors causing soil variation, which is reflected in one or more of the soil characteristics, may be used as criteria of grouping areas with similar characteristics that reflect an underlying process affecting yield variability in the field. To analyze causes of soil variation, factor analysis was applied to my data. It is a technique used to summarize data and investigate the relationships among observed soil properties.

The correlation coefficient matrices among soil properties at two depths (0 –15 and 15 – 30 cm), from which factor analysis was performed, are shown in the Tables A1 and A2, of appendix A. The correlation coefficient matrix shows that there were various degrees of correlation among soil properties. For example: (i) pH and electrical conductivity (EC) have the greatest number of significant correlated characters, followed by calcium (Ca), magnesium (Mg) and phosphorus (P); (ii) potassium (K), nitrate (NO_3) and ammonium (NH_4) have the least number of correlated characters, followed by measured bulk density (BD_m). The lack of correlation between BD_m and most soil physical and chemical properties presumably indicates that an external factor, such as soil management is affecting this property in the field.

Soil Properties Measured at 0 to 15 cm Depth

The original set of 22 soil properties determined at the 0 to 15 cm depth was reduced to five factor variables having eigenvalues greater than 1 (Table 1.11). The additional factors explained the remaining variation; however, the scree plot (not shown) suggested that only random noise was extracted by these additional factors and their interpretation was not attempted. These five factor variables explained 75.5% of the overall variation. The factor loadings (coefficient of correlation) can be used for functional interpretation (Table 1.11). Hair et al. (1992), suggest the following criteria of classification: (i) absolute loadings of 0.30 are considered significant, (ii) loadings of 0.40 are considered more important, and (iii) loadings of 0.50 or more are considered very significant.

Table 1.11. Factor analysis results after promax rotation for soil properties measured at 0 to15 cm depth. Gibbon, NE, 1997/98.

Variance Component	FV_1 ISFP	FV_2 PZnMn	FV_3 IDSE	FV_4 AN	FV_5 AN
Eigenvalue	12.07	3.35	2.98	2.54	2.04
Proportion (%)	38.93	11.39	9.62	8.19	6.60
Cumul. Proportion (%)	38.93	50.33	59.95	68.14	74.73
Variables †		**Factor loadings ‡**			
$pH_{1:1\text{-water}}$ – 97	**0.926**	-0.318	0.176	0.021	0.282
$pH_{1:1\text{-water}}$ – 98	**0.868**	-0.362	0.059	-0.041	0.317
$EC_{1:1\text{-water}}$ – 97	**0.815**	-0.203	0.218	-0.111	0.434
$EC_{1:1\text{-water}}$ – 98	**0.846**	-0.269	0.053	0.193	0.370
NO_3 – N 97	0.362	-0.024	-0.043	0.076	**0.832**
NO_3 – N 98	0.024	0.043	-0.189	**0.784**	0.008
NH_4 – N 97	0.235	-0.112	0.081	-0.083	**0.905**
NH_4 – N 98	0.157	-0.180	0.220	**0.475**	-0.121
P – Bray 97	-0.270	**0.764**	-0.244	-0.134	0.129
P – Bray 98	-0.382	**0.882**	-0.150	0.078	-0.366
P - Olsen	-0.344	**0.762**	-0.135	0.249	-0.481
K	-0.077	**0.782**	0.261	0.239	0.087
Ca	**0.895**	-0.227	0.448	0.146	0.337
Mg	**0.600**	-0.137	**0.892**	-0.034	-0.029
Na	0.158	0.147	**0.733**	0.086	0.272
Zn	-0.357	**0.595**	-0.425	0.027	0.103
Mn	**-0.862**	**0.595**	-0.099	0.161	-0.211
Cu	**0.744**	-0.011	**0.636**	0.129	0.098
Fe	**-0.559**	0.045	-0.290	0.271	0.228
CEC	**0.872**	-0.197	**0.554**	0.043	0.293
SOM – 97	**-0.868**	0.469	**-0.527**	0.363	-0.088
SOM – 98	**-0.702**	0.330	-0.220	**0.591**	-0.369
POM	-0.439	**0.452**	-0.266	0.326	-0.465
Total – N	**-0.846**	0.478	-0.447	0.378	-0.053
Sand	**-0.616**	0.104	-0.365	0.118	-0.062
Silt	-0.391	**0.572**	**-0.725**	0.234	0.037
Clay	**0.607**	**-0.536**	**0.782**	-0.253	-0.004
BD_m	-0.079	0.270	0.343	**0.691**	-0.131
BD_e	**0.850**	-0.402	**0.563**	-0.183	0.031
AWHC	-0.102	0.182	**-0.615**	-0.382	0.095

†EC = electrical conductivity, CEC = cation exchange capacity, SOM = soil organic matter, POM = particulate organic matter, BD_m = measured bulk density, BD = estimated bulk density, AWHC = available water hold capacity ‡ Numbers in bold indicates the variables with large factor loading were selected from each factor to create factor variable.

The first factor variable represented 39% of the variation. Large positive factor loadings were found for pH, electrical conductivity (EC), calcium (Ca), magnesium (Mg), copper (Cu), cation exchange capacity (CEC), clay, and estimated bulk density (BD_e), while negative loadings were found for manganese (Mn), iron (Fe), soil organic matter (SOM), total nitrogen (N), and sand (Table 1.11). Thus, the first factor can be interpreted as the ***inherent soil fertility potential*** (ISFP). It expresses general organo-mineralogical and physical-chemical properties of the soil, which are related to the original nature of soil parent material. A soil within one field receiving a higher score of the first factor is one with higher pH and EC, higher exchange capacity and content of bases, higher copper, and finer texture. Consequently, such a soil is relatively more fertile than the others. In addition, this factor reflects the influence of erosion on the soil fertility status. When topsoil is moved during erosion, the resulting cutting and filling creates areas with different pH, organic matter and clay content

The second factor variable, which explains 11% of soil variability (Table 1.11), is highly positively correlated with phosphorus (P) and moderately correlated with zinc (Zn), manganese (Mn), particulate organic matter (POM), silt, and clay. The positive moderate contribution of silt and negative contribution of clay suggests an effect of texture on the availability of P, Zn and Mn. This factor can be characterized as ***available phosphorus, zinc and manganese*** (PZnMn). The positive correlation between P, Zn, Mn and POM, suggests an influence of organic matter on these nutrients in soils. On the other hand, since P and Zn are expected to be quite low under the prevailing natural vegetation, higher P and Zn are usually related to an increase of farmer activity due to application of fertilizers.

The third factor variable, explaining 8% of soil variability (Table 1.11), is highly positively related to magnesium (Mg), sodium (Na), copper (Cu), CEC, clay and estimated bulk density (BD_e), and negatively correlated with SOM, silt and AWHC. The interpretation of this component is not easy. According to Ellis and Cardwell (1935), cited by Cox et al. (1998), Mg as opposed to Ca may promote the dispersion of clay from a soil, which reduces both, infiltration and water storage in soil. Even if water does penetrate the surface it is held strongly in very small pores formed in the dispersed soil (Cox et al., 1998). The negative correlation that was observed between Mg, Na, and AWHC could be associated with this effect (Table 1.11). Therefore, it is likely that the combination of Mg with Na magnifies the adverse soil properties, with effect on yield. This factor can be characterized as ***indirect deterioration of soil structure*** (IDSE)

Finally, the fourth and fifth factor variables, explaining 8% and 7% respectively of soil variability, are related to the ***available nitrogen***-AN ($N0_3$ and NH_4). Factor four is highly and positively related to $N0_3$ and NH_4 and SOM (Table 1.11). Factor five is characterized by high and positive loadings of both NO_3 and NH_4. The main difference between them is associated with the source of nitrogen. Factor four had SOM as the nitrogen source while factor five had fertilizer as the source of nitrogen. This is because the soil was sampled in 1997 just after fertilizer had been applied. These factors could be deleted when running analysis, but they were maintained, due to high differences in the values of NO_3 and NH_4 observed between the seasons.

Soil Properties Measured at 15 to 30 cm Depth

The same statistical analysis procedure applied to the soil physical – chemical properties measured in the topsoil were used to analyze the soil properties of the subsoil (15 to 30 cm depth). Also, the original set of 21 variables was reduced to five factor variables having eigenvalues (variance) greater than 1 (Table1.12). These factors explained 76% of the overall soil variation. The interpretation of each factor variable is similar to those discussed before. From Table 1.12 we can see that the variables included in each factor are with few exceptions similar to the results observed in soil properties of the 0 to 15 cm depth.

Four factor variables are very well defined and are interpretable without much difficulty. The first factor is related to **inherent soil fertility potential**; the third is related to ***micronutrients associated with organic matter***; the fourth is highly correlated with ***inorganic nitrogen***; and the fifth may be interpreted as the ***available phosphorus*** status. The second factor is highly and positively correlated with P, Mg, Na, Cu, sand, clay, and BD_m. But the high negative contribution of the characters such as silt and AWHC is difficult to interpret. However, compared to the third factor described for soil properties measured in the 0 to 15 cm depth, they are characterized by similar variables and could be interpreted the same way, i.e., ***indirect deterioration of soil structure***.

Table 1.12. Factor analysis results after promax rotation for soil properties measured at 15 to 30 cm depth. Gibbon, NE, 1997/98

Variance Component	FV_1	FV_2	FV_3	FV_4	FV_5
Eigenvalue	9.24	5.67	2.98	2.55	1.67
Proportion (%)	31.88	19.55	10.26	8.80	5.75
Cumul. Proportion (%)	31.88	51.43	61.69	70.50	76.24
Variables †			Factor loadings ‡		
$pH_{1:1\text{-water}}$ – 97	**0.962**	-0.021	-0.413	0.224	-0.292
$pH_{1:1\text{-water}}$ – 98	**0.943**	-0.153	-0.351	0.192	-0.231
$EC_{1:1\text{-water}}$ – 97	**0.865**	-0.098	-0.255	0.167	-0.235
$EC_{1:1\text{-water}}$ – 98	**0.890**	-0.110	-0.296	0.208	-0.171
NO_3-N-97	0.072	-0.329	0.305	**0.654**	0.120
NO_3-N-98	-0.144	-0.036	0.351	**0.659**	-0.178
NH_4-N-97	0.164	-0.155	0.081	**0.657**	-0.136
NH_4-N-98	0.247	0.395	-0.087	**0.594**	-0.348
P – Bray-97	-0.302	0.190	-0.098	-0.057	**0.850**
P – Bray-98	-0.322	**0.717**	0.061	-0.147	**0.892**
P - Olsen	-0.271	-0.092	0.467	0.040	**0.574**
K	-0.216	0.392	0.265	-0.379	**0.627**
Ca	**0.948**	0.211	-0.278	0.169	-0.134
Mg	0.393	**0.797**	-0.486	-0.218	0.164
Na	0.061	**0.653**	-0.081	-0.193	0.221
Zn	-0.050	0.187	**0.673**	0.262	0.142
Mn	**-0.854**	-0.037	**0.664**	-0.009	0.370
Cu	0.420	**0.616**	0.005	0.334	0.215
Fe	**-0.699**	-0.089	**0.811**	0.024	0.274
CEC	**0.919**	0.236	-0.300	0.095	-0.099
SOM	-0.488	-0.385	**0.885**	0.206	-0.008
Total – N	**0.780**	-0.196	**0.780**	0.000	0.124
Sand	-0.222	**0.495**	-0.264	0.034	-0.377
Silt	0.189	**-0.704**	0.226	**0.568**	0.275
Clay	-0.088	**0.530**	-0.107	**-0.687**	-0.097
BD_m	-0.118	**0.732**	0.040	-0.007	0.247
BD_e	0.483	0.482	**-0.852**	-0.207	0.018
AWHC	0.168	**-0.893**	0.079	0.332	-0.063

†EC = electrical conductivity, CEC = cation exchange capacity, SOM = soil organic matter, POM = particulate organic matter, BD_m = measured bulk density, BD_e = estimated bulk density, AWHC = available water hold capacity. ‡ Number in bold indicates the variables with large factor loading were selected from each factor to create new variables.

In general, the functional structures of the extracted factor variables are similar to the results of several studies on soil variability. Kyuma (1973a,b) reported in a factor analysis of 41 Malayan paddy soils in which four factors were found to be of major importance: skeletal organic matter status, available P status, chemical potentiality, and available N status. Later, Kyuma (1981) analyzed 600 Asian rice soils and described three major factors: chemical potentiality, organic matter/nitrogen status, and available P status. Kosaki and Yuo (1989) identified four major factors, inherent fertility, available P, acidity, and organic matter, in a study in Nigeria. Another study with corn grown on Andosols yielded four factors that were identified as organic matter factor, liming factor, available P factor, and exchangeable K factor (Kosaki and Kondo, 1992). In a study conducted within a rice field in Russia, Dobermann (1994) classified the variation of soil and plant properties in five factors: soil fertility, land preparation, nitrogen fertilizer application, seeding rate, and P-availability. More recently, in a study to investigate the relationship between several site variables and corn yields on five producers' fields in Iowa, Mallarino et al., (1999) described three factors which they termed conditions for early growth, soil fertility, and weed control.

RELATIONSHIPS BETWEEN SOIL PROPERTIES AND GRAIN YIELD

The relationships between several soil properties and grain yield are presented in Table 1.13. Grain yield positively or negatively correlated significantly ($P \leq 0.05$) with the most measured soil properties in both depths. This means that the variation of an individual soil property over the field can explain only a part of the variation in grain yield. If only one single variable is used to predict yield and response to fertilizer application, it might often fail because there is other factors as well as the selected variable that limit yield. Soil factors limiting production on the field must be identified to develop effective management systems.

Table 1.13. Simple correlation coefficient analyses between soil properties and grain yields. Gibbon, NE, 1997/98.

Depth 0 to 15 cm	Grain yield 1998	Grain yield 1997	Depth 15 to 30 cm	Grain yield 1997	Grain yield 1998
Grain yield-1997	**0.75**	1.00			
Variable			Variable		
$PH_{1:1\text{-water}}$-97	**-0.50** ‡	**-0.74**	pH-97	**-0.74**	**-0.53**
$pH_{1:1\text{-water}}$-98	**-0.42**	**-0.74**	pH-98	**-0.74**	**-0.49**
$EC_{1:1\text{-water}}$-97	**-0.35**	**-0.57**	EC-97	**-0.62**	**-0.41**
$EC_{1:1\text{-water}}$-98	-0.25	**-0.59**	EC-98	**-0.39**	**-0.62**
NO_3-97	-0.08	**-0.31**	NO3-97	0.02	0.18
NH_4-97	-0.22	0.00	NH4-97	**0.33**	**0.46**
NO_3-98	-0.19	**-0.34**	NO3-98	-0.22	-0.12
NH_4-98	-0.17	-0.07	NH4-98	-0.08	-0.08
P-Bray-97	**0.48**	**0.52**	P-Bray-97	**0.41**	0.15
P-Bray-98	**0.52**	**0.72**	P-Bray-98	**0.49**	0.25
P-Olsen	**0.42**	**0.59**	P-Olsen	**0.62**	**0.49**
K	**0.33**	**0.36**	K	**0.38**	0.14
Ca	**-0.50**	**-0.68**	Ca	**-0.56**	**-0.44**
Mg	**-0.63**	**-0.43**	Mg	-0.30	**-0.61**
Na	-0.26	-0.11	Na	0.12	-0.17
Zn	**0.48**	**0.51**	Zn	0.17	0.18
Mn	**0.55**	**0.77**	Mn	**0.81**	**0.64**
Cu	**-0.49**	**-0.74**	Cu	-0.04	-0.19
Fe	0.25	0.29	Fe	**0.74**	**0.68**
CEC	**-0.51**	**-0.62**	CEC	**-0.55**	**-0.46**
SOM-97	**0.71**	**0.68**	SOM-97	**0.54**	**0.64**
SOM-98	**0.38**	**0.54**	Total-N	**0.70**	**0.62**
POM-98	**0.43**	**0.54**	Sand	0.05	-0.15
Total-N	**0.68**	**0.66**	Silt	0.12	**0.38**
Sand	**0.34**	**0.42**	Clay	-0.17	**-0.36**
Silt	**0.68**	**0.61**	BDd	0.20	-0.13
Clay	**-0.73**	**-0.71**	BDc	**-0.51**	**-0.63**
BD_m	-0.13	0.00	AWHC	-0.07	**0.31**
BD_e	**-0.69**	**-0.65**			
AWHC	**0.35**	0.26			

† EC = electrical conductivity, CEC = cation exchange capacity, SOM = soil organic matter, POM = particulate organic matter, BD_m = measured bulk density, BD_e = estimated bulk density, AWHC = available water hold capacity. ‡ Correlation's are significant at the 5% level if they are higher than + 0.30 or lower than – 0.30.

A multivariate approach was evaluated in an attempt to overcome this problem and to identify and assess the major yield factor variables in the study field. Tables 1.14 and 1.15 present, respectively, regression equations describing the influence of the extracted factors of soil properties measured at 0 to 15 and 15 to 30 cm depths, on the corn grain yield. A complete equation with all factors as independent variables is given as well an optimized equation containing only the factors with significant influence. The component regression equations were used to quantify the impact of the functional factors on the corn yield. The relative contribution of the factors to the variation of the dependent variable (grain yield) can be assessed using the standardized regression coefficients (β weights) and the partial correlation coefficient (r_p). Figures 1.10 and 1.11 show the observed yields plotted against predict yields, based only on the equation model for which the coefficients of the factors are significant ($P \leq 0.10$).

For soil properties measured at 0 to 15 cm depth, the five factor variables extracted by factor analysis (Table 1.11) were interpretable as representing respectively, FV_1 = ***inherent soil fertility potential*** (ISFP); FV_2 = ***available phosphorus, zinc, and manganese*** (PZnMn); FV_3 = ***indirect deterioration of soil structure*** (IDSE); FV_4 and FV_5 = ***available nitrogen*** (AN). Seventy three percent (Adj. $R^2 = 0.73$) of the grain yield variation could be explained as a function of the factors of inherent soil fertility potential (ISFP) and available phosphorus, zinc and manganese (PZnMn) (model 4, Table 1.14).

Table 1.14. Regression models of the contribution of extracted factors of soil properties, measured at 0 to 15 cm depth, to the grain yield variation of corn. Gibbon, NE, 1997/98

Model no		FV_1	FV_2	FV_3	FV_4	FV_5	Intercept	Adj. R^2	SE of Estimate
01	**B**	-0.034	**0.272**[a]	0.018	-0.014	-0.053	11.28	**0.71**	0.55
	β	-0.269	0.632	0.008	-0.026	-0.008			
	r_p	-0.246	0.614	0.008	-0.048	-0.158			
02	**B**	**-0.034** [b]	**0.271**[a]	*****	-0.014	-0.054	11.28	**0.72**	0.55
	β	-0.263	0.629	*****	-0.025	-0.085			
	r_p	-0.322	0.638	*****	-0.048	-0.159			
03	**B**	**-0.031**[b]	**0.270**[a]	*****	*****	-0.052	11.28	**0.73**	0.54
	β	-0.261	0.627	*****	*****	-0.082			
	r_p	-0.319	0.637	*****	*****	-0.155			
04	**B**	**-0.036**[b]	**0.270**[a]	*****	*****	*****	11.28	**0.73**	0.54
	β	-0.280	0.627	*****	*****	*****			
	r_p	-0.347	0.632	*****	*****	*****			

B = regression coefficient; β = standardized regression coefficient; r_p = partial correlation coefficient; SE = standard error of estimate. Significance level: [a]$P < 0.0001$, [b]$P < 0.05$.

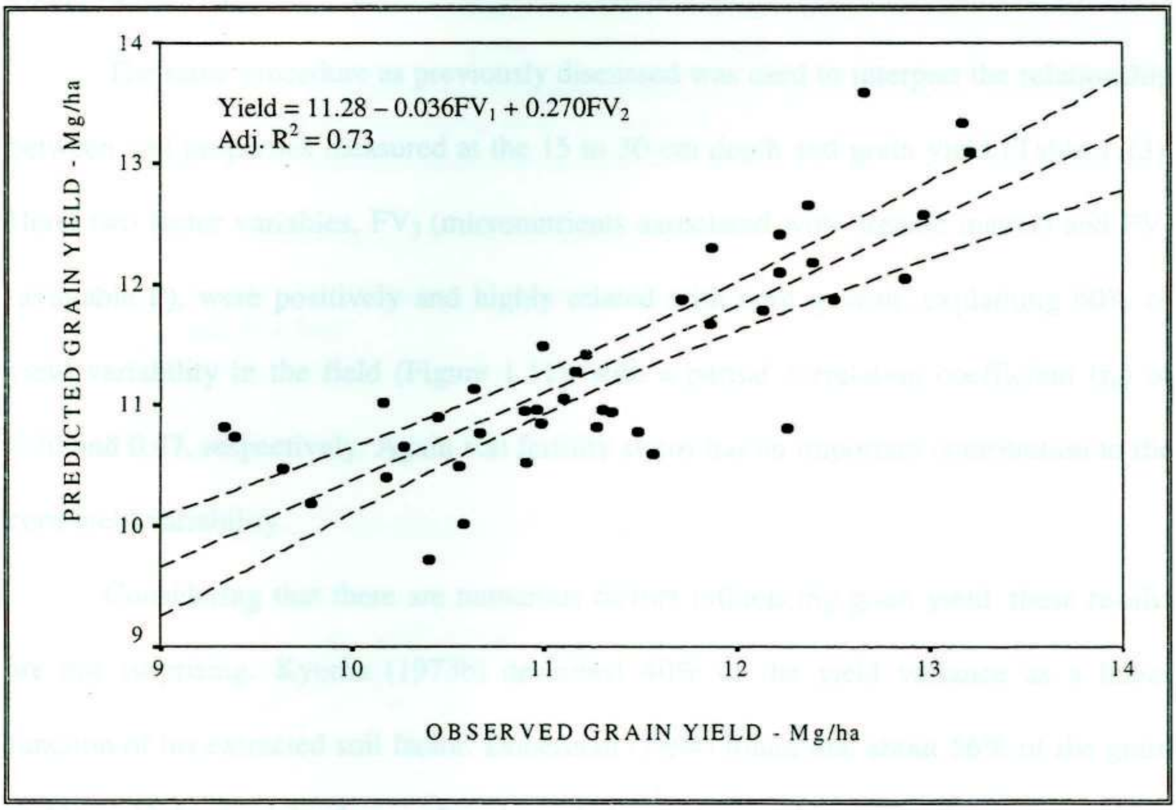

Figure 1.10. Observed and predicted grain yields with 95% confidence interval for the extracted factors for soil properties measured at 0 to 15 cm depth. The model is given in Table 1.14. Gibbon, NE, 1997/98

Given that yield is a function of many factors other than soil fertility, the Adj. R^2 of 0.73 can be regard as being sufficiently high. Therefore we can take the yield predicted by the following formula as the measure of soil fertility: Yield = 11.28 – $0.036FV_1$ + $0.270FV_2$, where yield is in Mg ha^{-1} and FV_1 and FV_2 are the factor variables, as defined before (Figure 1.10). The negative sign of the regression coefficient for FV_1-ISFP (r_p = -0.347) in this equation is derived from negative loading for some variables such as Mn, Fe, SOM, sand and silt (Table 1.11). All these variables, except Fe, have a strong positive correlation to grain yield (Table 1.13). On the other hand, variables such as pH, EC, Ca, Mg, and Cu, with positive landings on this factor, are negatively correlated with yield (Table 1.13).

The same procedure as previously discussed was used to interpret the relationship between soil properties measured at the 15 to 30 cm depth and grain yield (Table 1.13). Here, two factor variables, FV_3 (micronutrients associated with organic matter) and FV_5 (available P), were positively and highly related with corn growth, explaining 60% of yield variability in the field (Figure 1.11), with a partial correlation coefficient (r_p) of 0.70 and 0.47, respectively. Again soil fertility status has an important contribution to the corn yield variability.

Considering that there are numerous factors influencing grain yield, these results are not surprising. Kyuma (1973b) described 40% of the yield variance as a linear function of his extracted soil factor. Doberman (1994) found that about 56% of the grain yield could be explained as a function of the factors soil fertility, land preparation, seeding rate, and P-available.

Table 1.15. Regression models of the contribution of extracted factors of soil properties, measured in the 15 to 30 cm depth, to the grain yield variation of corn. Gibbon, NE 1997/98

Model no		FV_1	FV_2	FV_3	FV_4	FV_5	Intercept	Adj. R^2	SE of Estimate
01	**B**	-0.072	-0.031	**0.097[d]**	0.063	**0.151[b]**	11.34	**0.63**	0.62
	β	-0.291	-0.136	0.378	0.139	0.354			
	r_p	-0.318	-0.205	0.406	0.220	0.452			
02	**B**	-0.069	*****	**0.108[b]**	0.068	**0.128[d]**	11.33	**0.63**	0.63
	β	-0.281	*****	0.422	0.152	0.300			
	r_p	-0.303	*****	0.448	0.235	0.412			
03	**B**	-0.059	*****	**0.124[b]**	*****	**0.114[d]**	11.33	**0.61**	0.64
	β	-0.240	*****	0.480	*****	0.267			
	r_p	-0.260	*****	0.507	*****	0.371			
04	**B**	*****	*****	**0.162[a]**	*****	**0.144[c]**	11.33	**0.60**	0.65
	β	*****	*****	0.632	*****	0.338			
	r_p	*****	*****	0.704	*****	0.468			

B = regression coefficient; β = standardized regression coefficient; r_p = partial correlation coefficient; SE = standard error of estimate. Significance level: [a]$P < 0.001$, [b]$P < 0.01$, [c]$P < 0.005$, [d]$P < 0.05$.

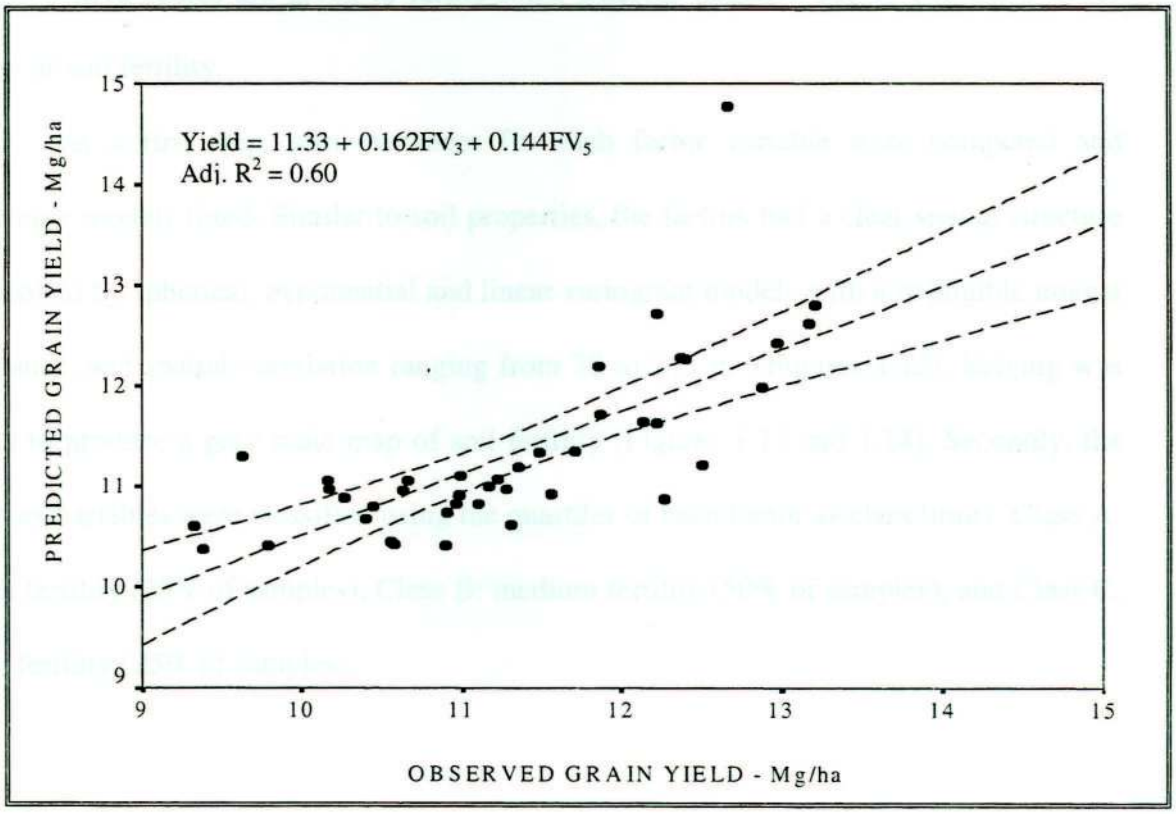

Figure 1.11. Observed and predicted grain yields with 95% confidence interval for the extracted factor variables for soil properties measured in the 15 to 30 cm depth. Model is given in Table 1.15. Gibbon, NE, 1997/98

On the other hand, Mallarino et al. (1999) found that although several groups of correlated variables could be identified for different fields, this does not necessarily mean that they explain yield variability (R^2 ranged from 0.01 to 0.67). They concluded that a cause and effect relationship should not be directly drawn from these relationships. The factors that are significantly related to yield can be help to understand the reasons for yield variability. This understanding can, in turn, be used to manage this particular field better.

Soil Fertility Mapping

The factor variables reflecting soil fertility status for both depths (Tables 1.14 and 1.15) had significant influence on the grain yield. Consequently, the scores of these factors may be used for mapping and evaluating soil fertility in the field, assuming that high positive scores are given to fertile soils, whereas negative scores express a lower level of soil fertility.

As a first step, semi-variances for each factor variable were computed and isotropic models fitted. Similar to soil properties, the factors had a clear spatial structure described by spherical, exponential and linear variogram models with a negligible nugget variance, and spatial correlation ranging from 78 to 213 m. (Figures 1.12). Kriging was used to produce a gray scale map of soil fertility (Figures 1.13 and 1.14). Secondly, the factors variables were classified using the quartiles of each factor as class limits: Class A: high fertility (25% of samples), Class B: medium fertility (50% of samples), and Class C: low fertility (25% of samples).

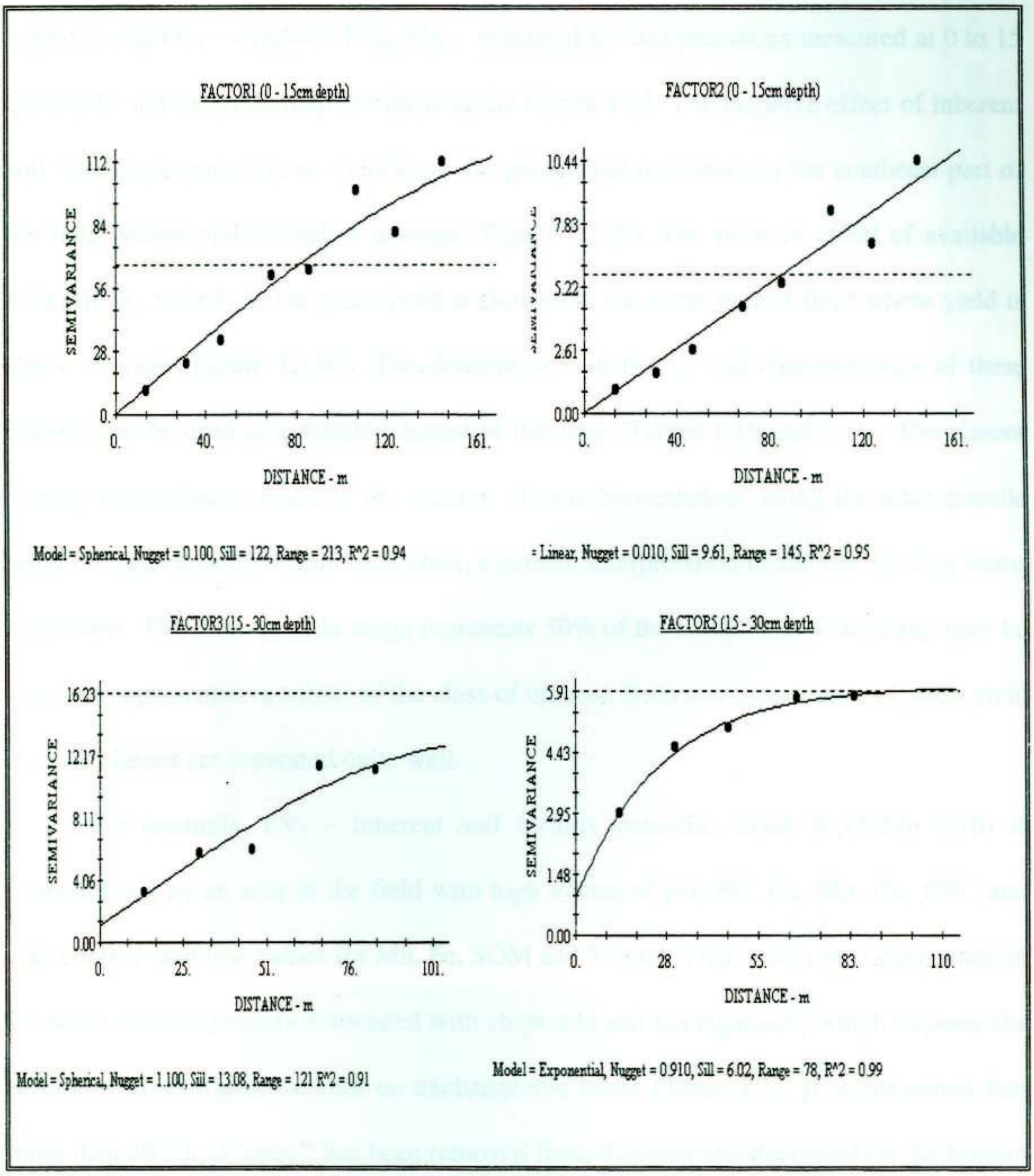

Figure 1.12. Experimental (•) and fitted variogram model (—) for factor variables significantly related to corn yield. Horizontal dashed line is the sample variance. Gibbon, NE, 1997/98

The resulting maps for the significant factor variable (FV_1 – inherent fertility potential and FC_2 – available P,Zn,Mn), extracted for soil properties measured at 0 to 15 cm depth, and the yield map are show in the Figure 1.13. The negative effect of inherent soil fertility potential (r_p = - 0.347) on the grain yield is evident in the southeast part of the field, where yield is below average (Figure 1.13B). The positive effect of available P,Zn,Mn (r_p = 0.63) in the grain yield is showed in the north part of field where yield is above average (Figure 1.13C). The descriptive statistics of soil characteristics of these classes may be used as a detailed legend of this map (Tables 1.16 and 1.17). The classes overlap each other in many of the features shown. Nevertheless, using the inter-quartile ranges of the variables within each class, a general interpretation of the soil fertility status is possible. The inter-quartile range represents 50% of the samples in a class and may be seen as a representative subset of the class of interest. Both soil properties and grain yield in these classes are separated quite well.

For example, FV_1 – inherent soil fertility potential, class A (Table 1.16) is characterized by an area in the field with high values of pH, EC, Ca, Mg, Cu, CEC and clay content, and low values for Mn, Fe, SOM and N-total. This occurs in consequence of the water erosion process associated with slope and soil management, which exposes the subsoil with its higher content on exchangeable bases (Table 1.1). It is presumed that more than 30 cm of topsoil has been removed from this area and deposited on the bottom part of field. Class B and C characterize areas with good conditions for corn growth (yield > 11.3 Mg ha^{-1}), mainly in terms of pH and SOM (Table 1.16).

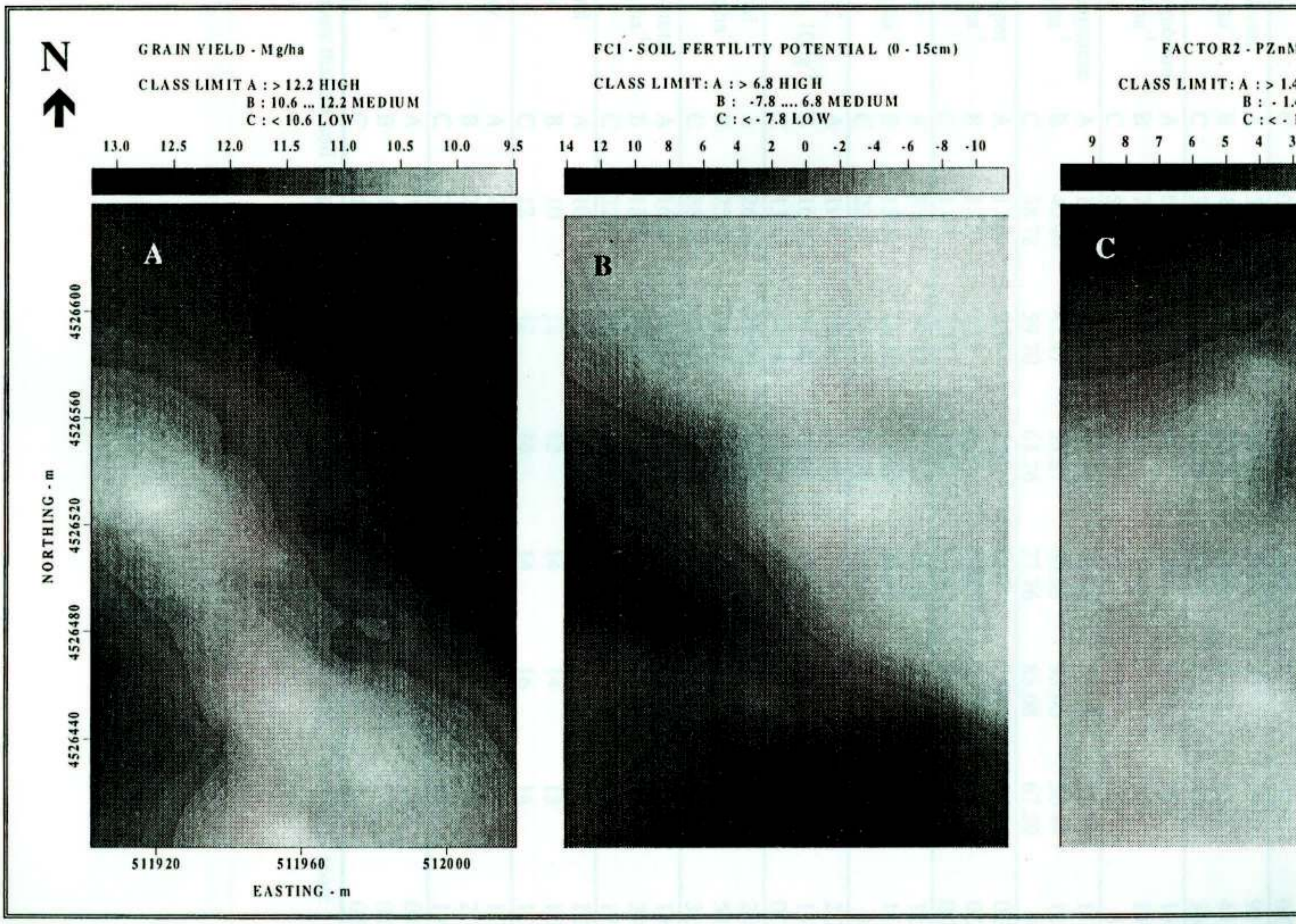

Figure 1.13. Image maps of average grain yield (A), soil fertility status based on FV_1 (B) inherent soil fert
available P, Zn, Mn, for soil properties measured at 0 to 15cm depth. Gibbon, NE, 1997/98.

Table 1.16. Descriptive statistics for the factor variable, FV_1- inherent soil fertility potential, for soil properties measured at 0 to 15 cm depth. Gibbon, NE, 1997/98.

Variable	Class	Min	25%	Median	75%	Max	Mean	S.D
$pH_{1:1\text{-water}}$	A	6.55	6.97	7.18	7.30	7.41	7.11	0.25
	B	5.84	6.27	6.42	6.62	6.81	6.41	0.25
(+)†	C	5.98	6.00	6.04	6.08	6.37	6.07	0.11
$EC_{1:1\text{-water}}$	A	0.50	0.61	0.64	0.69	0.75	0.64	0.07
dS m^{-1}	B	0.35	0.45	0.49	0.57	0.76	0.51	0.10
(+)	C	0.31	0.35	0.37	0.46	0.55	0.39	0.07
Calcium	A	5762	6336	6518	7797	8599	6910	931
Kg ha^{-1}	B	4648	5108	5274	5499	6252	5357	451
(+)	C	3578	3737	4039	4430	4575	4064	366
Magnesium	A	650	926	987	1098	1231	984	162
Kg ha^{-1}	B	734	868	933	1030	1196	959	130
(+)	C	589	629	691	730	775	675	61
Manganese	A	17.40	24.36	31.65	40.35	55.46	32.50	11.48
Kg ha^{-1}	B	40.40	45.47	53.87	60.88	93.96	56.44	12.73
(-)	C	58.78	59.70	63.76	77.76	85.08	67.59	9.56
Copper	A	1.86	2.36	2.68	2.87	2.94	2.60	0.34
Kg ha^{-1}	B	1.75	2.11	2.20	2.37	2.85	2.24	0.27
(+)	C	1.47	1.58	1.68	1.79	2.28	1.72	0.22
Iron	A	8.86	11.37	13.33	18.49	52.86	17.86	12.80
Kg ha^{-1}	B	15.33	18.72	21.22	28.47	66.53	24.89	11.56
(-)	C	22.57	26.93	29.75	35.07	55.02	32.44	9.02
CEC	A	19.47	19.86	20.65	24.24	25.13	21.55	2.23
meq $100g^{-1}$	B	16.92	17.30	18.03	18.80	22.20	18.40	1.41
(+)	C	13.42	14.18	14.64	15.43	15.80	14.77	0.76
SOM	A	26.35	28.90	30.34	31.72	32.99	30.04	2.16
Mg ha^{-1}	B	25.65	31.03	32.99	38.38	44.58	34.66	5.09
(-)	C	38.13	41.54	44.58	47.67	50.21	44.69	3.57
N – total	A	1656	1932	2002	2038	2183	1974	139
Kg ha^{-1}	B	1853	2018	2160	2307	2614	2176	202
(-)	C	2297	2394	2562	2704	2854	2560	179
Sand	A	10	10	12	12	14	12	1.26
%	B	10	12	12	14	14	13	1.19
(-)	C	12	12	14	14	16	14	1.21
Clay	A	28	30	31	32	34	31	1.70
%	B	24	30	32	32	36	31	2.71
(+)	C	24	24	26	26	28	26	1.40
BD_e	A	1.21	1.21	1.22	1.22	1.23	1.22	0.008
g cm^{-3}	B	1.18	1.19	1.21	1.21	1.23	1.21	0.013
(+)	C	1.17	1.18	1.18	1.19	1.19	1.18	0.006

† Means that the soil properties have positive (+) or negative (-) loadings within of the factor score

Descriptive statistics for classes of the factor variable two (FV_2-avalaible P, Zn,Mn), which had a significant and positive relationship with grain yield ($r_p = 0.63$) are shown in the Table 1.17. Class C characterizes an area located in the northwest part of field (Figure 1.13C), with low yields. This area is characterized by lower content of phosphorus (10 mg kg^{-1}), zinc (0.84 mg kg^{-1}) and manganese (18 mg kg^{-1}), with values below critical levels established for corn production. In addition, this area has high pH and low organic matter content.

Table 1.17. Descriptive statistics for the factor variable, FV_2- available P, Zn, Mn, for soil properties measured at 0 to 15 cm depth. Gibbon, NE, 1997/98.

Variable	Class	Min	25%	Median	75%	Max	Mean	S.D
P-Bray	A	21.69	30.00	39.01	44.38	62.27	38.64	11.60
Kg ha^{-1}	B	15.67	22.47	26.14	28.36	29.03	24.98	4.02
(+)†	C	15.99	18.44	21.02	27.24	31.17	22.06	5.02
Potassium	A	643	714	835	883	1010	819	122
Kg ha^{-1}	B	547	693	754	789	878	740	85
(+)	C	557	613	678	737	1027	702	122
Zinc	A	1.94	2.13	2.31	2.57	3.02	2.38	0.33
Kg ha^{-1}	B	1.45	1.58	1.74	2.03	2.68	1.85	0.33
(+)	C	1.28	1.52	1.97	2.15	2.41	1.85	0.35
Manganese	A	58.96	63.76	72.61	81.40	93.96	73.76	11.07
Kg ha^{-1}	B	24.36	45.23	53.87	59.86	66.30	51.12	12.31
(+)	C	17.39	30.45	44.10	45.37	60.88	39.75	12.98
POM	A	7.72	8.72	9.67	11.07	12.21	9.82	1.50
Mg ha^{-1}	B	7.06	8.44	9.11	9.66	10.86	9.00	1.00
(+)	C	4.28	6.99	8.06	8.85	8.96	7.78	1.40
Silt	A	58	60	62	62	62	61	1.41
%	B	54	56	57	58	60	57	1.65
(+)	C	52	54	56	58	60	56	2.60
Clay	A	24	24	26	26	28	26	1.58
%	B	26	30	30	32	34	30	1.87
(-)	C	26	32	32	34	36	32	2.83

† Means that the soil properties have positive (+) or negative (-) loadings within of the factor score

At the 15 to 30 cm depth, two factor variables explaining 60% of yield variability were identified. These factors were designated as FV_3 – available micronutrients associated with organic matter and FV_5 – available phosphorus. The patterns of these factors match quite well with the yield map (Figure 1.14). The most fertile part was located on the southeastern corner of the area (dark shaded), corresponding to the concave slope or depression in the bottom of the field. Such an area inherently has some advantages in forming fertile soil. A concave or depression landform is less exposed to erosion, but is subject to deposition of eroded material from the upper part of the slope. The descriptive statistics of soil characteristics for the factor variables, FV_3 and FV_5, are presented in Table 1.18. The main difference observed among the classes is related to the nutrients P, Zn, Mn, Fe, N-total, and organic matter. Class A, classified as high fertility status (Figure 1.14A,B), is characterized by higher content of these nutrients, with values above the critical level established for corn. Since P, Zn, Fe, and Mn, have low mobility in soils, organic matter in the subsoil is the main source of these nutrients to the plant, and probably could explain both the high positive correlation with grain yield and the inclusion of SOM in the FV_3. The values for estimated bulk density (BD_e) do not vary among classes. Its association with FV_3 is difficult to explain.

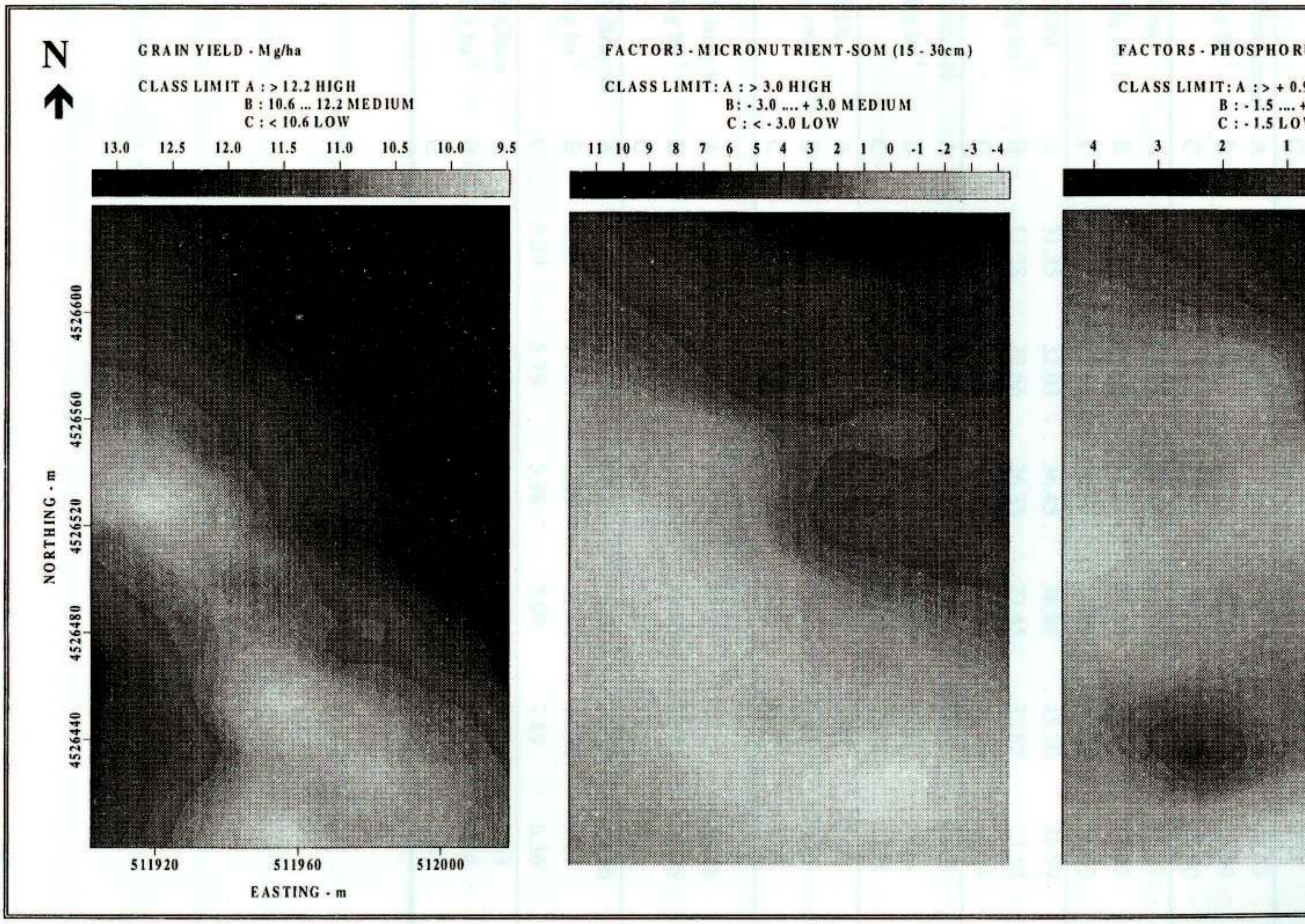

Figure 1.14. Image maps of average grain yield (A), available micronutrient associated to organic matter (B), a phosphorus (C), based on factor variables extracted from soil properties measured in the 15 to 30 cm depth. Gi

Table 1.18. Descriptive statistics for the factor FV_3-micronutrients associated with organic matter, and factor FC_5-available phosphorus, for soil properties measured in the 15 to 30 cm depth. Gibbon, NE, 1997/98.

Variables	Class	Min	25%	Median	75%	Max	Mean	S.D
				Factor Variable – FV_3				
Zinc	A	0.69	0.88	0.91	0.94	3.89	1.17	0.96
Kg ha^{-1}	B	0.70	0.75	0.90	0.97	1.72	0.93	0.23
	C	0.64	0.68	0.70	0.73	0.96	0.74	0.10
Manganese	A	35.28	41.67	47.04	55.11	66.10	48.63	9.48
Kg ha^{-1}	B	6.53	10.15	24.35	27.43	39.24	21.09	10.71
	C	6.82	12.08	15.75	19.32	24.02	15.70	5.55
Iron	A	26.71	28.97	31.16	41.18	57.11	35.17	9.46
Mg ha-1	B	9.14	14.09	16.01	21.38	29.76	17.23	5.50
	C	9.80	10.65	12.97	13.89	19.56	13.23	3.09
SOM	A	31.35	32.03	36.45	38.86	45.20	36.59	4.72
Mg ha^{-1}	B	17.28	22.66	26.33	27.45	32.82	25.52	4.00
	C	12.87	15.07	15.61	18.35	23.43	16.64	2.89
Total -N	A	1847	1884	2074	2261	2552	2118	239
Kg ha^{-1}	B	1022	1296	1479	1643	1905	1458	230
	C	1108	1217	1262	1319	1377	1255	87
BDc	A	1.19	1.20	1.21	1.22	1.22	1.21	0.01
g cm^{-3}	B	1.22	1.23	1.23	1.24	1.26	1.23	0.01
	C	1.23	1.25	1.26	1.26	1.27	1.25	0.01
				Factor Variable – FV_5				
P-Bray 97	A	15.28	21.15	26.73	32.22	46.13	28.48	10.18
Kg ha^{-1}	B	7.14	10.34	12.12	14.97	23.81	13.35	4.14
	C	7.09	7.91	9.45	11.05	12.55	9.51	18.98
P-Bray 98	A	13.99	15.89	17.23	25.01	30.19	19.46	5.40
Kg ha^{-1}	B	5.95	7.70	8.96	11.41	14.94	9.37	2.50
	C	5.29	5.79	5.98	7.09	7.89	6.36	0.83
P-Olsen	A	1.22	2.42	3.73	3.94	5.56	3.53	1.31
Kg ha^{-1}	B	0.88	1.53	2.18	2.83	3.16	2.16	0.77
	C	0.88	1.28	1.42	2.13	2.63	1.63	0.56

ASSESSING ON SITE SOIL AND EVIRONMENTAL DEGRADATION

The research site has been cultivated for over 25 years, under intensive soil and crop management such as moldboard plowing, irrigation and input of agrochemicals. Under these conditions, where long-term land use is known, information on the spatial variability of soil properties can be used as an indicator of soil degradation.

The existence of an uncultivated area located in close proximity to the experimental field and on similar soil and landscape (Figure 1.3) can be used as a reference point. This area has been under alfalfa (***Medicago sativa*** L.) for many years. Because of the great difference in soil management (mainly tillage), the relative difference between soil properties measured in these two areas could be used as indicator of soil and environmental degradation.

The soil properties selected for this propose were: pH as an indicator of acidification; electrical conductivity (EC) indicating osmotic condition and salinization; measured bulk density (BD_m) indicating compaction; and soil organic matter (SOM) and particulate organic matter (POM) indicating effects of tillage and water erosion on reduction of soil organic matter.

The results of the analyses of these soil properties are summarized in Table 1.15. The mean values of pH and EC are higher in the area cultivated in corn, mainly in the second transect which is located in a part of the field characterized by convex landform and which is highly eroded. The strong negative correlation observed between pH, EC, and grain yield (Table 1.13) is caused by the effect of pH on nutrient availability and carbonates on electrical conductivity, rather than the direct effect of pH and EC on yield. Because the content of sodium in soil is low (Table 1.8), it has a low contribution for electrical conductivity. According to Smith and Doran (1996), soils are considered slightly saline if the EC for 1:1 soil-to-water mixture ($EC_{1:1}$) exceeds 1.0 to 1.4 dS m^{-1} for coarse and fine textured soils, respectively. However, the salt tolerance of agriculture crops varies considerably and, for corn values of $EC_{1:1\text{-water}}$ of 1.0 –1.2 dS m^{-1} are mentioned as threshold, above which, yield will begin to decline. Contour maps of pH and $EC_{1:1\text{-water}}$, compared to grain yield are displayed in Figure 1.15. Since that electrical conductivity of a soil is determined by a combination of water content, dissolved salt, clay and mineralogy, it has been used successfully to characterize and map soil attributes. For example, Eigenberg et al (2000) showed that sequential measurement of soil electrical conductivity was a reliable indicator of the relative potential for losses of soil nutrients by leaching.

The main difference observed between the two areas was in the organic matter content. The area in alfalfa has an average of 26% more organic mater (20 Mg ha^{-1}) than the area cultivated in corn. This is of interest for two reasons. First, the area in corn has an annual addition of organic matter of 8.0 to 10 Mg ha^{-1} (assuming an average grain yield of 10 Mg ha^{-1}). Secondly, unlike the corn field, the area in alfalfa is used for hay. It receives no addition of organic matter, except for root growth.

The intensive uses of tillage and high inputs of N-fertilizer are the main factors affecting the rate of crop residue decomposition in the corn field. The primary effect of tillage is putting the residue into intimate contact with soil microbes. The uniform applications of N-fertilizer through irrigation water to the low nitrogen corn residue increase decomposition. The relatively higher content of POM, the active pool of the organic matter in soils, in the corn field could be an indicator of this effect.

One other important parameter, measured bulk density, shows similar values for both areas and for both depths (Table 1.15). The estimated value of bulk density of this field, based on the percentages of clay, silt, sand, and organic matter (Rawls, 1983), was predicted to be 1.20 g cm^{-3}. The values measured in the field (1.3 to 1.6 g cm^{-3}) suggest a compaction effect of cropping practices and wheel traffic by agricultural equipment. No generally accepted rule of thumb exists which states that a certain bulk density limits plant productivity. However, some studies have been conducted which address this parameter in predicting detrimental effects to plant growth. Bowen (1981) and Arshad et al. (1996), suggested that a bulk density of 1.50 to1.55 g cm^{-3} can impede root growth in a silty clay loam and, thus, will reduce yield. Based on this information and on the values of bulk density, mainly those measured at 15 to 30 cm depth it is probable that problems of compaction are occurring in part of the field. However, as grain yield was not negatively correlated with bulk density, it appears that compaction doesn't constitute a limiting factor for corn, or the use of irrigation minimizes its effect. As demonstrated by Phene and Beale (1976), with use of high-frequency irrigation, corn roots developed normally in a sandy loam soil, where the A2 horizon was compacted (bulk density equal to 1.7 – 1.9 g cm^{-3}).

Table 1.15 Descriptive statistics of soil properties measured in adjacent alfalfa and corn fields. Gibbon, NE, 1998.

Variable † and Depth	Transect	Crop	Statistical parameters					
			Min	Max	Median	Mean ‡	Std. Dev.	CV (%)
$pH_{1:1\text{-water}}$ (0 – 15 cm)	01	**Alfalfa**	**5.87**	**6.47**	**6.18**	**6.19a**	**0.22**	**3.6**
	02	Corn	6.04	7.55	7.08	6.88b	0.59	8.7
	03	Corn	6.13	6.71	6.43	6.43a	0.23	3.5
	04	Corn	6.06	7.06	6.44	6.52a	0.29	4.5
	05	Corn	5.89	7.07	6.30	6.43a	0.37	5.8
$pH_{1:1\text{-water}}$ (15 – 30 cm)	01	**Alfalfa**	**6.20**	**7.22**	**6.53**	**6.55A**	**0.31**	**4.7**
	02	Corn	5.96	7.76	7.13	6.98A	0.74	10.7
	03	Corn	5.82	7.49	6.33	6.49A	0.51	7.8
	04	Corn	5.82	7.43	6.35	6.61A	0.58	8.8
	05	Corn	5.92	7.51	6.27	6.54A	0.62	9.5
$EC_{1:1\text{-water}}$ dS m^{-1} (0 – 15 cm)	01	**Alfalfa**	**0.22**	**0.48**	**0.26**	**0.28a**	**0.08**	**30.2**
	02	Corn	0.30	0.51	0.33	0.39b	0.09	23.6
	03	Corn	0.20	0.36	0.28	0.28a	0.04	13.5
	04	Corn	0.26	0.41	0.28	0.31a	0.05	17.1
	05	Corn	0.22	0.59	0.28	0.32a	0.11	34.3
$EC_{1:1\text{-water}}$ dS m^{-1} (15 – 30 cm)	01	**Alfalfa**	**0.18**	**0.56**	**0.18**	**0.23A**	**0.13**	**57.0**
	02	Corn	0.22	0.52	0.43	0.37B	0.11	31.0
	03	Corn	0.22	0.46	0.26	0.29A	0.08	26.2
	04	Corn	0.23	0.50	0.29	0.35B	0.11	32.6
	05	Corn	0.23	0.57	0.31	0.36B	0.13	34.0
BD_m g cm^{-3} (0 – 15 cm)	01	**Alfalfa**	**1.30**	**1.45**	**1.40**	**1.40a**	**0.05**	**3.3**
	02	Corn	1.38	1.46	1.43	1.42a	0.03	2.0
	03	Corn	1.32	1.46	1.42	1.40a	0.05	3.7
	04	Corn	1.34	1.49	1.43	1.43a	0.04	2.9
	05	Corn	1.40	1.58	1.46	1.46b	0.06	4.0
BD_m g cm^{-3} (15 – 30 cm)	01	**Alfalfa**	**1.40**	**1.63**	**1.50**	**1.50A**	**0.08**	**5.2**
	02	Corn	1.42	1.64	1.51	1.53A	0.07	4.8
	03	Corn	1.44	1.63	1.56	1.54A	0.06	4.2
	04	Corn	1.47	1.61	1.54	1.54A	0.05	3.2
	05	Corn	1.49	1.66	1.60	1.58B	0.05	3.5
SOM Mg ha^{-1} (0 – 15 cm)	01	**Alfalfa**	**76**	**83**	**78**	**78a**	**2.08**	**2.6**
	02	Corn	40	59	47	48b	7.12	14.7
	03	Corn	49	62	57	57b	4.26	7.5
	04	Corn	52	63	56	57b	3.42	6.0
	05	Corn	53	94	69	70b	16.28	23.2
POM Mg ha^{-1} (0 – 15 cm)	01	**Alfalfa**	**5.50**	**11.27**	**7.27**	**7.53a**	**1.79**	**23.8**
	02	Corn	4.28	9.87	7.33	7.54a	1.61	21.3
	03	Corn	7.93	11.07	8.86	9.09b	0.95	10.5
	04	Corn	7.72	10.39	9.56	9.21b	0.88	9.5
	05	Corn	7.06	12.21	8.79	9.45b	1.58	16.8

† EC = electrical conductivity, SOM = soil organic matter, POM = particulate organic matter, BD_m = measured bulk density. ‡ Means followed by the same letters do not present significant differences at 0.05 % level by t-test.

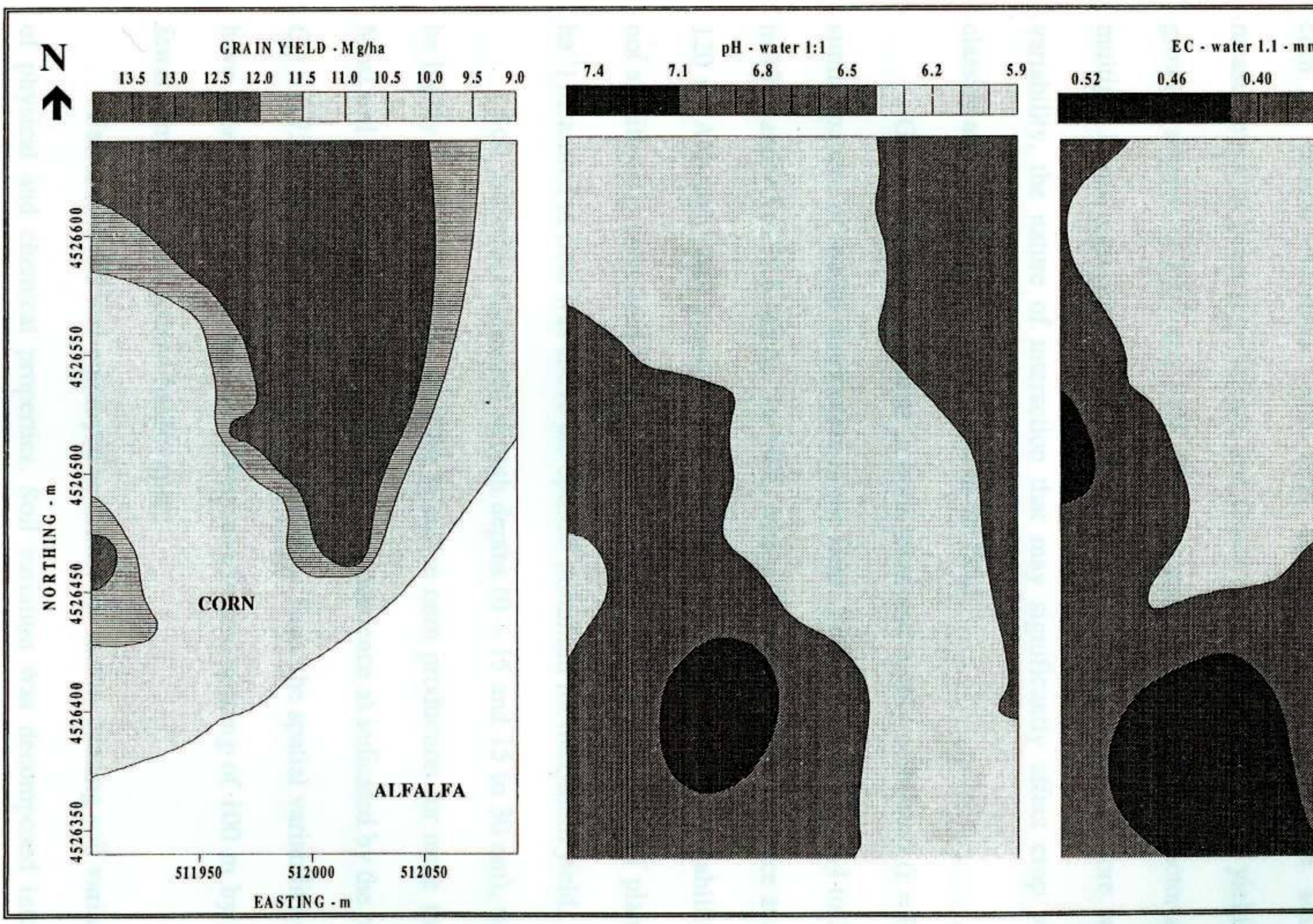

Figure 1.15. Contour maps of average grain yield, pH, and electrical conductivity ($EC_{1:1}$-water), measured at 0
a field cropped with alfalfa and irrigated corn. Gibbon, NE, 1998.

SUMMARY AND CONCLUSIONS

Spatial variability of soil physical and chemical properties and its relationship to crop growth and development was assessed in a silty clay loam soil cultivated to irrigated corn in central Nebraska. The field studies involved extensive soil sampling, measurement of plant populations, leaf tissue composition, and grain yields during the growing seasons of 1997 and 1998. Classical statistics, geostatistics, factor analysis, and multiple linear regression were used as principal techniques to explore soil and crop variability, the nature of interaction that may significantly affect crop yield, and to classify and map soil properties status in the field.

Grain yields were similar in both years and highly correlated ($r = 0.75$), with a similar pattern of spatial distribution in the field. Yields ranged from 8.4 to 13.8 Mg ha^{-1} in 1997 and 9.7 to 12.8 Mg ha^{-1} in 1998, with a strong spatial dependence at a distance of 120 m. Although plant population presented spatial and temporal variability, they were not significantly correlated with grain yields. The minimum number of plants (~ 70,000 ha^{-1}) measured in field was above the optimal minimum for maximum yield.

Soil properties measured at both depths (0 – 15 and 15 to 30 cm), were found to be highly variable in a field used for intensive corn production for more than 25 years. Most soil properties showed a strong spatial dependence as indicated by the ratio $C_1/(C_0 + C_1) > 0.75$, with range values exceeding 100 m. Thus, the spatial variability of soil could have been captured by using a relatively coarse grid-spacing of 100 m by 100 m, with fewer sampling points spaced further apart.

Factor analysis was employed to extract the factors causing soil variation in terms of physical and chemical properties. Soil variation was decomposed into five factor variables, each of which was interpreted under the field conditions for growing corn. These factor variables accounted for 75% of the total variance and were termed: (i) inherent soil fertility potential, (ii) available phosphorus, (iii) indirect deterioration of soil structure, (iv) available micronutrients associated with organic matter, and (v) available nitrogen.

Regression models based on these factors showed that soil fertility status as related to available phosphorus, zinc and manganese, and organic matter, explained 73% of corn yield variability. Image maps based on the scores of each factor variable were useful in displaying the pattern of the soil variation in the experimental field.

The identification in the field of areas with low and high yields and their possible causes indicates a potential use for site-specific soil and crop management technologies. The stability and strong spatial structure in the variability of grain yields and soil physical- chemical properties during two growing seasons is also a good indicator of the potential of this technology.

The indication of beginning soil degradation in part of the area was assessed by comparing values of soil properties measured in the field under different systems of management. Loss of organic matter due to erosion, intensive tillage and input of nitrogen fertilizer, and compaction were some indicators of this degradation. Also, differences in grain yield of 4.0 to 5.0 Mg ha^{-1} observed under uniform management indicates soil degradation and inefficiency of agriculture production.

APENDIX A

Table A1. Simple correlation coefficients between soil physical-chemical properties measured at 0 to depth. Gibbon, NE, 1997/98.

Variables	pH 97	pH 98	EC 97	EC 98	NO_3 97	NO_3 98	NH_4 97	NH_4 98	P-Bray 97	P-Bray 98	P Olsen	K
pH-97	1.00											
pH-98	**0.89**	1.00										
EC-97	**0.81**	**0.69**	1.00									
EC-98	**0.82**	**0.82**	**0.72**	1.00								
NO_3-97	**0.40**	**0.37**	**0.54**	**0.41**	1.00							
NO_3-98	0.06	0.01	-0.01	**0.35**	0.05	1.00						
NH_4-97	0.25	0.25	**0.46**	0.28	**0.78**	-0.03	1.00					
NH_4-98	0.13	0.00	-0.05	0.18	0.07	**0.47**	-0.09	1.00				
P-Bray-97	**-0.31**	-0.24	-0.09	-0.21	0.06	-0.10	0.16	-0.27	1.00			
P-Bray-98	**-0.41**	**-0.42**	-0.26	**-0.38**	-0.23	-0.08	**-0.39**	-0.19	**0.68**	1.00		
P-Olsen	**-0.34**	**-0.37**	-0.25	-0.30	-0.29	0.03	**-0.44**	-0.08	**0.49**	**0.88**	1.00	
K	-0.15	-0.17	-0.03	-0.05	0.04	0.04	0.00	-0.01	**0.49**	**0.58**	**0.46**	1.00
Ca	**0.84**	**0.75**	**0.73**	**0.82**	**0.39**	0.17	0.30	0.21	-0.29	**-0.37**	**-0.32**	0.15
Mg	**0.43**	**0.31**	**0.42**	**0.32**	0.01	-0.04	0.09	0.27	-0.27	-0.21	-0.20	0.21
Na	0.00	-0.02	0.16	0.12	0.16	0.03	0.29	0.11	-0.07	-0.04	-0.10	**0.38**
Zn	-0.26	-0.22	-0.27	**-0.31**	0.07	-0.11	-0.03	-0.21	**0.48**	**0.46**	0.31	0.28
Mn	**-0.88**	**-0.83**	**-0.74**	**-0.77**	-0.29	0.04	-0.23	-0.04	**0.41**	**0.54**	**0.44**	**0.39**
Cu	**0.61**	**0.50**	**0.57**	**0.58**	0.19	0.09	0.10	0.29	-0.21	-0.15	-0.12	0.29
Fe	**-0.45**	**-0.36**	**-0.45**	-0.28	0.01	0.05	0.07	-0.02	-0.01	0.06	0.01	0.01
CEC	**0.75**	**0.66**	**0.67**	**0.75**	**0.32**	0.12	0.27	0.24	-0.27	**-0.35**	**-0.34**	0.22
SOM-97	**-0.72**	**-0.65**	**-0.66**	**-0.56**	-0.22	0.24	-0.19	0.12	**0.34**	**0.40**	**0.38**	0.20
SOM-98	**-0.60**	**-0.60**	**-0.61**	**-0.49**	**-0.35**	**0.36**	**0.37**	0.10	0.00	**0.31**	**0.46**	0.14
POM-98	**-0.41**	**-0.43**	**-0.33**	**-0.36**	-0.24	0.25	**-0.37**	0.04	0.27	**0.58**	**0.56**	0.12
Total-N	**-0.71**	**-0.66**	**-0.58**	**-0.55**	-0.17	0.25	-0.12	-0.12	**0.34**	**0.39**	**0.38**	0.23
Sand	**-0.45**	**-0.51**	**-0.31**	**-0.47**	-0.17	0.00	-0.03	-0.25	0.12	0.15	0.21	-0.07
Silt	**-0.36**	-0.21	**-0.37**	-0.11	0.00	0.26	-0.13	-0.13	**0.42**	**0.47**	**0.40**	0.23
Clay	**0.50**	**0.41**	**0.45**	**0.31**	0.08	-0.22	0.13	0.22	**-0.42**	**-0.47**	**-0.43**	-0.16
BD_m	0.03	-0.03	-0.04	-0.02	-0.02	**0.32**	-0.06	0.14	-0.03	0.18	**0.37**	0.27
BD_e	**0.73**	**0.66**	**0.63**	**0.55**	0.27	-0.17	0.13	0.19	**-0.36**	**-0.32**	-0.28	-0.13
AWHC	-0.14	-0.06	-0.08	-0.08	0.03	-0.12	-0.02	-0.24	0.29	0.17	0.04	-0.06

Table A1. Continuation

Variables	Na	Zn	Mn	Cu	Fe	CEC	SOM 97	SOM 98	POM	Total N	Sand	Silt	Clay	BDd
Zn	-0.22	1.00												
Mn	0.13	**0.39**	1.00											
Cu	**0.54**	-0.28	**-0.43**	1.00										
Fe	-0.03	0.14	**0.38**	**-0.52**	1.00									
CEC	**0.46**	**-0.35**	**-0.63**	**0.85**	**-0.44**	1.00								
SOM-97	-0.24	**0.50**	**0.75**	**-0.64**	**0.48**	**-0.74**	1.00							
SOM-98	-0.13	0.22	**0.65**	**-0.33**	**0.37**	**-0.54**	**0.71**	1.00						
POM	-0.18	0.22	**0.40**	**-0.33**	0.09	**-0.46**	**0.43**	**0.51**	1.00					
N-total	-0.14	**0.43**	**0.73**	**-0.58**	**0.43**	**-0.72**	**0.97**	**0.71**	**0.46**	1.00				
Sand	-0.28	0.11	**0.37**	**-0.54**	0.27	**-0.56**	**0.57**	**0.47**	0.30	**0.58**	1.00			
Silt	-0.27	**0.57**	**0.45**	**-0.35**	**0.33**	**-0.42**	**0.58**	**0.37**	**0.35**	**0.51**	0.09	1.00		
Clay	**0.36**	**-0.54**	**-0.55**	**0.54**	**-0.41**	**0.60**	**-0.74**	**-0.52**	**-0.43**	**-0.69**	**-0.52**	**-0.89**	1.00	
BD_m	0.24	0.05	0.16	0.22	-0.03	0.04	0.18	**0.46**	0.23	0.24	0.10	-0.13	0.07	1.00
BD_e	0.24	**-0.47**	**-0.71**	**0.67**	**-0.45**	**0.74**	**-0.96**	**-0.60**	**-0.36**	**-0.93**	**-0.55**	**-0.55**	**0.72**	0.02
AWHC	**-0.31**	0.29	0.09	-0.21	0.00	-0.20	0.15	-0.08	0.00	0.10	0.12	**0.53**	**-0.51**	**-0.67**

† CEC = cation exchange capacity, SOM = soil organic matter, POM = particulate organic matter, BD_m = measured bulk density, BD_e = density, AWHC = available water holding capacity. Correlations are significant at the 5 % level if they are higher than + 0.30 or lowe

Table A2. Simple correlation coefficients among soil physical-chemical properties measured at 15 to 30
1997/98.

Variables †	pH 97	pH 98	EC 97	EC 98	NO_3 97	NO_3 98	NH_4 97	NH_4 98	P-Bray 97	P-Bray 98	P Olsen
pH-97	1.00										
pH-98	**0.97**	1.00									
EC-97	**0.86**	**0.87**	1.00								
EC-98	**0.89**	**0.88**	**0.89**	1.00							
NO_3-97	0.06	0.12	0.06	0.05	1.00						
NO_3-98	-0.06	-0.11	-0.08	0.00	0.25	1.00					
NH_4-97	0.20	0.19	0.09	0.11	**0.75**	0.19	1.00				
NH_4-98	**0.31**	0.18	0.18	0.26	0.06	**0.59**	0.25	1.00			
P-Bray-97	**-0.41**	**-0.36**	**-0.35**	**-0.32**	0.00	-0.12	-0.12	-0.22	1.00		
P-Bray-98	**-0.44**	**-0.39**	**-0.36**	**-0.33**	-0.02	-0.12	-0.19	**-0.31**	**0.93**	1.00	
P-Olsen	**-0.37**	**-0.34**	-0.22	-0.12	0.11	0.18	-0.23	-0.14	**0.31**	**0.44**	1.00
K	**-0.35**	**-0.34**	**-0.33**	**-0.32**	-0.09	-0.20	**-0.32**	-0.23	**0.50**	**0.59**	**0.46**
Ca	**0.89**	**0.84**	**0.79**	**0.79**	0.04	-0.09	0.16	**0.33**	-0.29	-0.29	-0.24
Mg	0.30	0.19	0.17	0.18	**-0.33**	-0.29	-0.20	0.25	0.23	0.14	-0.19
Na	-0.08	-0.18	-0.15	-0.12	-0.27	-0.14	-0.04	0.12	0.20	0.24	-0.06
Zn	-0.14	-0.13	-0.04	-0.12	0.30	0.23	0.17	0.17	0.01	0.06	0.14
Mn	**-0.90**	**-0.87**	**-0.74**	**-0.74**	0.07	0.29	0.13	-0.18	**0.36**	**0.45**	**0.57**
Cu	**0.32**	0.22	0.18	0.23	0.02	0.15	0.13	**0.46**	0.14	0.11	0.01
Fe	**-0.77**	**-0.73**	**-0.60**	**-0.60**	0.22	0.27	-0.06	-0.18	0.17	0.27	**0.54**
CEC	**0.84**	**0.78**	**0.72**	**0.73**	0.01	-0.12	0.11	**0.31**	-0.26	-0.26	-0.23
SOM	**-0.49**	**-0.41**	**-0.33**	**-0.41**	0.29	**0.40**	0.16	-0.11	-0.11	0.00	0.29
Total-N	**-0.80**	**-0.74**	**-0.58**	**-0.63**	0.11	0.28	-0.11	-0.20	0.01	0.20	**0.40**
Sand	-0.13	-0.23	-0.07	-0.20	-0.15	0.08	-0.09	0.29	-0.11	-0.19	-0.11
Silt	0.18	0.27	0.20	0.23	**0.45**	0.22	0.26	0.08	0.00	0.00	0.25
Clay	-0.13	-0.17	-0.19	-0.15	**-0.43**	**-0.31**	-0.25	-0.08	0.07	0.10	-0.22
BD_m	-0.15	-0.21	-0.12	-0.18	-0.14	0.00	-0.10	0.17	0.30	**0.34**	0.15
BD_e	**0.46**	**0.38**	**0.34**	**0.38**	**-0.32**	**-0.40**	-0.18	0.13	0.12	0.00	-0.30
AWHC	0.20	0.28	0.19	0.24	**0.35**	0.14	0.22	-0.15	-0.23	-0.26	0.02

Table A2. Continuation

Variables †	Na	Zn	Mn	Cu	Fe	CEC	SOM	N Total	Sand	Silt	Clay	BDd
Zn	0.11	1.00										
Mn	0.03	**0.35**	1.00									
Cu	**0.47**	**0.39**	-0.18	1.00								
Fe	0.00	**0.51**	**0.88**	-0.14	1.00							
CEC	**0.31**	-0.04	**-0.75**	**0.50**	**-0.60**	1.00						
SOM-97	-0.24	**0.44**	**0.67**	-0.21	**0.73**	**-0.48**	1.00					
Total-N	-0.06	**0.39**	**0.88**	-0.30	**0.87**	**-0.72**	**0.85**	1.00				
Sand	0.07	-0.09	0.02	0.07	-0.05	-0.09	-0.22	-0.04	1.00			
Silt	**-0.42**	0.04	0.02	-0.04	0.07	0.00	**0.32**	0.07	**-0.52**	1.00		
Clay	**0.45**	0.00	-0.03	0.00	-0.05	0.06	-0.25	-0.05	0.02	**-0.86**	1.00	
BD_m	**0.34**	0.21	0.18	**0.45**	0.09	-0.09	-0.09	0.05	**0.32**	-0.27	0.12	1.00
BD_e	**0.32**	**-0.38**	**-0.65**	0.29	**-0.71**	**0.49**	**-0.98**	**-0.83**	0.25	**-0.35**	0.26	0.22
AWHC	**-0.48**	-0.13	-0.11	**-0.35**	-0.03	0.05	0.24	0.00	**-0.44**	**0.71**	**-0.57**	**-0.86**

†CEC = cation exchange capacity, SOM =soil organic matter, BD_m = measured bulk density, BD_e = estimated bulk density, AWHC = available water holding capacity. Correlation's are significant at the 5 % level if they are higher than 0.30 or lower than

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CHAPTER 2

EXPLORING CAUSE AND EFFECT RELATIONSHIPS IN YIELD VARIABILITY

INTRODUCTION

Site-specific farming has introduced a management system through which the farmers can begin analyzing and dealing with soil and crop variability. Site-specific farming is based upon the recognition that fields used for agriculture production are not uniform. Variations of soil physical properties, nutrient levels and water content occur from field to field and within fields. These spatial variations result from many factors such as previous farming practices, topography, and nutrient application inaccuracy.

With site-specific technology, farmers are adjusting application rates of lime, manure, fertilizers, pesticides, seed rate, hybrid or variety, water and tillage. There are several steps in development a management plan for precision farming: (i) identify the variability, (ii) characterize variability, and (iii) rank the limiting factors and develop an action plan. The most meaningful factors to include in a management zone strategy will be those with the most direct effect on crop yield.

BACKGROUND

Spatial variability in crop yield is frequently related to variability in soil properties. In an experiment conducted to asses the potential causes of corn yield variability, Coelho et al. (1999), found that variation in Mn, clay, NH_4, and P in the surface 15-cm soil depth, accounted for 79% of the variability in corn grain yield, as determined by the stepwise regression. This was partitioned into 61% associated with

Mn, 11% with clay, 3% with NH_4, and 4% with P. The calculated value of Pearson's correlation coefficients (r) for these variables with grain yield were 0.78, -0.77, -0.33, and 0.51, respectively for Mn, clay, NH_4 and P. Corn grain yield ranged from 8.4 Mg ha^{-1} to 13.8 Mg ha^{-1} and averaged 11.3 Mg ha^{-1} with a standard deviation of 1.37 Mg ha^{-1}. Based on this information, an experiment was conducted in the following season (1998) to evaluate corn responses to P, Mn and their interactions, in restoring productivity to eroded soil.

MATERIAL AND METHODS

Experimental Layout

Based on a contour map of grain yield harvest in 1997 (Fig.2.1), the experimental field was divided in two general areas of management: one area with grain yield below the average of 11.3 Mg ha^{-1}, while the other had yield above the average. In each area, four new plots close to existing plots were established to apply treatments of Mn, P, or Mn plus P as identified by regression analysis. Plots measuring 6 m by 9.6 m (12 rows by 6 m long) were divided in three subplots measuring 6 m by 3.2 m (4 rows by 6m long), for application of treatments. Also, control plots with no treatment were included.

Treatments

Three treatments were applied to the corn: 1) 92 kg of P_2O_5 ha^{-1} as triple super phosphate, banded at 10 cm to the side of plants and incorporated into the soil at the four leaf growth stage; 2) Mn was applied on the corn foliage at a rate of 1.1 kg ha^{-1} as $MnSO_4$ at the four and eight-leaf growth stages; and 3) a combination of treatment 1 plus 2. The $MnSO_4$ used was completely water-soluble and had a pH of 6.8 in solution.

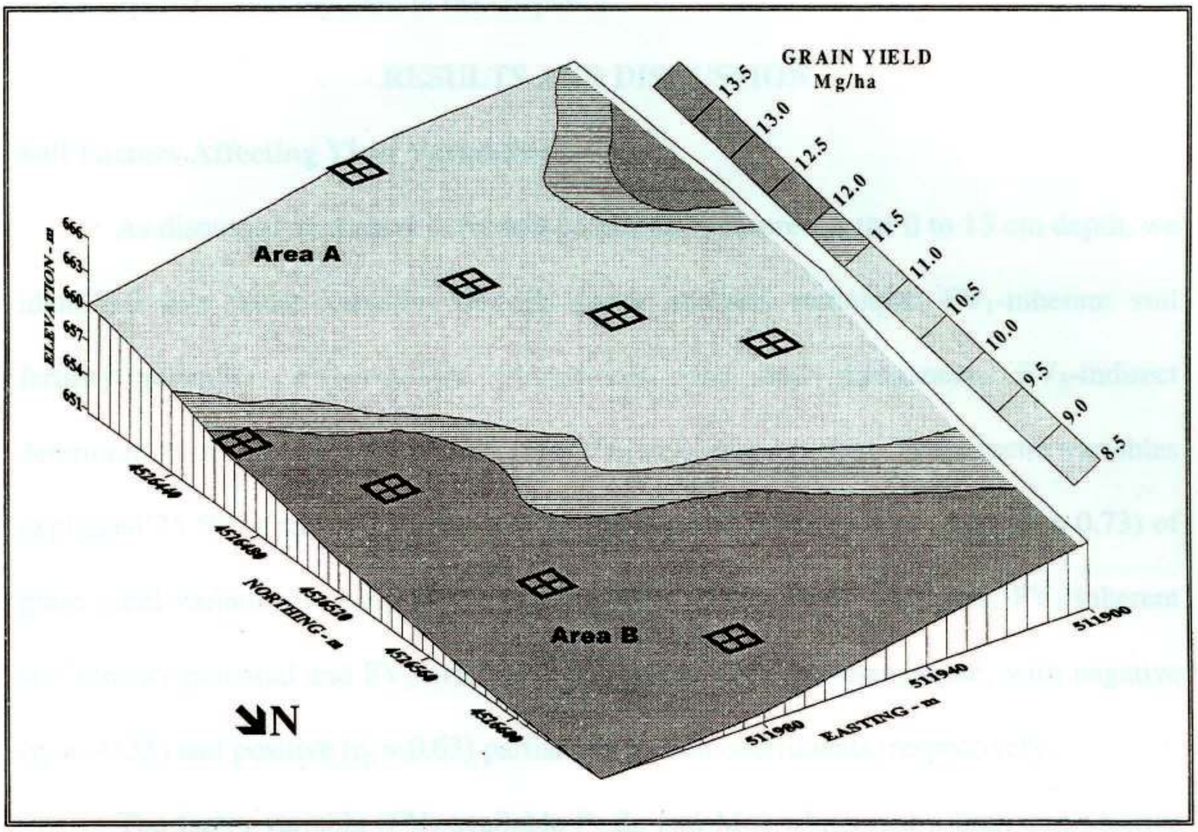


Figure 2.1. Contour map of corn grain yield in 1997, overlaid on topography. The squares represent the plots located in the field for treatment application. Gibbon, NE, 1998.

Statistical Analyses

Data were analyzed statistically by analysis of variance and orthogonal comparison methods using the procedures of SAS system for mixed models. In addition, grain yield, P and Mn in soil were analyzed using a semivariogram analysis and kriging interpolation for precise contour map generation.

Modeling to Predict the Response of Corn to Fertilizer

The CERES – Maize model (DSSAT Version 3, International Benchmark Sites Network for Agrotechnology), was used in this study to simulate corn yields under different treatments. The data used as inputs to the model were collected in the first year of the experiment, as reported in the chapter 1.

RESULTS AND DISCUSSION

Soil Factors Affecting Yield Variability

As discussed in chapter 1, for soil properties measured at the 0 to 15 cm depth, we identified five factor variables through factor analysis technique: FV_1-inherent soil fertility potential, FV_2-available phosphorus zinc and manganese, FV_3-indirect deterioration of soil structure, and FV_4 and FV_5-available nitrogen. These factor variables explained 75.5% of the overall soil variability. Seventy three percent (Adj. $R^2 = 0.73$) of grain yield variation was explained as a function of two factor variables, FV_1-inherent soil fertility potential and FV_2-available phosphorus, zinc and manganese, with negative ($r_p = -0.35$) and positive ($r_p = 0.63$) partial correlation coefficients, respectively.

The factor variable (FV_2-available P, Zn and Mn) which had a high and positive correlation ($r_p = 0.63$) with grain yield included P, Zn, Mn, POM, silt and clay. To prioritize the importance of these variables on grain yield, backward stepwise regression technique was applied using the original variables. The results are shown in Table 2.1 and Figure 2.2. The soil properties P-Bray1, Mn-DTPA, and clay explained 73% (Adj. $R^2 =$ 0.73) of yield variability. The relative contribution of these variables to the variation of grain yield (dependent variable), as measured by the partial correlation coefficient (r_p) were 0.30, 0.54 and – 0.61, respectively (Table 2.1). These results are similar to those obtained by Coelho et al. (1999), as presented in the initial part (background) of this chapter.

Table 2.1. Regression models for original soil properties (0 –15 cm depth), contributing to the grain yield variation of corn, as defined by factor analysis. Gibbon, NE 1997

Model no		P Bray1	Zn	Mn	SOM	POM	Silt	Clay	Intercept	Adj. R^2	SE
01	B	0.018	0.110	**0.020**[b]	0.009	0.110	0.013	-0.115	10.86	**0.72**	0.55
	β	0.160	0.043	0.330	0.060	0.150	0.035	-0.350			
	r_p	0.260	0.067	0.390	0.060	0.260	0.029	-0.230			
02	B	0.017	0.123	**0.019**[b]	0.008	0.129	****	**-0.127**[a]	12.00	**0.73**	0.54
	β	0.16	0.048	0.33	0.054	0.15	****	-0.39			
	r_p	0.26	0.078	0.39	0.057	0.26	****	-0.44			
03	B	0.017	0.136	**0.022**[a]	****	0.111	****	**-0.135**[a]	12.43	**0.73**	0.53
	β	0.153	0.053	0.36	****	0.153	****	-0.41			
	r_p	0.25	0.087	0.50	****	0.27	****	-0.53			
04	B	**0.019**[c]	****	**0.022**[a]	****	0.108	****	**-0.141**[a]	12.86	**0.74**	0.52
	β	0.17	****	0.36	****	0.15	****	-0.43			
	r_p	0.295	****	0.512	****	0.26	****	-0.57			
05	B	**0.019**[c]	****	**0.023**[a]	****	****	****	**-0.155**[a]	14.10	**0.73**	0.54
	β	0.178	****	0.395	****	****	****	-0.476			
	r_p	0.299	****	0.540	****	****	****	-0.611			

B = regression coefficient; β = standardized regression coefficient; r_p = partial correlation coefficient. SE = standard error of estimate. Significance level: [a]$P < 0.01$, [b]$P < 0.05$, [c]$P < 0.10$.

To look at the relations between yield and nutrient status (P and Mn) geostatistically, variograms were computed and spherical models fitted to them (Figure 2.2). Kriging was used to produce a gray scale map of grain yield, phosphorus and manganese (Figure 2.3). When classifying maps of soil test phosphorus the cut-off points of < 16 (30 kg ha^{-1}), 16 to 24 (30 – 50 kg ha^{-1}) and > 25 mg P kg^{-1} soil (> 50 kg ha^{-1}), were used to separate the data into three distinct classes of low, medium, and high, respectively. The cut-off for soil test phosphorus was based on fertilizer recommendations for the state of Nebraska (Hergert et al., 1995). For manganese, the cut-off of 15 mg kg^{-1} soil (35 kg ha^{-1}) was used as a critical level in soils for corn production (Mascagni and Cox, 1984).

The variograms of these three variables (Figure 2.2) resemble one another, as do the patterns on the maps. They have strong spatial structure with a range of 120 to 150 m. One is tempted to conclude that there must be at least a casual relation between the variables. Inspection of the maps shows that the relation is positive. Where the yield is large, the content of phosphorus and manganese is high and vice versa. The available phosphorus and manganese are approaching deficiency in parts of the field, yet are plentiful elsewhere. Here we have a clear case for differential application of fertilizers and use of the modern technology of precision farming. The spatial scale makes it technologically feasible.

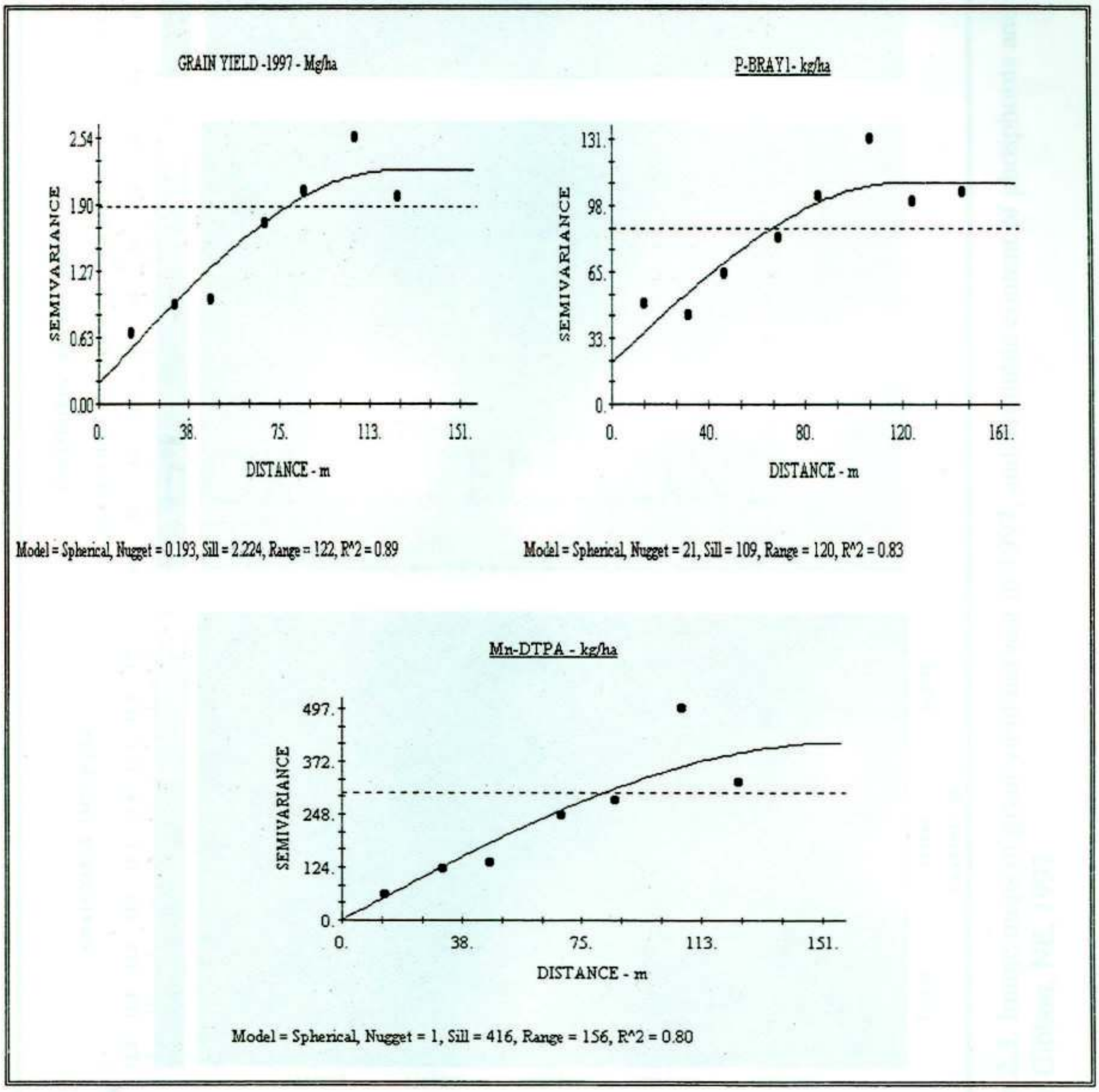


Figure 2.2. Experimental (•) and fitted variaogram model (—) for grain yield and available phosphorus and manganese in soil at 0 to 15cm depth. Gibbon, NE, 1997/98.

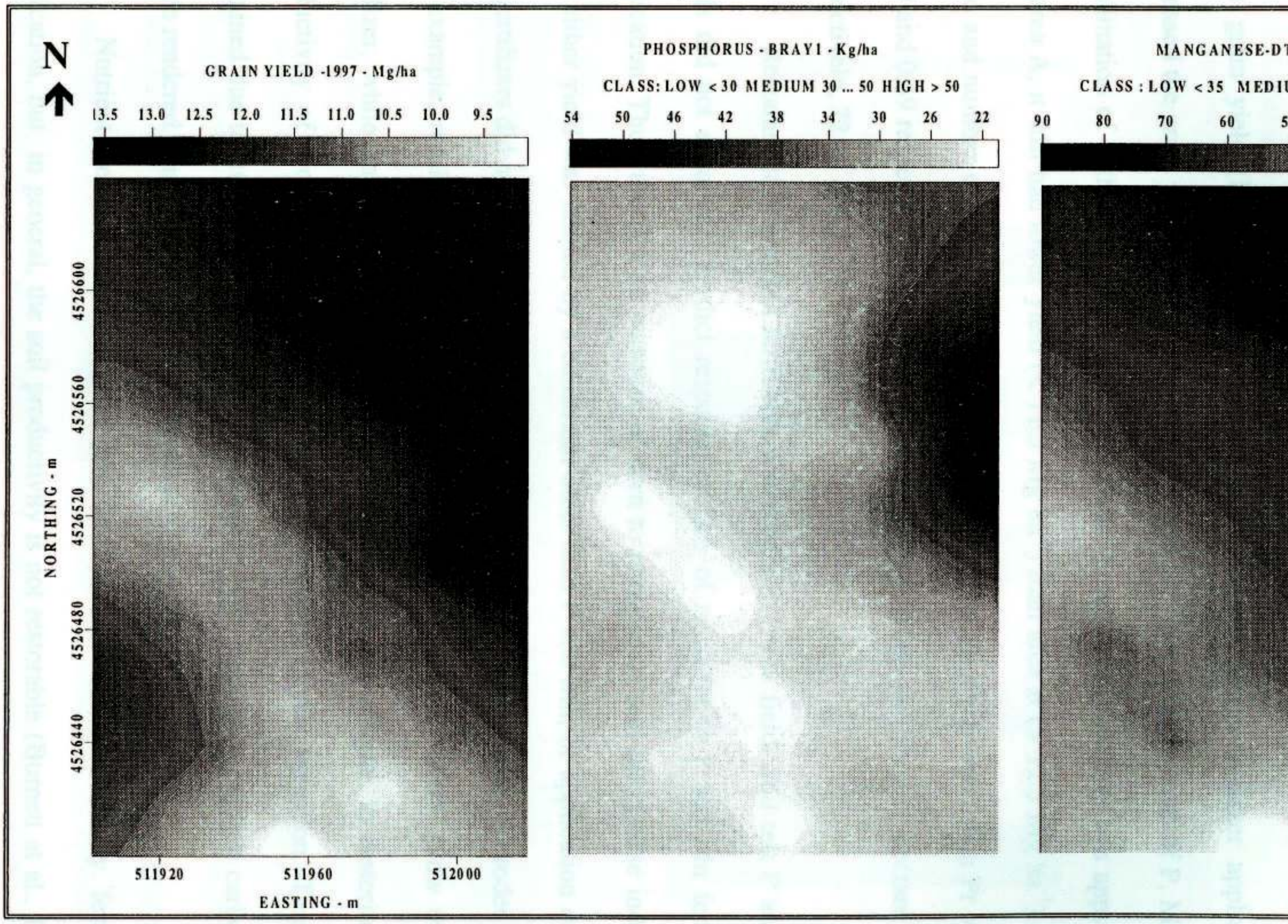


Figure 2.3. Image maps of grain yield harvest in 1997, and available content of phosphorus and manganese in s
depth. Gibbon, NE, 1997.

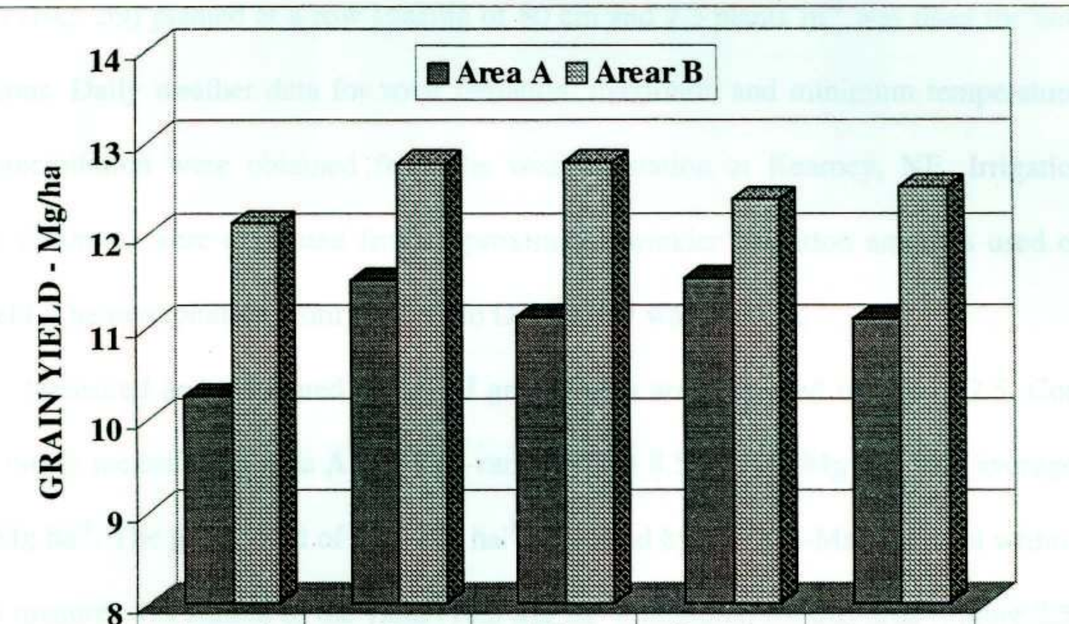
Corn Response to Phosphorus and Manganese

Although statistical analysis of data indicated a strong and positive relationship between the spatial variability of phosphorus and manganese in the soil and grain yield, the application of P and Mn fertilizers did not improve significantly ($Pr > F = 0.26$) the corn grain yield (Figure 2.4). Compared to the control, extra fertilizer application increased the grain yield by 1.25, 0.86 and 1.27 Mg ha^{-1} due to application of P, Mn and combination of both fertilizers respectively. Even though extra fertilizer was applied to the area **A**, it still had lower yield (< 11.5 Mg ha^{-1}) than area **B** (> 12.5 Mg ha^{-1}). Corn stand and number of ears per plant were not affected by the treatments, with $Pr > F$ of 0.49 and 0.69 respectively. The average of numbers of plants and ears per hectare were, respectively, 72.44 and 73.62 thousand.

Response to P and Mn fertilizers was erratic over the field. Soil test P and Mn levels did not accurately predict response or lack of response to P and Mn fertilizer application. Thus, the lack of response of corn to phosphorus and manganese indicates that either yield was limited by a constraint other than P and Mn, or application of P or Mn fertilizers did no adequately alleviate the deficiency of these nutrients in eroded soils. For example, results of experiments conducted by Larney et al. (1995) show that P-fertilizer, while having some remedial action, was a poor surrogate in restoring the productivity of eroded soil even with adequate moisture under irrigation. This was explained due to its immobilization by an inherently high amount of calcium carbonate, which rendered it unavailable for plant uptake at higher soil pH values.

Nutrient deficiencies in eroded soil can usually be corrected by fertilizer application, but in general, the soil productivity is not restorable (Burnett at al., 1985).

Phosphorus, K, N, or Zn applications to silt loam did not produce significant yield restoration in seven crops tested on artificially eroded soils (Carter et al., 1985). The application of manure and crop residue are the main alternatives found to be efficient in restoring productivity of eroded soils by substituting for lost topsoil (Larney and Janzen, 1996; Robbins et al., 1997).



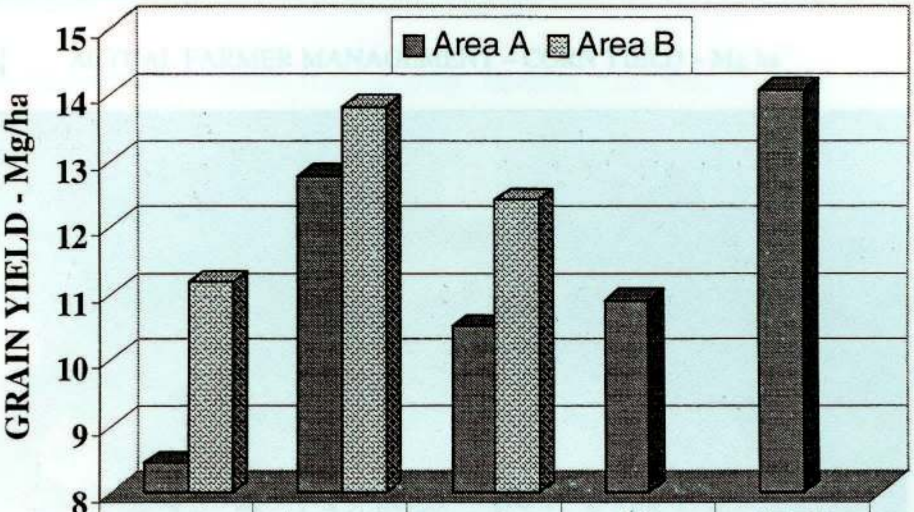
	Control	P	Mn	P + Mn	Average
Area A	10.25	11.5	11.11	11.52	11.10
Arear B	12.12	12.77	12.79	12.38	12.52

Figure 2.4. Effect of phosphorus and manganese on corn grain yield. Gibbon, NE, 1998.

Observed and Simulated Grain Yields

According to previous research conducted in similar conditions and discussed before, the best alternative that for farmer has for recovering the corn grain yield on degraded area A of this field is to use manure. With the use of CERES-Maize model we estimated the corn grain yield in area **A** by simulating two situations: (i) application of manure at 25 Mg ha^{-1} (dry-weight basis) before planting time and incorporated into the soil at 10 cm depth, plus 100 kg ha^{-1} of ammonium phosphate (11 – 48 – 0) at planting time and 50 kg of N ha^{-1} applied side-dress as ammonium nitrate; and (ii) no manure, considering only the residue (2 Mg ha^{-1}) of the previous soybean crop, incorporated into the soil at 10cm depth, plus 100 kg ha^{-1} of ammonium phosphate (11 – 48 – 0) at planting time and 100 kg of N ha^{-1} applied side-dress as ammonium nitrate. A commercial maize hybrid (NC^{+} 59) planted at a row spacing of 80 cm and 7.3 plants m^{-2} was used for both situations. Daily weather data for solar radiation, maximum and minimum temperature, and precipitation were obtained from the weather station at Kearney, NE. Irrigation inputs (300mm) were estimated from approximate sprinkler irrigation amounts used on the field. The precipitation from May/97 to October/97 was 334mm.

Measured and simulated values of grain yields are presented in Figure 2.5. Corn grain yields measured in area **A** in 1997, ranged from 8.5 to 11.0 Mg ha^{-1} and averaged 10.5 Mg ha^{-1}. The grain yield of 10.9 Mg ha^{-1} simulated by CERES-Maize model without use of manure, was similar to the yield (10.5 Mg ha^{-1}) measured for this area (Figure 2.5). With the use of manure, the CERES – Maize model simulated a grain yield of 14.1 Mg ha^{-1}, similar to the high grain yield (13.8 Mg ha^{-1}) measured on the best area of the field (Figure 2.5). On this area **B**, the corn grain yield ranged from 12.0 to 13.5 Mg ha^{-1} and averaged 12.4 Mg ha^{-1} (Figure 2.5). The restorative ability of manure as simulated by CERES-Maize model for area **A** agrees with other studies in that the beneficial effects of manure in restoring soil productivity were much greater that those for inorganic fertilizer (Aina and Egolum, 1980; Dormaar et al., 1988; Larney et al.; 1996).



	MIN	MAX	AVER.	NO MANURE	WITH MANURE
Area A	8.44	12.77	10.5	10.9	14.06
Area B	11.17	13.82	12.4		

Figure 2.5. Comparison of observed (minimum, maximum, average) and simulated corn grain yields for areas A and B for different management, no manure and with manure application to area A. Gibbon, NE, 1998.

Figure 2.6 shows yield maps of observed corn yield based on management practices used by farmer and simulated yield which would have been obtained by manure application to eroded area **A**. As predicted by the model, this case study demonstrated the benefit of manure to recover the corn grain yield in eroded area A, with 35% yield increase (3.7 Mg ha^{-1}) as compared to the use of chemical fertilizer. However, this may only be noticeable in the first year, due to the erosion problem that is present in the area.

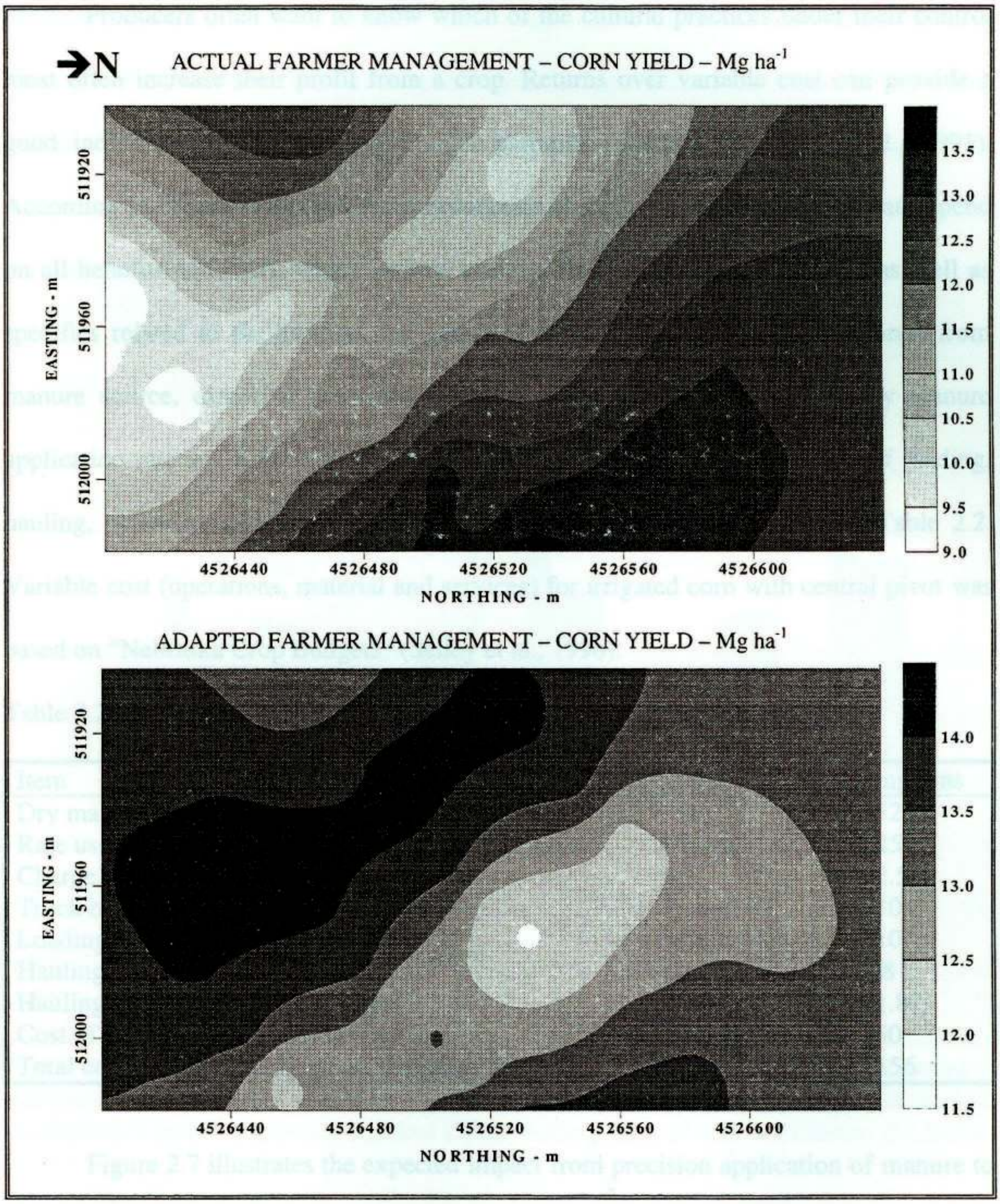


Figure 2.6. Observed corn yield based on farmer management practices in 1997 (upper part) and simulated yields (lower part), which would have been obtained by manure application to eroded area A. Gibbon, NE, 1998.

Economic Aspects

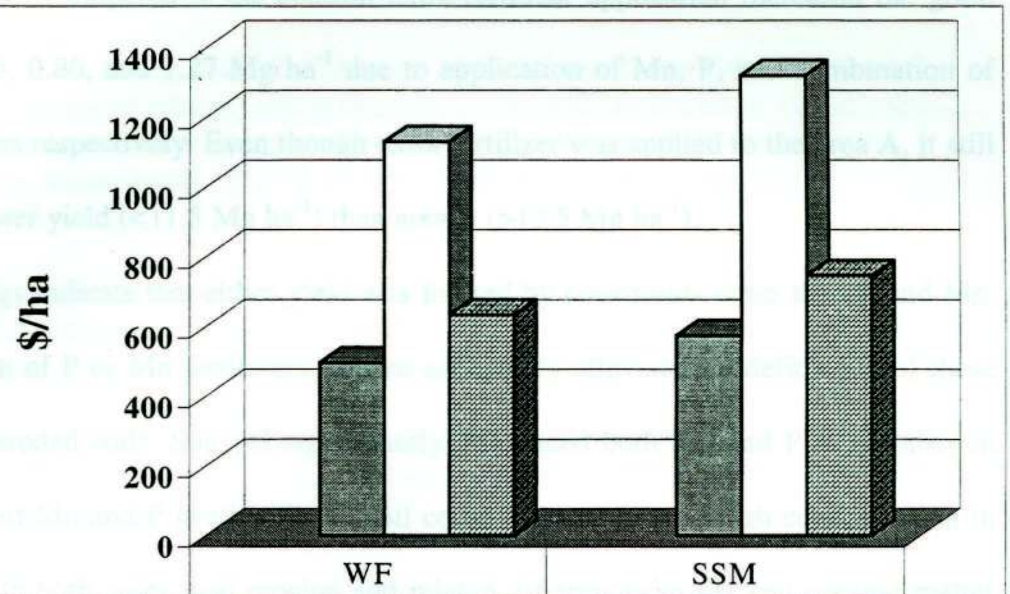
Producers often want to know which of the cultural practices under their control most often increase their profit from a crop. Returns over variable cost can provide a good indication of the profitability of a particular practice (Peterson et al., 1991). According to Freeze et al. (1993) the economics of manure as a soil amendment depend on all benefits and costs, which include loading, hauling and spreading cost, as well as specifics related to the location and nature of the application site (e.g., distance from manure source, extent of soil erosion, crop grown). For a 25 Mg ha^{-1} dry manure application rate and 8 km distance from a manure source, the time and cost of loading, hauling, spreading and incorporating manure into the soil are presented in Table 2.2. Variable cost (operations, material and services) for irrigated corn with central pivot was based on "Nebraska Crop Budgets" (Selley et al., 1996).

Table 2.2. Input values for calculation of variable costs with the use of manure.

Item	Units	Assumptions
Dry matter in manure	%	52
Rate used in the field – dry manure	Mg ha^{-1}	25
Charge of manure	\$ T^{-1}	2.5
Truck box manure capacity	T load $^{-1}$	10
Loading time of truck	Min load $^{-1}$	10
Hauling distance one way	Km	8
Hauling and spreading dry manure	Hours ha^{-1}	1.87
Cost of hauling and spreading	\$ hour^{-1}	50
Total cost – charge, hauling and spreading manure	\$ ha^{-1}	156

Figure 2.7 illustrates the expected impact from precision application of manure to the area **A** cultivated in irrigated corn. The use of SSM increased corn yield by 17% (1.9 Mg ha^{-1}). This translates to a change in economic returns of \$112 per hectare per year. The importance of these results (Figure 2.6) is that they permit comparison of SSM with

field information and measure the return to whole field information since this can be attained without investment in SSM-technology. These estimates are conservative, as they ignore the benefit of manure in reducing the use of chemical fertilizer and improving soil structure and tilth, which reduces tillage power requirements. They also ignore the potential for residual yield benefit that may occur beyond the 2-yr horizon considered in this experiment.



	WF	SSM
Grain yield - Mg/ha	11.3	13.2
Total cost - $/ha	496	574
Total return - $/ha	1,130	1,320
Net return - $/ha	634	746

Figure 2.7. Grain yield and profitability for site-specific management (SSM) compared to management to the whole field (WF), with irrigated corn. SSM include cost of manure divided by 2 years considering residual effect. Selling price of corn = $100/ton ($2.54/bu)

SUMMARY AND CONCLUSIONS

Although it was possible to identify areas with low and high yields and determine the possible causes associated with them, the application of Mn and P fertilizers did not improve significantly the corn grain yield. Apparently differences in plant Mn and P concentration were a result of secondary crop responses associated with other factors affecting yield. Compared to the control, extra fertilizer application increased the grain yield by 1.25, 0.86, and 1.27 Mg ha^{-1} due to application of Mn, P, and combination of both fertilizers respectively. Even though extra fertilizer was applied to the area **A**, it still presented lower yield (<11.5 Mg ha^{-1}) than area **B** (>12.5 Mg ha^{-1}).

These findings indicate that either yield was limited by constraints other than P and Mn, or application of P or Mn fertilizers did not adequately alleviate the deficiency of these nutrients in eroded soils. Soil pH significantly influenced both Mn and P availability in soil. Enhanced Mn and P availability in soil could account for the high concentration in plant tissue. In both cases, soil erosion and related differences in pH and organic matter were the primary causes of variability in nutrient availability. Soil maps of available Mn and P showed that much of the area contained medium levels of soil Mn and low levels of soil P. The results suggest the need for careful interpretation when using statistical models to seek cause and effects relationships related to yield variability in fields. Contour and soil survey maps still appear to be useful in understanding yield variability within a field.

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CHAPTER 3

SPATIAL VARIABILITY OF SANDY SOIL PROPERTIES AS RELATED TO IRRIGATED CORN MANAGEMENT

INTRODUCTION

New farming methods have frequently allowed expansion of cultivation into areas that were previously considered unsuitable. Example includes irrigated corn production on sandy soils of the high Plains through use of center-pivot irrigation. According to Lichtenberg (1989), the spread of center pivot technology was most rapid on sandy soils. A self-propelled sprinkler system has the capacity to adjust delivery water volumes to accommodate sandy soils and rolling terrain, it can navigate rolling hills, and requires less labor than conventional sprinkler systems.

Only slightly over 10% of irrigated producers in Nebraska are operating on sandy soils (Juliano, 1997). However this proportion is important because the conversion of lower quality lands to irrigated farming will result in greater erosion hazard and ground water contamination by agriculture chemicals. Since the aim of site-specific crop management is to find a balance between optimal yield, maximum profit and minimal environmental pollution, these irrigated areas on sandy soils are good candidates for application of this technology.

MATERIALS AND METHODS

Evaluation Site

A field in Adams County, in the Platte River Valley of south - central Nebraska was selected for study. The site is a 53 ha field, located in northwest Adams County (40° 39' 32''N 98° 42' 24''W), Nebraska, at an elevation of 600 m above mean sea level. Approximately ¼ of the area at this site is planted to perennial grass (Reed Canary) which is used for hay and ¾ of the area has been cropped with continuous corn under conventional tillage and center-pivot sprinkler irrigation for the past twenty five years (Figure 3.2).

The climate is fairly uniform throughout the county. Temperatures below -17°C (0°F) in winter and above 38°C (100°F) in summer are common. The mean annual temperature is 11°C (51°F), and the average annual rainfall is 665 mm (26.6 inches). The average growing season is about 160 days (Soil Survey, 1974). During the growing seasons of 1997 and 1998 (May 1st to October 7th) the weather station located at Shelton-NE, which is ~ 4 Km from this site, registered precipitation of 353mm (14 inches) and 484mm (19 inches), respectively, with different patterns of distribution during the 1997 and 1998 growing seasons (Figure 3.1). The potential evaporation, based on a calculation using a modified Penman equation, were similar in both years, around of 875 mm (35 inches), about twice the annual precipitation. The average annual evapotranspiration (ET) of the corn crop in Central Nebraska is around of 600 mm (24 inches).

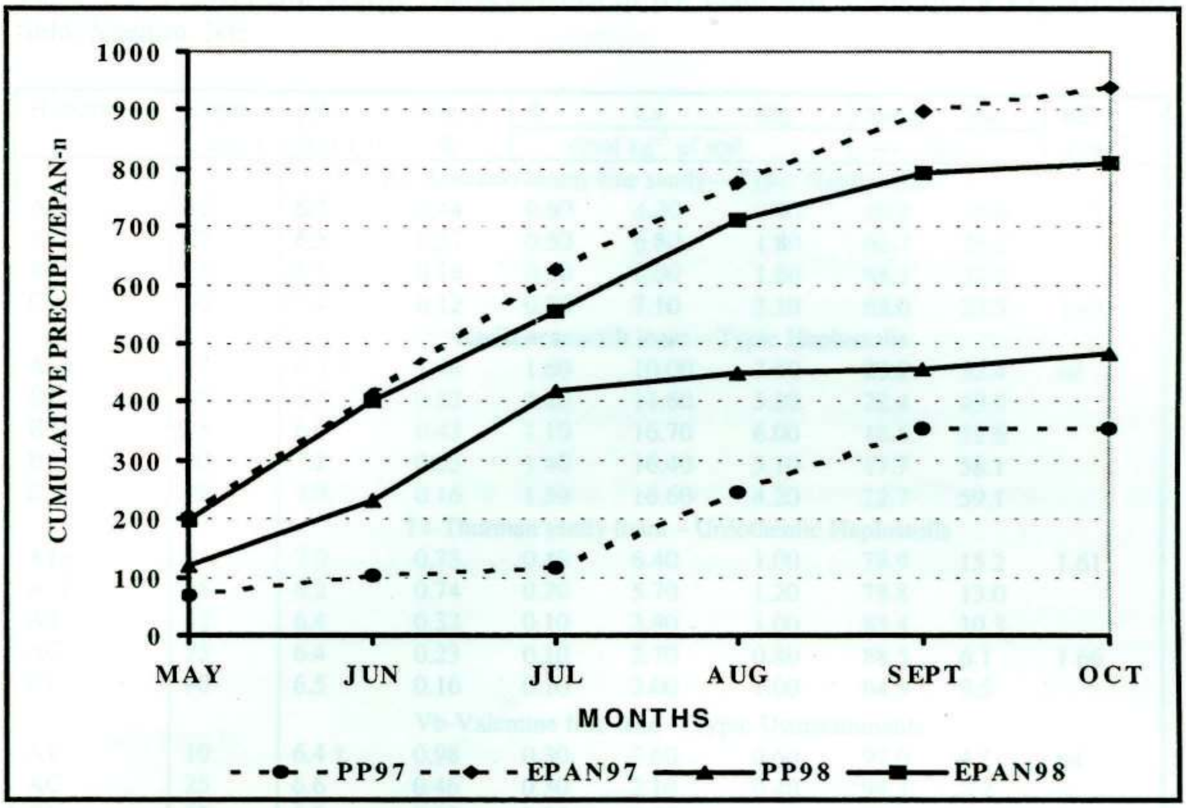

Figure 3.1. Cumulative precipitations (PP) and potential evapotranspiration (EPAN) at Shelton, NE, during growing seasons of 1997 and 1998.

Soils were formed in three kinds of parent material, loess, eolian sands, and alluvium, and consist of following soil series and groups: An-Anselmo loam fine sandy (coarse-loamy, mixed, superactive, mesic Typic Haplustolls); Ks-Kenesaw silt loam (coarse-silty, mixed, mesic Typic Haplustolls; Tx-Thurman sandy loamy (sandy, mixed, mesic Udorthentic Haplustolls); VbC-Valentine fine sand (mixed, mesic Typic Ustipsamments) (Figure 3.2). The topography of the area is hummocky, and the hummocks range from 0.6 to 4.5 m in height (Soil Survey, 1974). Chemical and physical soil profile characteristics of the main soil series of the experimental field are presented in Table 3.1.

Table 3.1. Typical soil profile characteristics of the main soil series of the experimental field. Shelton, NE

Horizon	Depth	pH	Org. C	K	Ca	Mg	Sand	Silt	BD ‡
	cm	H_2O 1:1	%	cmol kg^{-1} of soil			------ %-----		g cm^{-3}
		An-Anselmo loamy fine sandy – Typic Haplustolls							
A1p	15	6.7	0.44	0.60	4.20	0.90	80.8	13.6	1.51
A12	27	6.5	0.37	0.50	6.80	1.80	63.7	25.2	
AC	55	6.7	0.16	0.30	6.00	1.80	68.1	22.5	
C1	95	7.4	0.12	0.50	7.10	2.10	68.0	22.5	1.47
		Ks-Kenesaw silt loam – Typic Haplustolls							
A1p	17	6.3 †	1.09	1.60	10.00	3.50	28.8	52.4	nd
B21	30	6.7	0.82	1.20	14.60	5.20	22.4	49.0	
B22	45	6.9	0.43	1.10	16.70	6.00	16.6	52.6	
B3	80	7.2	0.23	1.40	16.40	5.10	17.7	58.1	
C1	95	7.9	0.16	1.50	16.60	4.20	22.7	59.1	
		Tx-Thurman sandy loam – Urdothentic Haplustolls							
A1p	8	7.0	0.73	0.40	6.40	1.00	78.9	15.2	1.61
A12	35	6.2	0.74	0.20	5.70	1.20	78.8	13.0	
A3	52	6.4	0.32	0.10	3.90	1.00	83.4	10.3	
AC	75	6.4	0.23	0.10	2.70	0.80	88.5	6.1	1.66
C1	90	6.5	0.16	0.10	3.00	1.00	84.9	9.5	
		Vb-Valentine fine sand – Typic Ustipsamments							
A1	10	6.4 †	0.98	0.30	3.60	0.60	92.0	4.1	nd
AC	25	6.6	0.46	0.30	2.10	0.40	94.7	2.2	
C1	45	6.7	0.22	0.20	2.00	0.60	95.0	1.8	
C2	80	6.9	0.09	0.10	1.50	0.20	96.6	1.0	

† pH in water 1:5. ‡ Field state. nd = not determined. Source: Adapted from National Cooperative Soil Survey – USA.

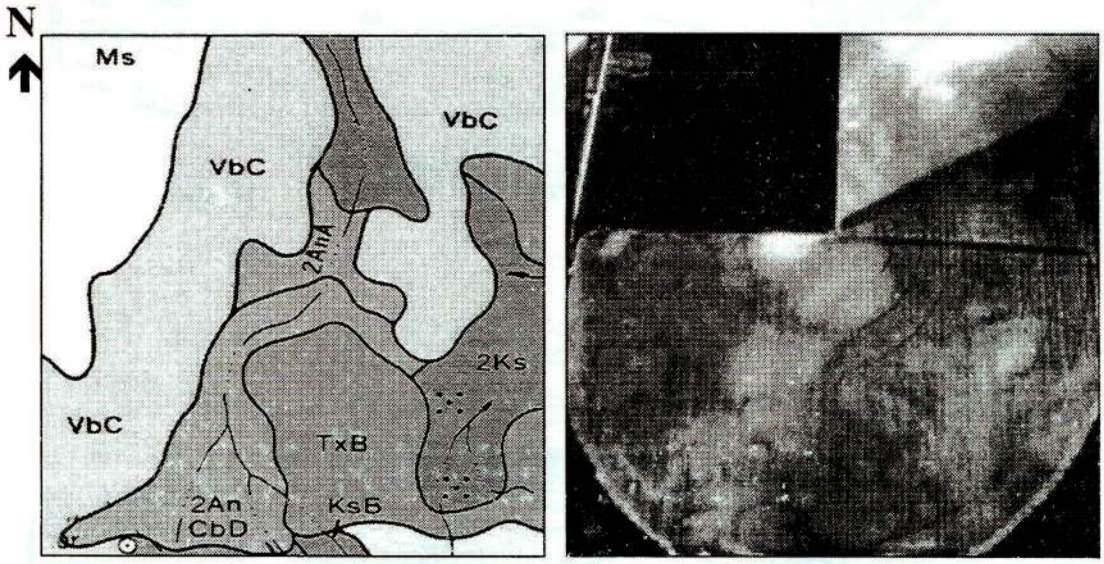

Figure 3.2. The left figure is soil survey map made in 1967 and the right an aerial photograph taken of experimental field in May 1997. SE ¼, sec.18, T8N, R12W.Adams County-NE. (Soil Survey, 1974 and USDA-ARS-Lincoln, NE).

Experimental Design and Sampling Procedure

Replicated transects, at 30 m intervals from south to north, were established across soil types. Forty plots (10.8 m wide by 12 m length), spaced at 20 m were placed continuously along of transect from east to west, for soil sampling and crop evaluation. Also, one transect with 10 plots was established in the area with perennial grass to represent a benchmark for effect of soil management on the soil properties for the field cropped with corn (Figure 3.3). The Global Positioning System (GPS) technology was used to permit the precise and repeatable locating of plots with in the field.

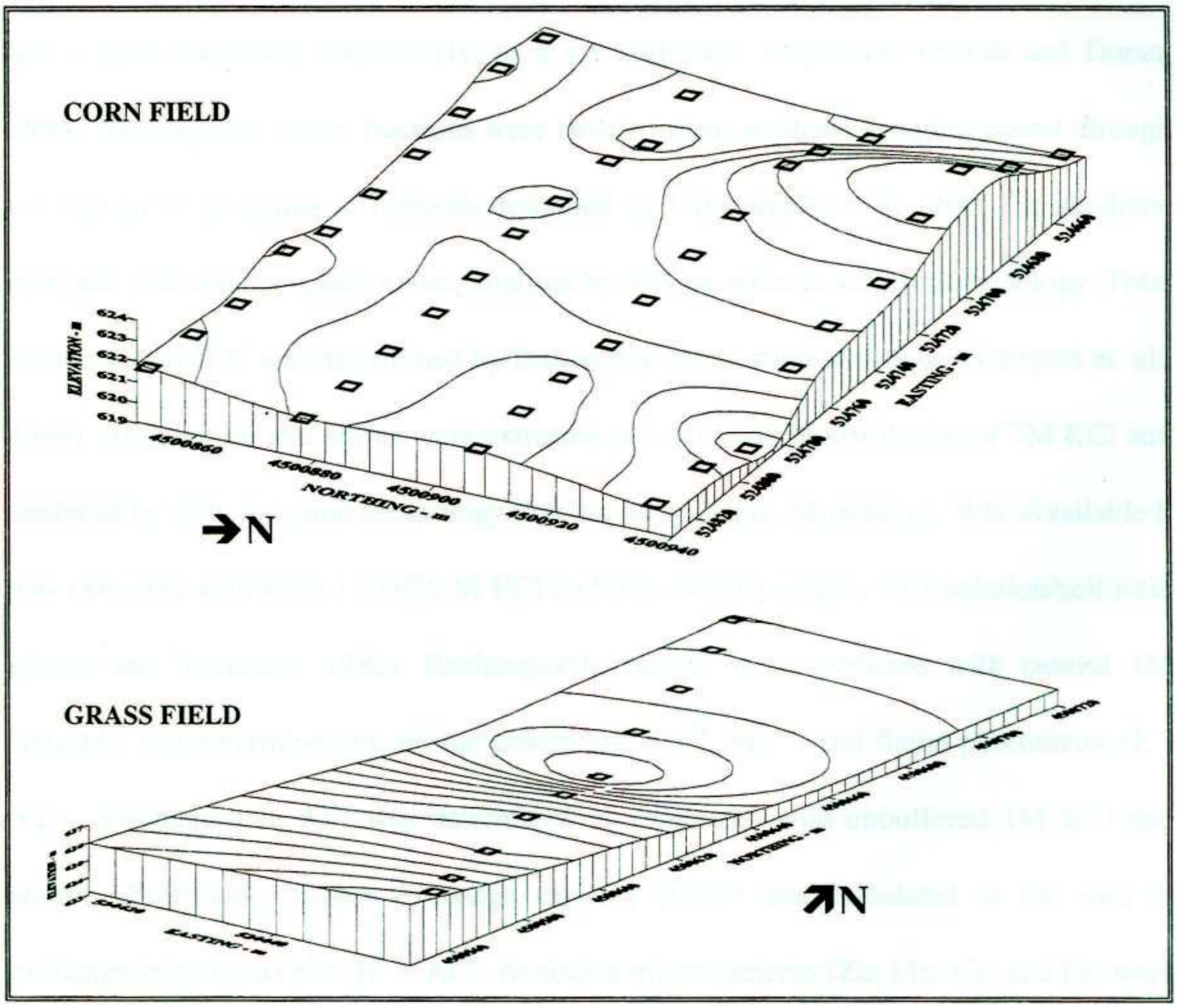

Figure 3.3. Three-dimentional surface contour map of the experimental area with corn (upper part) and grass (lower part) showing the transects and plot distribution.

Soil Sampling and Analysis

The field was sampled in June 1997 and 1998, when the corn was in the V3 to V4 stage. Soil samples were collected for analysis by using a 17.6 mm (inside diameter) hand probe. Soil samples were taken from between the rows (2nd to 10th rows), 15 cm to the side of each row center, within an area that was 3m from the beginning and end of plots. Eighteen cores per plot were collected to a depth of 30cm, from a 104m^2 area and divided into two depth increments (0 to 15 and 15 to 30 cm). All soil samples were air-dried, and ground to pass a 2 mm screen.

Soil electrical conductivity (EC) and pH was measured with a conductivity meter and a glass electrode, respectively, in a 1:1 soil/water suspension (Smith and Doran, 1996). Soil organic matter fractions were isolated from air-dried samples passed through a 2 mm sieve according to methods described by Cambardella et al. (2000), to facilitate total and particulate organic matter analysis by loss on ignition (LOI) methodology. Total carbon and total N was determined by Dumas dry combustion technique (Schepers et. al., 1989). Ammonium and nitrate were extracted in a 10:1 solution/soil ratio of 2M KCl and analyzed by flow injection technology (Lachat Instruments, Milwaukee, WI). Available P was extracted with Bray 1 (0.025 M HCl and 0.03 NH_4F) using a 10:1 solution/soil ratio (Olsen and Sommers, 1982). Exchangeable cations were extracted with neutral 1M NH_4OAc and determined by atomic absorption (Ca^{2+}, Mg^{2+}) and flame photometry (K^+, Na^+). Exchangeable Al^{3+} was determined by extraction with unbuffered 1M KCl and atomic absorption. Cation exchange capacity (CEC) was calculated as the sum of exchangeable cations plus $H^+ + Al^{3+}$. Available micronutrients (Zn, Mn, Cu, and Fe) were extracted using DPTA and determined by inductively coupled plasma optical emission spectrometry (ICP-OES) (North Dakota Agriculture Experiment Station, 1988). Sand, silt and clay fractions were determined through sieve and pipette analysis (Gee and Bauder, 1986). Bulk density was estimated according to Doran and Mielke (1984), based on the soil volume sampled in each plot, using the flowing expression: volume of probe ($V = \pi r^2h$) times number of soil samples in each plot, divided by the dry soil weight at 105°C. Also, bulk density was predicted from soil particle size analyses and soil organic matter contents according to the method described by Rawls (1983). Available water holding capacity (AWHC), defined as the difference between the water content at matric potentials of –0.033 Mpa and –1.5 Mpa, was estimated from particle size distribution, organic matter, and bulk density, according to methods described by Gupta and Larson (1979).

Crop Evaluation and Analysis

Soil testing provides information on patterns in soil fertility and other soil conditions, but plant growth, development and vigor provides a more direct and integrative indication of plant response to soil properties and management. Plant performance across a landscape was determined by measurement of plant population, plant nutrient content, and grain yields evaluated during the growing seasons of corn. Ear leaf blades were selected at random from 20 corn plants in each plot at early silking growth stage. The leaf tissue was dried at 70°C, ground, and analyzed for nutrient content. Plant population counts were made in the center (6m) of each row, in 12 rows before harvest. Corn ears were hand-harvested from each of the central plots (4 rows x 3 m length), were dried and shelled, and the grain water content determined using a portable grain moisture tester. The water content of the grain was adjusted to 15.5% before reporting final yields.

Statistical Approach

Summary statistics for the data sets were obtained from univariate procedure in SAS. Each variable was tested for normality by adding the normal option (SAS Institute, 1995). The null hypothesis was that data sets were normally distributed and it was rejected when $P \leq 0.05$.

Groups of correlated variables (excluding plant population and yield) were defined using factor analysis. Before applying factor analysis, each soil chemical-physical property and nutrient concentration in leaf dry matter, were standardized (Reyment and Joreskog 1993).

Factors were extracted with the factor procedure of the SAS package using the principal factor analysis method and promax oblique (non-orthogonal) rotation method (SAS Institute, 1995). Factor Variable Score (FV) was calculated as a linear combination of the standardized variables multiplied by the correspondent coefficients (loadings) of original variables (McCoy, 1998). Stepwise regression (backward) was performed to verify the relationships between factor variable score and corn yield. Grain yield was the dependent variable and the factor variable scores were the independent variables.

Geostatistical software (GS^+ V3.1, Gamma Design Software, St. Plainwell, MI) was used to analyze the spatial structure of the standardized data of soil properties, nutrient concentration in leaf dry matter, and non- transformed data of plant population and grain yield, to define the semi-variograms. Semi-variance calculations were based on an active lag distance, which ranged of 100 to 180 m, separated by an average distance of 17 m. Between 35 and 185 pairs of points were used in the semivariance calculations. Selection of models for semivariograms was made principally on visual fit, regression coefficient (R^2), and reduced sums of squares (SSR) which provided an indication of how well the model fit the semivariogram data.

The factor variable scores were then used as new variables in geo-statistical mapping and as inputs for a simple soil quality classification. The sample set was classified in 3 classes, high, medium and low, based on the quartiles of the extracted soil factor. The inter-quartile ranges of the soil properties in each case were used for a final soil fertility evaluation.

Surffer (Golden Software, Golden, CO) was used to make the maps. The elevation was interpolated by point-kriging using the default settings of a linear semivariogram. The contour maps were also interpolated by point-kriging, but using the modeled semi-variograms for each standardized soil property and plant parameter measured in the field.

For further details the reader is referred to the "Statistical Approach" section of chapter 1 (p.49)

RESULTS AND DISCUSSION

ASSESSING MAGNITUDES OF SPATIAL VARIABILTIY

Inspection of the soil survey map shows that before the introduction of center-pivot irrigation in the experimental area, the field had been used for dry land crops restricted mainly to the soil types: Anselmo loamy fine sandy, Kensaw silt loam, and Thurman sandy loam. Valentine fine sandy and Median sandy loam (Ms) soils were in native grass (Soil Survey, 1994). Although, different soil types existed in the field, uniform soil and crop management has been used for corn production over the last twenty-five years. Thus, under this situation, a great variability in soil and crop characterisrics was expected.

Grain yield, Plant Population, and Nutritional Status of Corn

The results of grain yields, corn stands and nutrient concentrations in the leaf are summarized in Table 3.2. Field mean corn yield (12.5 Mg ha^{-1}) was greater than the average for irrigated corn in central Nebraska (10.4 Mg ha^{-1}). This is consistent with the depiction of center-pivot irrigation as a land-augmenting technology that reduces soil productivity differential (Lichtenberg, 1989).

Although rainfall during growing season of 1998 was 37% (130 mm) higher than 1997 (Figure 3.1), the grain yields were similar in both years (Table3.2), and not significantly different ($Pr > F = 0.58$). Correlation between years for grain yield values was positive and significant ($r = 0.53$), which suggest that the pattern of spatial variability was similar in both years. Also, yields were normally distributed, with low coefficients of variation (CV's < 10%) and small differences between the mean and median, favoring yields around the average (Table 3.2). However, corn yield varied spatially, ranging from 9.6 to 14.5 Mg-ha^{-1} in 1997 and 11.0 to 14.4 Mg ha^{-1} in 1998.

Plant population presented spatial and temporal variation, and ranged from 61,110 to 83,490 plants ha^{-1} in 1997 and 60,190 to 76,850 plants ha^{-1} in 1998, with no significant difference ($Pr > F = 0.61$) between years (Table 3.2). A significant correlation ($r = 0.45$) was observed between corn stand and grain yield in 1997, and regression analysis applied to this data fitted a quadratic model with adjusted $R^2 = 0.27$. The maximum yield was obtained with 79,540 plants ha^{-1} at harvest.

Table 3.2. Descriptive statistic of grains yields plant populations and nutrient concentration in the leaf below and opposite the first ear at early silking growth stage. Shelton, NE, 1997/98.

Variable	Suffic.	Statistical parameters						
	Range †	Min	Max	Median	Mean	Std. Dev.	CV (%)	Wilks-Shapiro
Yield, Mg ha^{-1} (97)	*****	9.60	14.50	12.73	12.52	1.12	8.92	0.96^{ns}
Yield, Mg ha^{-1} (98)	*****	10.96	14.38	12.53	12.62	0.86	6.83	0.96^{ns}
Stand, 1000 ha^{-1} (97)	*****	61.11	83.49	68.98	69.35	4.78	6.89	0.96^{ns}
Stand, 1000 ha^{-1} (98)	*****	60.19	76.85	70.37	70.00	3.20	4.58	0.96^{ns}
Nutrients	Nutrients in leaf dry matter g kg^{-1}							
Nitrogen	22 – 30	32.1	36.3	33.7	33.9	1.13	3.34	0.95^{ns}
Phosphorus	2 – 3	1.9	3.5	2.5	2.5	0.38	14.8	0.96^{ns}
Potassium	16 – 20	15.9	27.5	19.4	20.0	3.19	15.9	0.92**
Sulfur	2 – 3	1.6	2.8	2.2	2.2	0.26	12.3	0.97^{ns}
Calcium	2 – 6	3.3	7.2	5.0	5.0	0.85	17.1	0.98^{ns}
Magnesium	1.5 – 3	0.9	2.3	1.35	1.42	0.31	22.2	0.93*
Zinc	18 – 25	22	53	30	31	6.68	21.0	0.93*
Manganese	15 – 25	41	176	89	93	30	32.0	0.95^{ns}
Copper	2 – 5	7	13	10	9.73	1.60	16.7	0.93*
Iron	20 – 40	63	163	101	100	23	23.0	0.97^{ns}
Aluminum	20 – 300	32	118	68	68	16	24.0	0.97^{ns}

† Sufficiency range according to UNL Plant Test Analysis Laboratory. Wilks – Shapiro test for normality, significant at the *$P \leq 0.05$, **$P \leq 0.01$ probability levels. Significance indicates that the null hypothesis for normal distribution is rejected.

Nutrient concentrations in the leaf dry matter of corn, for all elements except manganese, were characterized by low variability as indicated by coefficients of variation less than 25% (Table 3.2). As indicated by the Wilks-Shapiro test for normality, the majority of nutrients, except K, Mg, Zn, and Cu were normally distributed, with similar values between mean and median. This could be a good indication of an efficient and uniform distribution of fertilizer, mainly N and P in the field. The excellent nutritional status of corn as indicated by nutrient concentration in leaf dry matter, as compared to sufficiency range for healthy plants (Table 3.2), is also an indication of efficient fertilizer management in this field.

To quantify the spatial dependency of plant variability in the field, semi-variograms were computed for each standardized plant variable and the parameters for the best fitting theoretical models are presented on Table 3.3. Semi-variograms indicated moderate to strong spatial structure as measured by ratio $C_1/(C_0 + C_1)$ with values ranging from 0.58 to 0.89. The great difference that was observed for the range (100 to 200 m) of spatial correlated variability for grain yield between years (Table 3.3) is not easily understood. Probably, as observed by Jaynes and Colvin (1997) this difference could be associated with the difference of intensity and distribution of rainfall during the growing seasons. The range was significantly correlated to precipitation. However, using a coarse grid spacing of 100 m by 100 m it is possible to capture the variability of corn crop in this field.

Using geostatistical methods (semi-variogram and kriging), a contour map was generated for average grain yield and overlaid on the topographic map (Figure 3.4). Average corn yield was moderately spatially dependent (proportion variance = 0.58) with the isotropic semi-variogram fitted by the spherical model, giving a range of 98 m.

Table 3.3. Geostatistics for grain yields, corn stands, and standardized plant nutrients concentration in the leaf below and opposite of the first ear at early silking growth stage. Shelton, NE, 1997/98.

Variable	Active † Lag (m)	Step (m)	Nugget C_0	Sill † C_0+C_1	Range † a (m)	R^2	Proportion $C_1/(C_0+C_1)$ ‡	Model †
Yield-97	130	17	0.590	1.432	98	0.85	0.58	SPH
Yield-98	180	17	0.220	1.260	219	0.95	0.83	SPH
Stand-97	160	10	11.22	30.80	144	0.94	0.64	LIN
Stand-98	180	17	5.69	14.75	161	0.63	0.61	LIN
Nutrient	Nutrients in leaf dry matter g kg^{-1}							
N	100	17	0.114	1.100	56	0.99	0.89	SPH
S	150	17	0.237	1.073	85	0.75	0.78	EXP
P	100	17	0.129	0.888	51	0.91	0.85	SPH
K	150	17	0.268	1.198	151	0.90	0.84	SPH
Ca	150	17	0.166	1.062	111	0.70	0.84	SPH
Mg	150	17	0.372	1.106	110	0.53	0.66	SPH
Zn	150	17	0.180	1.157	94	0.57	0.84	EXP
Mn	150	17	0.213	1.180	104	0.77	0.82	SPH
Cu	150	17	0.343	1.263	122	0.94	0.73	SPH
Fe	150	17	0.480	1.205	112	0.97	0.60	SPH
Al	150	17	0.232	1.174	80	0.96	0.80	SPH

† Active lag, the distance to which variograms are computed. Active step, the lag increment used. Nugget, semi-variance at zero spacing. Sill, semi-variance at spacing > range. Range, distance after which values are not correlated. ‡ Proportion of spatial structure, measure the proportion of sample variance ($C_0 + C_1$) that is explained by spatially structured variance C_1. Model: SPH = spherical, EXP = exponential, and LIN = linear

Since yield variability is spatially structured and stable between the growing seasons, it is possible to define a potential zone for management within the field. Based on the yield map and using the average yield as a threshold, the field was divided in two areas of management. One with yields below the average (12.5 Mg ha^{-1}) and another one with yields above average (Figure 3.4).

Higher yields, above average (> 12.5 Mg ha^{-1}) were observed in the northeast part of the field (Figure 3.4), characterized by soil with better texture and organic matter content such as Kenesaw silt loam (Table 3.1). Low yields, around of 9.0 Mg ha^{-1} were located on the west part of field on soils with a high content of sand, such as the

Valentine fine sand. Thus it is very well characterized that soil type had a strong influence on the pattern of spatial distribution of corn grain yield

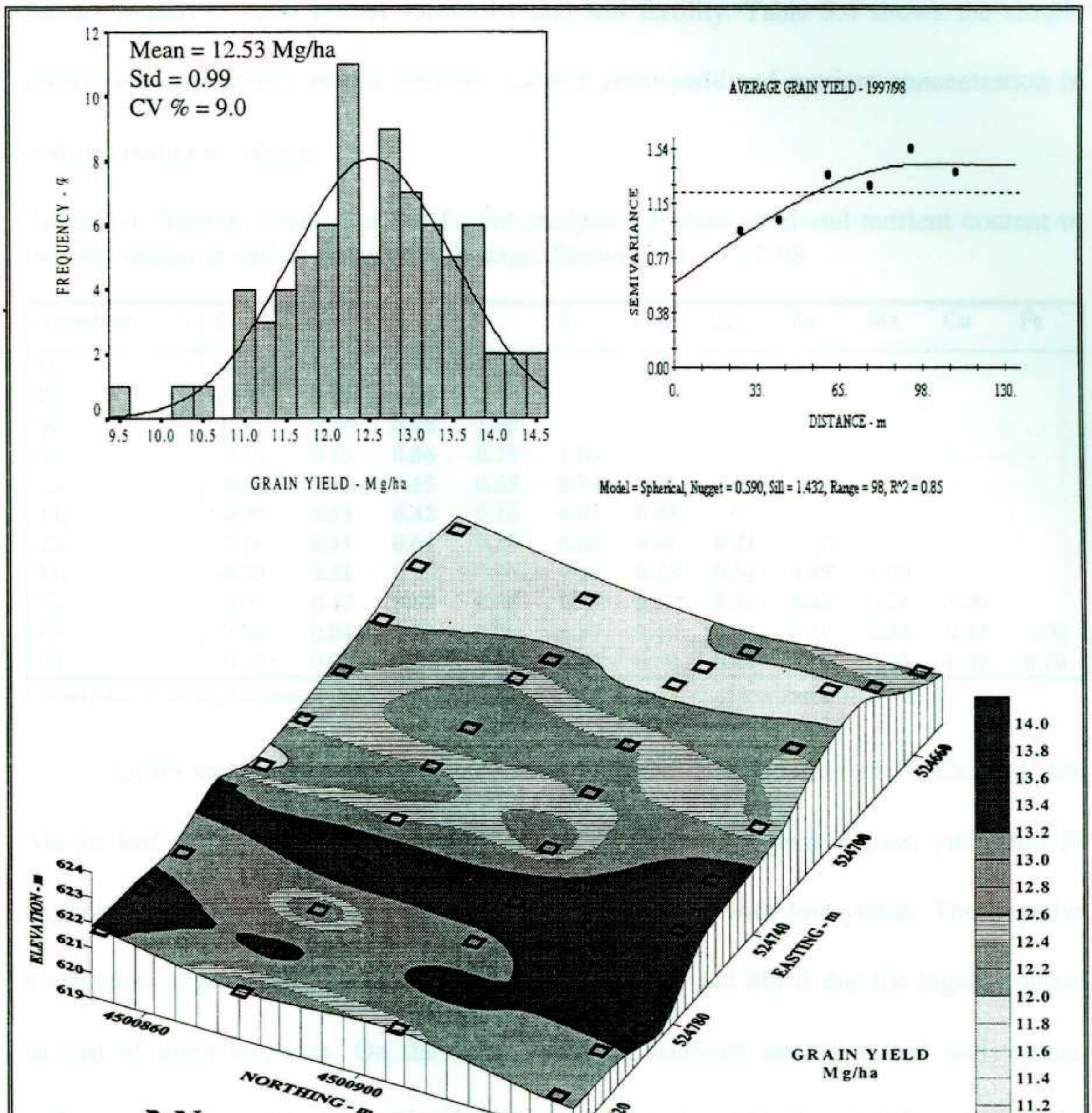

Figure 3.4. Contour map of average grain yield overlaid on topography. Transects and plots are represented by squares. The small figures on top are the frequency distribution and semi-variogram, respectively, for average grain yield. Shelton, NE, 1997/98.

The nutritional status of corn as measured by the concentration of nutrients in the leaf dry matter at early silking growth stage, could be a starting point for identifying factors related to yield spatial variability and soil fertility. Table 3.4 shows the simple correlation coefficients matrix between harvest grain yield and nutrient concentration in leaf dry matter at silking.

Table 3.4. Simple correlation coefficient analyses of grain yield and nutrient content in leaf dry matter at early silking growth stage. Shelton, NE, 1997/98

Variables	GY	N	P	K	S	Ca	Mg	Zn	Mn	Cu	Fe
N	**-0.32**	1.00									
P	-0.02	0.16	1.00								
K	0.11	-0.16	**0.88**	1.00							
S	-0.14	0.15	**0.86**	**0.76**	1.00						
Ca	**-0.32**	**0.46**	**0.65**	**0.39**	**0.73**	1.00					
Mg	**-0.39**	**0.53**	**0.42**	0.16	**0.54**	**0.83**	1.00				
Zn	-0.16	**0.41**	**0.61**	**0.38**	**0.62**	**0.61**	**0.42**	1.00			
Mn	**-0.33**	**0.31**	0.23	-0.07	**0.46**	**0.55**	**0.54**	**0.58**	1.00		
Cu	0.03	-0.13	**0.67**	**0.68**	**0.77**	**0.52**	**0.31**	**0.49**	0.28	1.00	
Fe	0.09	0.04	0.27	0.08	**0.37**	**0.40**	**0.33**	0.19	**0.34**	**0.43**	1.00
Al	-0.16	0.03	**0.34**	0.19	**0.50**	**0.50**	**0.46**	0.08	**0.33**	**0.39**	**0.70**

Correlation's are significant at the 5 % level if they are higher than + 0.30 or lower than – 0.30

Grain yield was negatively correlated with the concentration of N, Ca, Mg, and Mn in leaf dry matter. The negative correlation observed between grain yield and N, suggest excess of N-fertilizer applied in part of the field with low yields. The negative correlation of grain with the others nutrients, mainly Ca and Mg is due the higher content in soil of these nutrients. On the other hand, all nutrients are correlated with others, reflecting their complex interaction in the physiological and biochemical functions in the plant. These interactions make it difficult to interpret the data and to identify cause and effect relationships. Such inter-correlation between variables illustrates the need for analysis techniques that are based on grouping of variables.

Groups of correlated variables were defined using factor analysis performed by an oblique rotation using principal-factor method and the promax criterion. This approach is used to detect the maximum variation and co-variation in the observed data. Table 3.5 shows the eigenvalues, the proportion of the total variance and the loading of each three factors derived from factor analysis.

Table 3.5. Factor analysis results after the promax method of oblique rotation for nutrient content in leaf dry matter. Shelton, NE, 1997/98.

Variance Components	Factor Variables		
	FV_1	FV_2	FV_3
Eigenvalue	5.40	1.97	1.45
Proportion (%)	49.15	17.95	13.24
Cumul. Proportion (%)	49.15	67.10	80.34
Variables	**Factor loadings †**		
Nitrogen	-0.010	**0.780**	0.043
Sulfur	**0.940‡**	0.422	0.312
Phosphorus	**0.923**	0.052	0.151
Potassium	0.627	**0.818**	0.534
Calcium	0.376	**0.826**	0.493
Magnesium	**0.919**	0.527	0.508
Zinc	0.616	**0.719**	0.130
Manganese	0.237	**0.738**	0.454
Copper	**0.843**	0.231	0.507
Iron	0.280	0.260	**0.884**
Aluminum	0.347	0.283	**0.917**

† Absolute loadings of 0.30 are considered significant, loadings of 0.40 are considered more important, and loadings of 0.50 are considered very significant ‡ Number in bold indicates the variables with large factor loading (coefficients) were selected from each factor to create new factor variable

The original set of 11 variables was reduced to three factor variables having eigenvalues greater than 1. The first three principal factor variables created accounted for 80% of the overall variation of the nutrients content in leaf dry matter of corn in the field at the early silking stage. The first factor represented 49% of the total variation, and high positive coefficients occurred for to S, P, Mg and Cu. The second factor variable explained 18% of the variation and high positive correlation coefficients were found for

N, K, Ca, Zn, and Mn. The third factor variable explained 13% and was highly related to Fe and Al (Table 3.5).

Since tissue analysis may suggest an optimum nutrient level, the factor variables could be interpreted as indicators of the nutritional status of corn. These factors are directly related to soil fertility status when others factors, such as light, temperature, moisture, and the physical conditions of the soil are favorable for crop growth and development.

To study the relationships between the factor variables and grain yield multiple linear regression models (Backward-stepwise regression), was used to identify and assess the major factors affecting final grain yield in the field. Only those factors, which were significant at the 10% level ($P \leq 0.10$) to predict yield were retained in the model. Grain yield was the dependent variable and the factors were the independent variables. Equations describing the influence of the extracted factors to the corn yield variation are presented in Table 3.6.

Table 3.6. Regression models of the contribution of extracted factors of nutrient content in leaf dry matter at early silking to the grain yield variation of corn. Shelton, NE 1997/98

Model		Factors Variables			Intercept	Adj.	SE of
no		FV_1	FV_2	FV_3		R^2	estimate
01	B	0.104^{ns}	-0.218^{ns}	0.00	12.58	0.043	1.03
	β	0.303	-0.551	0.00			
	r_p	0.155	-0.295	0.00			
02	B	0.104^{ns}	-0.217^{ns}	****	12.58	0.068	1.02
	β	0.302	-0.551	****			
	r_p	0.169	-0.298	****			
03	B	****	-0.117^{ns}	****	12.57	0.065	1.02
	β	****	-0.296	****			
	r_p	****	-0.296	****			

B = regression coefficient; β = standardized regression coefficient; r_p = partial correlation coefficient; SE = standard error of estimate. ns = not significant at 10% level.

The factor variables, composed by different group of correlated nutrient concentrations in leaf dry matter, which define the nutritional status of corn in the field, had no significant association with grain yield variability. The regression coefficient (B) which measure the contribution of the factors to the variation of the dependent variable (yield) was not significant at $P \leq 0.10$ (Table 3.6-model 3). Thus, since the nutritional status of corn indirectly measured soil fertility in the field we can presume that soil fertility at this sit wasn't an important factor affecting corn yield variability.

Soil Physical and Chemical Properties

The experimental field was highly heterogeneous in its physical and chemical characteristics. Only pH, P, K, Mn, Fe, POM, total-N, and BD_m were normally distributed. The other variables were negatively or positively skewed (Table 3.7). Soil pH had the smallest CV's (4 – 11%) at both depths, followed by BD (measured and estimated). For all others variables CV's exceeded 35%. At both depths, the largest CV's were for inorganic-N, available micronutrients, and sand content. Except for Ca, Mg, Na, and Cu, elemental concentrations in the upper 15 cm were greater than at 15-30 cm depth, but there were no distinct differences in CV's between two depths (Table 3.7). An examination of outliers in the data showed that some locations in the field had exceptionally higher values of inorganic-N and extracted bases in the topsoil. Presumably, the main process that affects the spatial variability of soil properties at this site is related to the different soil types across the field.

Table 3.7. Descriptive statistic for soil physical and chemical properties. Shelton, NE, 1997/98.

Variables	Depth (cm)	Statistical parameters						
		Min	Max	Median	Mean	Std. Dev.	CV (%)	Wilks-Shapiro†
$PH_{1:1\ water}$ (97)	0 – 15	4.62	6.67	5.39	5.47	0.46	8	0.96^{ns}
	15 – 30	4.94	7.26	5.52	5.56	0.42	7	0.82**
$PH_{1:1\ water}$(98)	0 – 15	4.56	5.53	4.92	4.95	0.21	4	0.96^{ns}
	15 – 30	4.70	7.17	5.22	5.43	0.57	11	0.85**
$EC_{1:1\ water}$ (97)	0 – 15	0.10	0.64	0.21	0.23	0.10	43	0.87*
dS m^{-1}	15 – 30	0.10	0.36	0.17	0.18	0.07	37	0.91**
$EC_{1:1\ water}$ (98)	0 – 15	0.13	0.28	0.16	0.17	0.033	19	0.89**
dS m^{-1}	15 – 30	0.11	0.37	0.16	0.18	0.064	35	0.86**
$N0_3$-N, kg ha^{-1} (97)	0 – 15	4.16	63.92	16.94	21.29	14.56	68	0.84**
	15 – 30	3.17	26.54	8.97	9.70	4.65	48	0.88**
$N0_3$-N, kg ha^{-1} (98)	0 – 15	9.80	25.51	14.13	14.95	3.43	23	0.89**
	15 – 30	6.70	17.56	10.18	10.51	2.75	26	0.90**
NH_4-N, kg ha^{-1} (97)	0 – 15	5.51	258	43.90	74	71	96	0.83**
	15 – 30	2.44	167	8.73	16	27	170	0.43**
NH_4-N, kg ha^{-1} (98)	0 – 15	2.06	9.40	3.64	3.93	1.43	36	0.86**
	15 – 30	1.62	5.92	2.84	2.81	0.87	31	0.92*
P-Bray1, kg ha^{-1} (97)	0 – 15	26	173	58.7	65	30	46	0.85**
	15 – 30	20	108	49.6	22	22	41	0.94^{ns}
P-Bray1, kg ha^{-1} (98)	0 – 15	32	108	61	63	20	31	0.95^{ns}
	15 – 30	24	120	47	51	21	51	0.83**
K, kg ha^{-1}	0 – 15	147	868	444	424	191	45	0.95^{ns}
	15 – 30	108	719	335	334	143	43	0.96^{ns}
Ca, kg ha^{-1}	0 – 15	760	4465	1668	1822	870	48	0.86**
	15 – 30	1035	7345	2300	2853	1511	53	0.85**
Mg, kg ha^{-1}	0 – 15	144	842	276	314	151	48	0.86**
	15 – 30	172	978	345	425	197	46	0.89**
Na, kg ha^{-1}	0 – 15	10	34	15	17	6	35	0.89**
	15 – 30	11	54	21	25	11	44	0.88**
Zn, kg ha^{-1}	0 – 15	0.73	9.01	3.51	3.78	1.76	47	0.91**
	15 – 30	0.53	5.82	1.07	1.40	0.89	64	0.67**
Mn, kg ha^{-1}	0 – 15	16	86	53	52	17	32	0.98^{ns}
	15 – 30	13	73	39	41	16	38	0.95^{ns}
Cu, kg ha^{-1}	0 – 15	0.40	2.61	0.87	1.02	0.50	49	0.86**
	15 – 30	0.46	3.78	1.33	1.44	0.72	50	0.92*
Fe, kg ha^{-1}	0 – 15	22	155	67	70	27	39	0.96^{ns}
	15 – 30	11	89	40	44	20	46	0.94^{ns}
CEC, meq $100g^{-1}$	0 – 15	4.03	15.61	6.40	7.24	2.70	37	0.86**
	15 – 30	3.79	17.73	7.57	8.50	3.78	44	0.88**
SOM, Mg ha^{-1} (97)‡	0 – 15	9	49	22.57	24	9.6	40	0.93**
	15 – 30	5	33	13.88	16	8.0	50	0.91**
SOM, Mg ha^{-1} (98)‡	0 – 15	18	44	29	29	7	26	0.93*
	15 – 30	4.36	29.65	13.46	14.56	5.5	38	0.96^{ns}

† Wilk-Shapiro test for normality, significant at the $*P \leq 0.05$ and $**P \leq 0.01$ probability levels. Significance indicates that the null hypothesis of normal distribution is rejected. ‡ Different methods of analyses were used for soil organic matter in 1997 and 1998.

Table 3.7. Continuation

Variables	Depth (cm)	Statistical parameters						
		Min	Max	Median	Mean	Std. Dev.	CV (%)	Wilks-Shapiro †
POM, Mg ha^{-1} (98)	0 – 15	7.18	15.03	11.20	11.21	1.90	17	0.97^{ns}
Total-N, kg ha^{-1}	0 – 15	821	1856	1366	1372	284	17	0.95^{ns}
	15 – 30	330	1800	1035	1060	296	33	0.98^{ns}
Sand, %	0 – 15	41	84	74	70	12	47	0.86**
	15 – 30	22	88	65	61	20	61	0.89**
Silt, %	0 – 15	8	42	17	20	9	36	0.88**
	15 – 30	4	56	23	26	16	38	0.89**
Clay, %	0 – 15	3	21	9	10	4	45	0.92*
	15 – 30	6	24	12	13	5	38	0.88**
BD_m, g cm^{-3}	0 – 15	1.32	1.63	1.48	1.48	0.08	5	0.97^{ns}
	15 – 30	1.40	1.94	1.74	1.72	0.12	7	0.94*
BD_e, g cm^{-3}	0 – 15	1.18	1.56	1.41	1.39	0.12	8	0.91**
	15 – 30	1.17	1.58	1.43	1.41	0.12	9	0.90**
AWHC, cm^3 cm^{-3}	0 – 30	0.053	0.223	0.130	0.139	0.05	36	0.92*

† Wilk-Shapiro test for normality, significant at the $*P \leq 0.05$ and $**P \leq 0.01$ probability levels. Significance indicates that the null hypothesis of normal distribution is rejected. BD_m and BD_e are bulk density measured and estimated, respectively.

Consequently, the uniform management that has been used for a long time on this field didn't reduce the variability in soil physical and chemical properties.. For example, it is well known that sandy soils are very low in phosphorus and zinc, and applications of these nutrients are commonly necessary for good corn growth. The content of available P in the surface 0-15 cm of this field ranged from 20 to 173 kg ha^{-1} (10 to 80 mg kg^{-1}) and 50% of the samples had available P concentrations of 60 kg ha^{-1} (30 mg kg^{-1}). The content of zinc ranged from 0.73 to 9.0 kg ha^{-1} (0.3 to 4.0 mg kg^{-1}) and averaged 3.8 kg ha^{-1} (2.0 mg kg^{-1}) (Table 3.7). According to Hergert et al. (1995) corn yield increase may be expected from P and Zn fertilizers applications, when soil test are below 16 (P-Bray1) and 0.8 (Zn-DTPA) mg kg^{-1} of soil, respectively.

Geostatistical analyses were performed using all standardized (zero mean and unit variance) soil physical and chemical properties measured in the field at 0 to 15 cm and 15 to 30 cm depths. Parameters for isotropic semivariograms for each soil property at both depths are presented in Tables 3.8 and 3.9. Examinations of the semivariograms showed that the range of spatial correlation varied among soil properties. Except for inorganic-N, P, Mn and Fe with short ranges of spatial correlation (< 50 m), all the other variables were spatially correlated to a distance of 140 m, which suggests that the spatial dependence of these properties may be probably determined by soil type.

Table 3.8. Geostatistics analysis for standardized soil properties measured at 0 to 15 cm depth. Shelton, NE, 1997/98

Variable	Active † Lag (m)	Active † Step (m)	Nugget † C_0	Sill † C_0+C_1	Range † a (m)	R^2	Proportion $C_1/(C_0+C_1)$ †	Model †
$PH_{1:1}$	163	17	0.440	1.41	144	0.90	0.68	LIN
$EC_{1:1}$	163	17	0.298	1.28	135	0.90	0.76	SPH
NO_3-N	150	17	0.149	1.05	26	0.00	0.84	SPH
NH_4-N	150	17	0.196	1.14	50	0.15	0.83	EXP
P	180	17	0.096	1.02	34	0.02	0.91	SPH
K	180	17	0.440	1.03	80	0.52	0.57	SPH
Ca	163	17	0.455	1.33	144	0.96	0.90	LIN
Mg	163	17	0.367	1.37	144	0.91	0.73	LIN
Na	180	17	0.230	1.15	100	0.84	0.80	SPH
Zn	163	17	0.760	1.15	144	0.67	0.34	LIN
Mn	163	20	0.001	1.01	54	0.85	0.99	SPH
Cu	163	17	0.470	1.18	154	0.92	0.60	SPH
Fe	140	17	0.180	1.02	34	0.10	0.82	SPH
CEC	163	17	0.523	1.28	144	0.97	0.59	LIN
SOM	163	17	0.027	1.75	144	0.96	0.98	LIN
POM	163	17	0.420	1.30	155	0.83	0.67	SPH
Total-N	163	17	0.001	1.85	144	0.98	0.99	LIN
Sand	163	17	0.001	1.82	144	0.98	0.99	LIN
Silt	163	17	0.001	1.79	144	0.98	0.99	LIN
Clay	163	17	0.001	1.84	144	0.95	0.99	LIN
BD	163	17	0.290	1.58	144	0.98	0.81	LIN

† Active lag, the distance to which variograms are computed. Active step, the lag increment used. Nugget, semi-variance at zero spacing. Sill, semi-variance at spacing > range. Range, distance after which values are not correlated. ‡ Proportion of spatial structure, measure the proportion of sample variance (C_0 +C_1) that is explained by spatially structured variance C_1. Model: SPH = spherical, EXP = exponential, and LIN = linear.

The short range of spatial correlation (< 50 m) observed for P, Mn and Fe, could be associated with the variability in the application of a blend of fertilizers for these nutrients in the field. The greater spaced range (140 m) of correlation, observed for organic matter (Tables 8 and 9), the main natural source of P, Mn, and Fe in soils, is also an indication of the variability induced by management practices, such as fertilizer applications. Due to the relative undisturbed conditions of the subsurface of soil, no pattern of spatial dependence had been observed for soil properties measured at 20 to 40 cm depth (Chung et al.;1995). The similar pattern of spatial correlation observed in this study for soil properties at both depths may be related to soil texture and soil management used by the farmer. The farming activities tend to change the spatial structure of soil properties dramatically, mainly with the depth of tillage.

Table 3.9. Geostatistics analysis for standardized soil properties measured at 15 to 30 cm depth. Shelton, NE, 1997/98.

Variable	Active †		Nugget †	Sill †	Range †	R^2	Proportion	Model †
	Lag (m)	Step (m)	C_0	C_0+C_1	a (m)		$C_1/(C_0+C_1)$	
pH	100	17	0.180	0.95	42	0.60	0.81	SPH
EC	100	17	0.181	1.00	44	0.73	0.82	SPH
NO_3-N	100	17	0.201	0.87	32	0.48	0.77	SPH
NH_4-N	150	17	0.507	1.34	127	0.70	0.62	LIN
P	163	17	0.663	1.23	144	0.64	0.49	LIN
K	163	17	0.179	1.19	105	0.83	0.85	SPH
Ca	130	10	0.219	1.28	151	0.90	0.83	SPH
Mg	130	10	0.150	1.37	145	0.93	0.89	SPH
Na	150	17	0.251	1.35	154	0.83	0.81	SPH
Zn	130	10	0.001	1.01	37	0.23	0.99	SPH
Mn	150	17	0.104	1.09	57	0.89	0.90	SPH
Cu	130	17	0.063	1.21	128	0.88	0.95	SPH
Fe	130	17	0.218	1.03	34	0.19	0.78	SPH
CEC	130	17	0.104	1.47	169	0.94	0.93	SPH
OM	163	17	0.769	1.16	144	0.50	0.34	LIN
NT	163	17	0.615	1.27	144	0.78	0.52	LIN
Sand	163	17	0.127	1.64	194	0.96	0.92	SPH
Silt	163	17	0.161	1.66	203	0.94	0.90	SPH
Clay	163	17	0.063	1.46	152	0.98	0.95	SPH
BD_m	163	17	0.167	1.41	141	0.95	0.88	SPH

† Active lag, the distance to which variograms are computed. Active step, the lag increment used. Nugget, semi-variance at zero spacing. Sill, semi-variance at spacing > range. Range, distance after which values are not correlated. ‡ Proportion of spatial structure, measure the proportion of sample variance (C_0 +C_1) that is explained by spatially structured variance C_1. Model: SPH = spherical, EXP = exponential, and LIN = linear.

RELATIONSHIPS BETWEEN SOIL PROPERTIES

In general, some soil characteristics are mutually correlated. Hence, factors causing soil variation, which is reflected in one or more of the soil properties, may be used as criteria of grouping areas with similar characteristics. To analyze the cause of soil variation, we applied factor analysis, which is a mathematical technique used to summarize data and investigate the relationships among soil variables. It helps to understand the data pattern, particularly if some of the original variables are highly correlated.

The correlation coefficients matrix among soil properties at two depths, 0 to 15 cm and 15 to 30 cm, from which factor analysis start are shown in Tables 3.10 and 3.11. The correlation coefficient has revealed that there were various degrees of correlation among soil properties. For example, soil properties measured in the surface layer (0-15 cm), pH and electrical conductivity (EC) has the greatest number of significant correlated characters, followed by K, Ca and Mg. Phosphorus (P) and inorganic-N weren't correlated with other soil properties, implying that the content of these nutrients in soil is controlled by external factors, such as fertilizer application. However, different behavior was presented for soil properties measured at the 15 to 30 cm depth (Table 3.11). Electrical conductivity (EC) and pH had the least number of correlated characters, and extractable bases (K, Ca, Mg, Na) were highly correlated, due to the higher content of these elements in the underlying parent material of these soils.

Table 3.10. Simple correlation coefficients between soil physical-chemical properties measured at 0 to 15cm depth. Shelton, NE, for 1997 and 1998.

Variables †	$EC_{1:1}$	$PH_{1:1}$	NO_3	NH_4	P Bray	K	Ca	Mg	Na	Zn	Mn
$PH_{1:1}$	**0.47**	1.00									
NO_3	0.23	**-0.40**	1.00								
NH_4	-0.09	**-0.39**	**0.42**	1.00							
P-Bray	-0.15	-0.29	-0.13	0.06	1.00						
K	0.06	-0.27	-0.02	0.14	0.16	1.00					
Ca	0.08	-0.16	-0.09	0.08	-0.07	**0.70**	1.00				
Mg	-0.08	-0.19	-0.05	0.11	-0.12	**0.68**	**0.96**	1.00			
Na	0.03	-0.14	0.02	-0.04	0.14	**0.72**	**0.76**	**0.68**	1.00		
Zn	-0.06	-0.20	-0.02	0.09	0.00	**0.51**	**0.39**	**0.46**	**0.34**	1.00	
Mn	0.15	-0.21	0.07	0.26	0.22	**0.84**	**0.60**	**0.64**	**0.58**	**0.42**	1.00
Cu	0.02	-0.16	0.02	0.16	-0.04	**0.77**	**0.93**	**0.94**	**0.76**	**0.44**	**0.74**
Fe	0.15	-0.20	0.12	0.14	0.28	**0.47**	0.00	0.03	0.20	**0.47**	**0.49**
CEC	0.03	-0.14	-0.06	0.09	-0.02	**0.80**	**0.97**	**0.95**	**0.76**	**0.45**	**0.73**
SOM	**0.74**	**0.67**	-0.17	-0.17	-0.05	0.00	-0.04	-0.07	-0.02	-0.12	0.13
POM	**0.56**	0.25	-0.14	-0.16	0.22	-0.05	-0.15	-0.12	-0.17	0.07	0.08
Total-N	**0.62**	0.44	-0.11	0.00	0.04	0.15	0.04	0.05	-0.04	-0.03	0.33
Sand	**-0.80**	**-0.68**	0.10	0.19	0.12	-0.01	0.06	0.08	0.06	0.18	0.14
Silt	**0.78**	**0.63**	-0.08	-0.17	-0.10	-0.02	-0.08	-0.11	-0.10	-0.21	0.11
Clay	**0.76**	**0.68**	-0.11	-0.21	-0.11	0.11	0.00	-0.02	0.06	-0.06	0.22
BD	**-0.68**	**0.44**	0.00	0.19	-0.01	-0.06	0.07	0.05	0.10	0.12	0.12
Variables	**Cu**	**Fe**	**CEC**	**SOM**	**POM**	**T-N**	**Sand**	**Silt**	**Clay**	********	********
Fe	0.15	1.00									
CEC	**0.95**	0.16	1.00								
SOM	0.01	0.03	0.03	1.00							
POM	-0.12	0.08	-0.19	-0.07	1.00						
Total-N	0.11	0.14	-0.13	0.15	**0.82**	1.00					
Sand	0.01	-0.01	-0.03	**-0.93**	**-0.61**	**-0.82**	1.00				
Silt	-0.06	-0.04	0.00	**0.91**	**0.62**	**0.82**	**-0.98**	1.00			
Clay	0.08	0.16	0.11	**0.81**	**0.51**	**0.72**	**-0.89**	**0.80**	1.00		
BD_m	0.02	-0.03	-0.06	**-0.69**	**-0.59**	**-0.70**	0.79	**-0.78**	**-0.72**		

† $EC_{1:1}$ = electrical conductivity (1 part soil and 1 part of water) CEC = cation exchange capacity, SOM = soil organic matter, POM = particulate organic matter, BD = bulk density, Correlation's are significant at the 5 % level if they are higher than + 0.30 or lower than – 0.30.

Table 3.11. Simple correlation coefficients between soil physical-chemical properties measured at 15 to 30 cm depth. Shelton, NE, for 1997 an 1998.

Variables †	$EC_{1:1}$	$PH_{1:1}$	NO_3	NH_4	P-Bray	K	Ca	Mg	Na	Zn	Mn
$pH_{1:1}$	**0.87**	1.00									
NO_3	0.13	-0.05	1.00								
NH_4	-0.08	-0.10	**0.58**	1.00							
P-Bray	0.17	0.17	-0.25	-0.40	1.00						
K	0.11	0.11	-0.27	-0.25	0.10	1.00					
Ca	0.08	0.00	-0.11	-0.08	0.14	**0.71**	1.00				
Mg	0.09	0.08	-0.17	-0.14	0.17	**0.82**	**0.91**	1.00			
Na	0.09	0.06	-0.18	-0.14	0.12	**0.74**	**0.88**	**0.89**	1.00		
Zn	-0.10	0.05	-0.03	**0.34**	-0.19	0.14	-0.09	-0.05	0.06	1.00	
Mn	0.21	0.24	-0.09	-0.21	0.02	**0.69**	0.18	**0.36**	0.34	0.29	1.00
Cu	0.15	0.12	-0.22	-0.18	0.22	**0.78**	**0.83**	**0.92**	**0.79**	0.02	**0.39**
Fe	0.13	0.23	-0.12	-0.19	-0.02	**0.49**	-0.03	0.11	0.12	**0.50**	**0.78**
CEC	0.20	0.12	-0.15	-0.16	0.19	**0.80**	**0.97**	**0.93**	**0.89**	0.07	**0.34**
SOM	-0.15	-0.31	0.13	0.01	-0.29	-0.09	0.07	-0.03	-0.10	0.29	-0.11
Total-N	-0.07	-0.23	0.19	0.09	-0.29	**-0.09**	0.03	-0.05	-0.14	0.25	-0.11
Sand	-0.22	-0.16	0.13	0.21	-0.19	**-0.80**	**-0.90**	**-0.92**	**-0.84**	0.11	**-0.40**
Silt	0.21	0.15	-0.10	-0.20	0.20	**0.78**	**0.91**	**0.90**	**0.83**	0.11	**0.37**
Clay	0.23	0.19	-0.24	-0.22	0.16	**0.80**	**0.84**	**0.91**	**0.80**	0.09	**0.47**
BD	**-0.69**	**-0.53**	0.14	**0.32**	-0.31	-0.16	-0.10	-0.07	-0.11	0.26	-0.26
Variables	Cu	Fe	CEC	SOM	T-N	Sand	Silt	Clay	BD	****	****
Fe	0.15	1.00									
CEC	**0.86**	0.11	1.00								
SOM	-0.08	-0.27	0.05	1.00							
Total-N	-0.11	-0.25	0.02	**0.97**	1.00						
Sand	**-0.85**	-0.11	**-0.94**	-0.03	-0.01	1.00					
Silt	**0.83**	0.08	**0.93**	0.03	0.20	**-0.99**	1.00				
Clay	**0.87**	0.18	**0.90**	0.04	0.01	**-0.95**	**0.91**	1.00			
BD_m	-0.09	-0.07	-0.26	-0.09	-0.17	0.24	-0.22	-0.30	1.00		

† $EC_{1:1}$ = electrical conductivity (1 part soil and 1 part water), CEC = cation exchange capacity, SOM = soil organic matter, BD_m = measured bulk density. Correlation's are significant at the 5 % level if they are higher than + 0.30 or lower than – 0.30.

Soil Properties Measured at 0 to 15 cm Depth

The original set of 21 soil properties measured at 0 to 15 cm was reduced to five factors variables (FV) having eigenvalues greater than 1. The first five factors (FV_1 to FV_5) account for 83% of the total variance. The remaining factors became less meaningful and were considered as errors, which included the random component of soil variation and various types of error produced in every stage of soil sampling and analysis.

Table 3.12 gives the factor pattern, or factor loading, which characterizes the nature of the first five derived factor variables. Factor pattern consists of the correlation coefficients between the employed variables and the derived principal component.

The first factor variable represented 31% of the variation. High coefficients, positive or negative, were associated with pH, EC, SOM, POM, N-total, sand, silt, clay, and measured bulk density (BD_m). Those variables express general physical, chemical and organic properties of the soil, which are related to the different soil types found in the experimental field. Thus, it may be interpreted as the " ***physical-chemical properties related to soil type***"(PCST). Those properties are very well characterized by soil profile analysis shown in Table 3.1. The Kenesaw silt loam differs from other soils, mainly by its texture and organic carbon content.

For the second factor variable, which explained 29% of soil variability (Table 3.12), high positive coefficients were seen for K, Ca, Mg, Na, Mn, Cu, and CEC. Those variables correspond to the exchange base status and cation exchange capacity, which are related to the original nature of a soil material formed under a specific environment. Hence, the second factor is considered to determine a potential fertility level of the soil, or the "***inherent fertility potential***"(IFP).

Table 3.12. Factor analysis results after promax rotation for soil properties measured at 0 to 15 cm depth. Shelton, NE, for 1997 and 1998.

Variance Component	Factor 1 PCST	Factor 2 IFP	Factor 3 MF	Factor 4 NF	Factor 5 AP
Eigenvalue	6.89	6.32	2.15	1.52	1.34
Proportion (%)	31.33	28.72	9.79	6.91	6.09
Cumul. Proportion (%)	31.33	60.04	69.83	76.74	82.83
Variables †	**Factor loadings ‡**				
$pH_{1:1}$-water	**0.647**	-0.207	-0.183	**-0.630**	-0.474
$EC_{1:1}$-water	**0.849**	-0.018	0.107	0.070	-0.159
NO_3-N	-0.073	-0.040	0.116	**0.845**	-0.108
NH_4-N	-0.178	0.133	0.138	**0.782**	0.185
P	-0.063	0.016	0.143	0.049	**0.895**
K	0.043	**0.845**	0.555	0.183	0.298
Ca	-0.073	**0.959**	0.151	0.020	-0.019
Mg	-0.083	**0.951**	0.188	0.076	-0.024
Na	-0.057	**0.815**	0.344	0.024	0.082
Zn	-0.120	**0.484**	**0.686**	0.064	0.137
Mn	0.184	**0.777**	**0.550**	**0.305**	**0.362**
Cu	-0.002	**0.969**	0.301	0.148	0.022
Fe	0.080	0.179	**0.895**	0.251	**0.375**
CEC	0.043	**0.983**	0.288	0.067	0.057
O.M.	**0.939**	-0.016	-0.039	-0.259	-0.054
P.O.M	**0.702**	-0.110	-0.021	-0.143	**0.374**
N – total	**0.869**	0.107	0.012	-0.061	0.167
Sand	**-0.979**	0.034	0.041	0.220	0.135
Silt	**0.956**	-0.066	-0.115	-0.187	-0.107
Clay	**0.892**	0.048	0.140	-0.268	-0.182
Bulk density	**-0.837**	0.020	0.080	0.089	-0.039

† EC = electrical conductivity –water 1:1, CEC = cation exchange capacity, SOM = soil organic matter, POM = particulate organic matter. ‡ Numbers in bold indicates the variables with large factor loading, based on assigned ranking were selected from each factor to create a new variable.

The third factor explaining 10% of soil variability (Table 3.12) was positively related to zinc (Zn) and iron (Fe), and manganese (Mn). Since zinc is expected to be quite low under the prevailing natural vegetation and soil parent material, higher zinc levels are usually related to increased human activity. The high correlation observed among Zn, Mn, and Fe, are probably due to application of a blend of fertilizers containing these micronutrients. Thus, this factor can be characterized as "***micronutrient fertilizer***" (MF).

The fourth factor (Table 3.12) which explained 7% of soil variability is apparently a "***nitrogen fertilizer***" (NF) factor, because nitrate and ammonium are highly and positively correlated but negatively related to pH. As the pH decreases the inorganic-N increases and vice versa. Thus, this component can be characterized as acidity caused by nitrification of ammoniacal nitrogen fertilizer applications and inefficient N use due to leaching losses. Soil acidification resulting from long use of N-fertilizers, have been reported (Patriquin et al., 1993, Bouman et al., 1995). The application of high levels of ammoniacal fertilizers to slightly acid soils resulted in a 1-unit drop in pH, within a period of 3 to 4 weeks (Smith and Doran, 1996). Although pH values as low as 4.5 were measured in field (Table 3.7), exchangeable acidity was low (Al^{3+} median = 0.15 cmol kg^{-1} of soil) with few values around 0.6 cmol Al kg^{-1} of soil.

Finally the fifth factor, explaining 6% of soil variability, a high positive coefficient was associated with phosphorus. Since the P-level is expected to be very low under the prevailing natural vegetation, higher phosphorus levels are usually related to increased farming activities, due to fertilizer application. The fifth component is called "***available phosphorus***"(AP).

Soil Properties Measured at 15 to 30 cm Depth

The same statistical analysis procedure applied to the soil physical-chemical properties measured at the topsoil was used to analyze the soil properties determined for subsoil (15 to 30 cm depth). Also, the original set of 20 variables was reduced to five factors having eigenvalues greater than 1 (Table 3.13). These factors explained 84% of the overall soil variation. The interpretation of each factor variable is similar to those discussed before. From Table 3.13, we can see that the variables included in each factor are, with few exceptions, similar to the results observed for soil properties that were measured for the surface layer (0 to 15 cm depth).

Table 3.13. Factor analysis results after promax rotation for soil properties measured at 15 to 30 cm depth. Shelton, NE, 1997/98.

Variance Component	Factor 1 IFP	Factor 2 AM	Factor 3 SBC	Factor 4 SOM	Factor 5 ANP
Eigenvalue	8.60	2.90	2.56	1.92	1.66
Proportion (%)	40.99	13.82	12.19	9.13	7.92
Cumul. Proportion (%)	40.99	54.81	67.00	76.12	84.04
Variables †	**Factor loadings ‡**				
$pH_{1:1\text{-water}}$	0.108	0.160	**0.869**	-0.266	-0.099
$EC_{1:1\text{-water}}$	0.162	0.065	**0.943**	-0.071	-0.054
NO_3-N	-0.174	-0.168	0.038	0.138	**0.761**
NH_4-N	-0.183	-0.095	-0.216	-0.050	**0.908**
P	0.192	-0.182	**0.302**	**-0.300**	**-0.587**
K	**0.838**	**0.625**	0.144	-0.026	**-0.315**
Ca	**0.948**	0.066	0.065	0.080	-0.151
Mg	**0.974**	0.245	0.089	-0.006	-0.218
Na	**0.906**	0.234	0.086	-0.087	-0.188
Zn	-0.080	**0.584**	-0.174	**-0.403**	**0.349**
Mn	**0.390**	**0.865**	0.289	-0.001	-0.222
Cu	**0.917**	**0.301**	0.125	-0.062	-0.266
Fe	0.111	**0.899**	0.170	-0.238	-0.145
CEC	**0.976**	0.197	0.217	0.081	-0.242
O.M.	0.002	-0.189	-0.128	**0.970**	0.065
N – total	-0.026	-0.165	-0.033	**0.960**	0.114
Sand	**-0.973**	-0.218	-0.248	-0.088	0.270
Silt	**0.961**	0.182	0.234	0.082	-0.245
Clay	**0.943**	**0.311**	0.269	0.100	**-0.324**
Bulk density	-0.185	0.015	**-0.838**	-0.233	**0.418**

† EC = electrical conductivity –water 1:1, CEC = cation exchange capacity, SOM = soil organic matter, POM = particulate organic matter. ‡ Numbers in bold indicates the variables with large factor loading based on assigned rankings, were selected from each factor to create new variable.

Five factors are quite well defined are interpretable without much difficulty. The first factor is related to ***"inherent soil fertility potential"*** (IFP), the second factor is related to "**available micronutrients**" (AM), the third factor is highly positively related to pH and EC, and negatively correlated with BD. That bulk density is negatively correlated with pH and electrical conductivity (EC), suggest some important characteristic that can effect plant growth, and could be interpreted as "***subsurface physical-chemical characteristics***" (SBC) The fourth factor reflects the "**soil organic matter**"(SOM), and finally the fifth factor is related to "***available nitrogen and phosphorus***" (ANP) that are moderately correlated with other soil properties (Table 3.13). Apart from N-inorganic, phosphorus is negatively correlated (- 0.58) with bulk density.

RELATIONSHIPS BETWEEN SOIL PROPERTIES AND GRAIN YIELD

The relationships between several soil properties and grain yield as indicated by simple correlation coefficients are presented in Table 3.14. Corn grain yields were positively or negatively correlated ($P \leq 0.05$) with many of the measured soil properties at both depts. This means that the variation of an individual soil property over the field can explain a part of the variation in grain yield but not all of it. The use of only a single variable to predict yield response to fertilizer application, might often fail because there are several other factors, besides the selected variable that, limit yield.

A multivariate approach was evaluated in an attempt to overcome this problem and to identify and assess the major yield-determining factors for the experimental field. Table 3.15 shows the regression equations describing the influence of the extracted factors of soil properties, measured at 0 to 15 and 15 to 30 cm depths, on corn grain yield.

A complete equation with all factors as independent variables is given, as well an optimized equation containing only the factors that are significantly related to yield variation.

Table 3.14. Simple correlation coefficient analyses between soil properties and grain yield. Shelton, NE, 1997/98.

Variable †	GY 98	GY 97	PP 97	PP 98	GY 97	PP 97	GY 98	PP 98
GY-97	**0.53** ‡	1.00						
CS-97		0.45	1.00					
CS-98	0.12			1.00				
	Soil depth – 0 to 15 cm				Soil depth – 15 to 30 cm			
$pH_{1:1\text{-water}}$-97		-0.01	0.04		0.20	0.11		
$pH_{1:1\text{-water}}$-98	**0.35**			-0.06			**0.51**	-0.04
$EC_{1:1\text{-water}}$-97		**0.41**	**0.31**		**0.54**	**0.35**		
$EC_{1:1\text{-water}}$-98	**0.58**			-0.04			**0.62**	0.04
NO_3-97		**0.39**	**0.37**		0.29	0.16		
NH_4-97		0.18	0.11		-0.04	-0.11		
NO_3-98	0.01			0.07			0.00	0.23
NH_4-98	-0.05			0.02			-0.33	0.03
P-Bray-97		0.30	0.06		0.16	0.18		
P-Bray-98	0.08			-0.21			**0.39**	-0.26
K	-0.03	**0.40**	**0.35**	0.01	**0.45**	**0.33**	0.24	-0.09
Ca	-0.29	0.23	0.23	-0.05	**0.43**	0.28	0.16	-0.20
Mg	-0.28	0.17	0.26	-0.02	**0.42**	**0.38**	0.21	-0.19
Na	-0.21	0.27	0.24	0.01	**0.32**	0.24	0.21	-0.14
Zn	-0.19	-0.15	-0.04	0.14	-0.02	-0.09	-0.20	0.09
Mn	0.07	**0.34**	0.29	-0.19	**0.32**	0.23	**0.33**	0.12
Cu	-0.25	0.29	0.31	-0.12	**0.53**	**0.51**	0.20	-0.14
Fe	0.15	-0.15	-0.01	-0.13	0.02	0.02	0.14	0.12
CEC	-0.18	0.26	0.29	-0.04	**0.45**		0.30	-0.16
SOM-97		0.19	0.03		0.24			
SOM-98	**0.63**			-0.19			0.08	0.17
POM-98	**0.54**			-0.19				
Total-N	**0.58**	0.26	0.09	-0.25			0.16	0.15
Sand	**-0.63**	**-0.45**	**-0.38**	0.23	**-0.50**	**-0.43**	**-0.32**	0.13
Silt	**0.63**	**0.50**	**0.40**	-0.20	**0.50**	**0.41**	**0.32**	-0.11
Clay	**0.54**	0.28	0.28	-0.26	**0.46**	**0.47**	0.30	-0.18
BD_m	**-0.57**	-0.06	-0.24	0.07	-0.08	-0.23	**-0.76**	0.00
BD_e	0.05	**-0.39**			**-0.59**		**0.31**	
AWHC ¶	**0.61**	**0.42**						

† GY = grain yield, PP = plant population, EC = electrical conductivity of 1:1 soil/water solution, CEC = cation exchange capacity, SOM = soil organic matter, POM = particulate organic matter, BD_m = measured bulk density, BD_e = estimated bulk density, AWHC = available water hold capacity. ‡ Correlation's in bold are significant at the 5% level if they are higher than + 30 or lower than – 0.30. ¶ AWHC at 30cm depth

The relative contribution of the factor variable to the variation of the dependent variable, grain yield, can be assessed using the standardized regression coefficients (β - weights) and the partial correlation coefficients (r_p). (Table 3.15).

Table 3.15. Regression models of the contribution of extracted factor variables (FV) of soil properties to the grain yield variation of corn. Shelton, NE, 1997/98.

Model no		FV_1 PCST	FV_2 IFP	FV_3 MF	FV_4 NF	FV_5 AP	Intercept	Adj. R^2	SE of estimate
		Soil properties measured 0 to 15 cm depth							
01	B	**0.089[a]**	**-0.051[b]**	0.035	0.047	0.085	12.62	0.46	0.64
	β	0.690	-0.360	0.128	0.100	0.154			
	r_p	0.683	-0.303	0.100	0.123	0.175			
02	B	**0.085[a]**	**-0.036[b]**			**0.127[c]**	12.62	**0.47**	0.63
	β	0.658	-0.258			0.227			
	r_p	0.685	-0.331			0.124			
		Soil properties measured 15 to 30 cm depth							
Model no		FV_1 IFP	FV_2 AM	FV_3 SBC	FV_4 SOM	FV_5 ANP	Intercept	Adj. R^2	SE of estimate
01	B	0.004	0.012	**0.231[a]**	**0.087[c]**	-0.069	12.63	0.54	0.58
	β	0.035	0.045	0.662	0.218	-0.188			
	r_p	0.039	0.049	0.689	0.311	-0.237			
02	B			**0.231[a]**	**0.083[c]**	**-0.079[c]**	12.63	**0.57**	0.56
	β			0.663	0.208	-0.214			
	r_p			0.687	0.309	-0.293			

B = regression coefficient; β = standardized regression coefficient; r_p = partial correlation coefficient; SE = standard error of estimate. Significance level: [a]P < 0.0001, [b]P < 0.05, [c]P < 0.10

For soil properties measured in the 0 to 15 cm layer the five factor variables extracted by the factor analysis technique were interpreted as representing physical chemical properties related to soil type (PCST), inherent soil fertility potential (IFP), micronutrients fertilizer (MF), nitrogen fertilizer (NF), and available phosphorus (AP). Forty seven percent (Adj. $R^2 = 0.47$) of the grain yield variation could be explained as a function of the factors, PCST-physical-chemical properties related to soil types, IFP-inherent soil fertility potential, and AP-available phosphorus (Table 3.15). Figure 3.5 shows the observed grain yields plotted against predicted yields based on the model equation, Yield = $12.62 + 0.085FV_1 - 0.036FV_2 + 0.127FV_5$, for which the regression coefficients of the factor variables, are significant at $P \leq 0.10$ (Table 3.15).

As indicated by the partial correlation coefficients (r_p), the factors variables, physical-chemical properties related to soil type (r_p = + 0.68) and inherent soil fertility potential (r_p = - 0.33), had opposite association with yield variability (Table 3.15). The negative effect of inherent soil fertility in the yield variability is an indication that other factors are limiting the grain yield potential in some part of the field. The highest values of the extracted bases (K, Ca, and Mg), associated to the low values of pH measured in this field (pH = 5.0), should not decrease corn yield.

The same procedure as discussed before, was used to interpret the relationships between soil properties measured at 15 to 30 cm and grain yield variability (Table 3.15). Here, two factors, SBS-subsurface characteristics (pH, EC, BD) and SOM-organic matter were positively and highly correlated with corn yield variability, and ANP-available nitrogen and phosphorus negatively correlated. These factors variables explained 57% (Adj. $R^2 = 0.57$) of yield variability in the field, with a partial correlation coefficients (r_p) of 0.68, 0.31, and – 0.29, respectively (Table 3.15). Figure 3.5, shows the observed grain yields plotted against predicted yields based on the equation model, Yield = $12.63 + 0.231FV_3 + 0.083FV_4 - 0.079FV_5$, which the regression coefficients of the factors are, significant ($P \leq 0.10$).

Although the experimental field is characterized by high variability in its soil physical and chemical properties, only 47% and 57% of corn yields variability were associated with soil variability at 0 to 15 cm and 15 to 30 cm depths, respectively. The low correlation between variables measured in the field and the proportion of yield variability accounted by the factors variables can be explained several ways. One explanation is that corn yields were affected by one or more unmeasured variables. Another explanation is that fertilizer applications and irrigation may have minimized the soil variability and lessened potential yield responses.

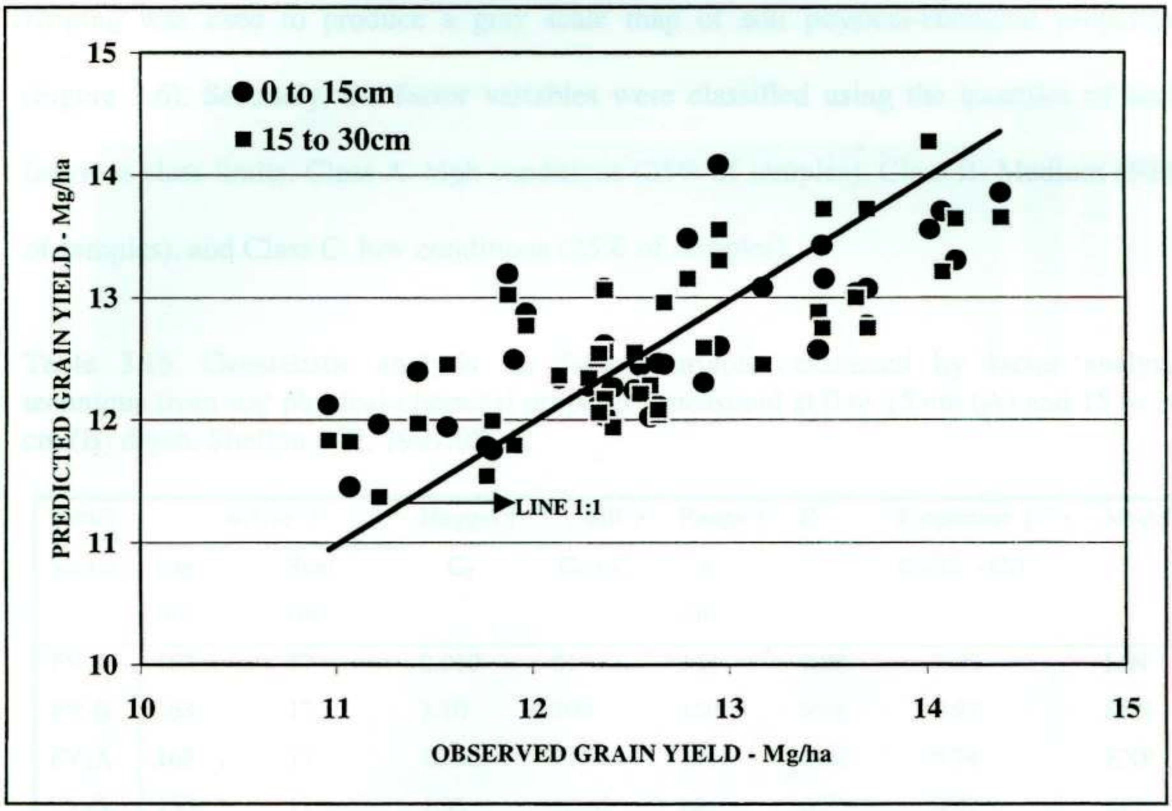

Figure 3.5. Observed and predicted grain yields as function of extracted factors variables of soil properties measured at depths of 0 to 15 and 15 to 30 cm. Shelton, NE, 1997/98. (Equation models are given in Table 3.15).

Soil Physical-Chemical Properties Mapping

The factors reflecting soil physical-chemical properties for both depths (Table 3.15) had significant influence on the corn grain yield variability. Consequently, the scores of these factors may be used for mapping and evaluating of soil conditions in the field, assuming that high positive scores represent present good physical and chemical conditions for corn growth and development, whereas negative scores represent inverse relationships with yield. As a first step, semivariances for each factor variable were computed and isotropic models fitted. Similar to soil properties, the factors had a clear spatial structure described by spherical, exponential and linear variogram models with negligible nugget variance, and spatial correlation ranging from 26 to 199 m (Table 3.16). Kriging was used to produce a gray scale map of soil physical-chemical properties (Figure 3.6). Secondly, the factor variables were classified using the quartiles of each factor as class limits: Class A: high conditions (25% of samples), Class B: Medium (50% of samples), and Class C: low conditions (25% of samples).

Table 3.16. Geostatistic analysis for factor variables extracted by factor analysis technique from soil physical-chemical properties measured at 0 to 15 cm (A) and 15 to 30 cm (B) depth. Shelton, NE, 1997/98.

Factor Scores	Active † Lag (m)	Active † Step (m)	Nugget † C_0	Sill † $C_0 + C_1$	Range † a (m)	R^2	Proportion ‡ $C_1/(C_0 + C_1)$	Model
FV_1A	163	17	0.010	81	144	0.98	0.99	LIN
FV_1B	163	17	3.10	100	159	0.93	0.97	SPH
FV_2A	163	17	12.30	47	199	0.96	0.74	EXP
FV_2B	130	17	1.35	10.65	68	0.77	0.87	SPH
FV_3A	120	10	2.67	11	58	0.74	0.75	EXP
FV_3B	100	17	0.01	5.52	53	0.98	0.99	SPH
FV_4A	163	17	0.230	3.52	26	0.00	0.93	SPH
FV_4B	180	17	0.82	5.01	67	0.22	0.83	EXP
FV_5A	163	17	0.34	2.41	26	0.00	0.85	SPH
FV_5B	100	10	1.66	4.48	97	0.82	0.63	SPH

† Active lag = distance to which variograms are computed. Active step = lag increment used. Nugget = semi-variance at zero spacing. Sill = semi-variance at space > range. Range = distance after which values are not correlated. ‡ Proportion of spatial structure, measure the proportion of sample variance (C0 +C1) that is explained by spatially structure variance C1. Model: SPH = spherical, EXP = exponential, L = linear

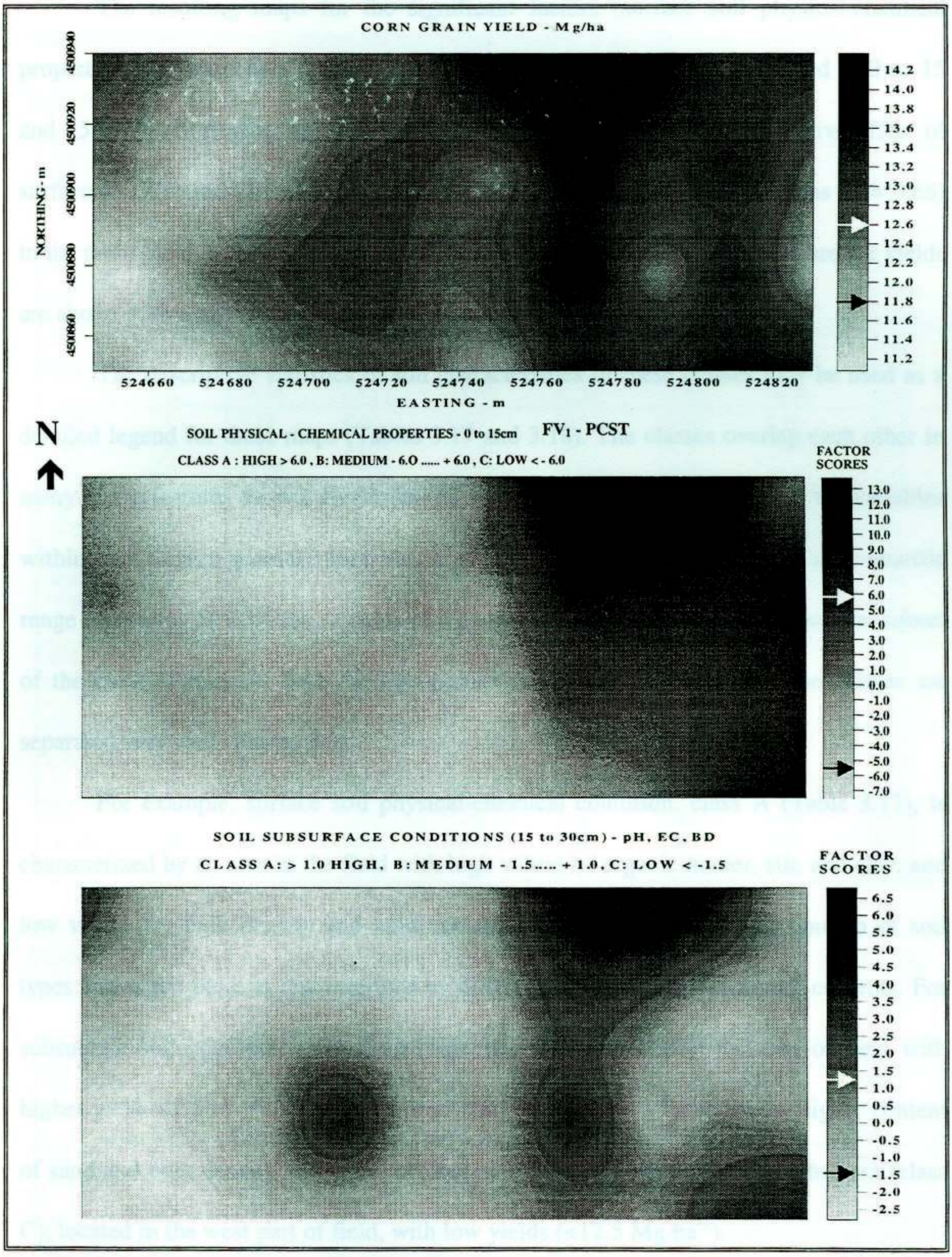

Figure 3.6. Images maps of average grain yield, surface (0 to 15 cm) soil physical-chemical properties and subsurface (15 to 30 cm) conditions. Shelton, NE, 1997/98. Arrows designate class (A,B,C) boundaries.

The resulting maps for the significant factors (surface soil physical-chemical properties and subsurface conditions), extracted for soil properties measured at 0 to 15 and 15 to 30 cm depths, and yield map are shows in Figure 3.6. The positive effect of surface soil physical-chemical properties ($r_p = 0.68$) and subsurface conditions ($r_p = 0.68$) in the grain yield is illustrated in the northeast part of field (dark shaded) where the yields are above of average (12.5 Mg ha^{-1}).

The descriptive statistics of soil characteristics of these classes may be used as a detailed legend for these maps (Tables 3.17 and 3.18). The classes overlap each other in many of the features shown. Nevertheless, using the inter-quartile ranges of the variables within each class, a general interpretation of soil conditions is possible. The inter-quartile range represents 50% of the samples in a class and may be seen as representative subset of the class of interest. Both, soil properties and yield variability in these classes are separated very well (Figure 3.6)

For example, surface soil physical-chemical condition, class A (Table 3.17), is characterized by an area in the field with high values of organic matter, silt, and clay, and low values for bulk density and sand content. This correlated with distribution of soil types across the field, as characterized by different sand and organic matter contents. For subsurface soil conditions, the main properties that characterize the area of field with higher yield (12.5 to 14.0 Mg ha^{-1}) are pH and bulk density (Table 3.18). Higher content of sand and bulk density and lower content of organic matter characterize the area (class C), located in the west part of field, with low yields (<12.5 Mg ha^{-1}).

Table 3.17.Descriptive statistics for the factor variable FV_1- physical – chemical properties related to soil type (PCST) for soil properties measured at 0 to 15 cm depth. Shelton, NE, 1997/98.

Variable	Class	Min	25%	Median	75%	Max	Mean	S.D
$PH_{1:1\text{-water}}$	C	4.56	4.66	4.92	4.99	5.23	4.87	0.195
	B	4.67	4.81	4.85	4.99	5.16	4.88	0.127
	A	4.89	4.97	5.20	5.35	5.53	5.18	0.217
$EC_{1:1\text{-water}}$	C	0.13	0.14	0.14	0.15	0.16	0.14	0.008
($dS\ m^{-1}$)	B	0.15	0.15	0.17	0.18	0.22	0.17	0.019
	A	0.20	0.20	0.22	0.23	0.28	0.22	0.024
OM	C	18.25	19.17	20.99	21.48	27.35	21.00	2.40
($Mg\ ha^{-1}$)	B	19.66	24.02	29.02	31.25	39.26	27.94	4.82
	A	34.34	35.12	37.02	41.12	43.83	38.20	3.50
POM	C	7.18	8.64	9.36	10.15	10.99	9.25	1.17
($Mg\ ha^{-1)}$)	B	7.37	10.93	11.44	12.71	14.32	11.46	1.55
	A	11.05	12.06	12.77	13.50	15.03	12.88	1.17
N – total	C	901	1030	1117	1196	1248	1108	114
($Kg\ ha^{-1}$)	B	821	1155	1372	1555	1718	1350	234
	A	1480	1612	1759	1806	1856	1704	136
Sand	C	78	80	81	82	84	81	1.64
(%)	B	61	69	74	79	82	74	5.97
	A	41	46	53	57	62	52	6.58
Silt	C	8	10	11	13	18	11	2.58
(%)	B	11	14	17	20	25	17	3.88
	A	25	28	31	39	42	33	5.96
Clay	C	3	7	8	8	9	7	1.67
(%)	B	6	7	9	11	14	9	2.45
	A	13	14	15	15	21	15	2.34
BD	C	1.45	1.51	1.56	1.59	1.63	1.54	0.056
($g\ cm^{-3}$)	B	1.44	1.45	1.50	1.53	1.55	1.49	0.039
	A	1.32	1.36	1.37	1.40	1.46	1.38	0.039

Table 3.18. Descriptive statistics for the factor variable FV_3-sub-surface soil conditions (SBC) for soil properties measured at 15 to 30 cm depth. Shelton, NE, 1997/98

Variable	Class	Min	25%	Median	75%	Max	Mean	S.D.
$PH_{1:1\text{-water}}$	C	4.70	4.87	4.93	5.22	5.79	5.07	0.340
	B	4.89	5.09	5.21	5.30	5.60	5.21	0.170
	A	5.40	5.79	6.34	6.45	7.17	6.24	0.520
$EC_{1:1\text{-water}}$	C	0.11	0.12	0.13	0.13	0.15	0.13	0.011
($dS\ m^{-1}$)	B	0.12	0.15	0.16	0.18	0.22	0.16	0.025
	A	0.21	0.25	0.27	0.28	0.37	0.28	0.047
P	C	31	38	43	55	89	47	16
($kg\ ha^{-1}$)	B	32	42	48	55	84	49	13
	A	24	34	46	94	120	59	35
BD	C	1.76	1.83	1.84	1.87	1.94	1.85	0.057
($g\ cm^{-3}$)	B	1.64	1.70	1.73	1.77	1.84	1.73	0.051
	A	1.40	1.49	1.56	1.68	1.75	1.57	0.118

ASSESSING ON SITE SOIL AND ENVIRONMENTAL DEGRADATION

The research site has been cultivated for over twenty-five years, under intensive soil and crop management; initially moldboard plowing and most recently ridge till systems, irrigation and input of agrochemicals. Under these conditions, where long-term land use is known, information on the spatial variability of soil properties can be used as an indicator of soil degradation.

The existence of an uncultivated area located in close proximity to the experimental field and on similar soil and landscape elements (Figure 3.2) can be used as a reference point. This area has been under perennial grass for many years and represents a return to the natural vegetation. Because of the great difference in soil management (mainly tillage), the relative difference between soil property measure in these two areas could be used as indicator of soil degradation.

The soil properties selected for this propose were: pH as an indicator of acidification and inefficient N use; electrical conductivity (EC) indicating salinization, potential nutrient loss and biological conditions; bulk density (BD) as an indicator of compaction; and soil organic matter (SOM) and particulate organic matter (POM) as indicators of the effect of tillage in reducing soil organic matter.

The results of the analysis of these soil properties are summarized in Table 3.19. The main differences observed for soil properties between the two areas refer mainly to the pH at both depths, and organic matter, particulate organic matter, and bulk density measured at the 15 to 30 cm depth.

Table 3.19. Descriptive statistics of soil properties measured in the area with perennial grass and cultivated with corn. Shelton NE, 1998

Variable †	Transect	Crop	Statistical parameters					
			Min	Max	Median	Mean ‡	Std. Dev.	CV (%)
$PH_{1:1\text{-water}}$	01	**Grass**	**5.48**	**6.41**	**6.11**	**6.00a**	**0.35**	**5.8**
(0 – 15cm)	02	Corn	4.74	5.34	4.89	4.94b	0.19	3.8
	03	Corn	4.67	5.16	4.94	4.92b	0.15	3.0
	04	Corn	4.82	5.35	4.94	4.99b	0.16	3.3
	05	Corn	4.56	5.53	4.83	4.95b	0.34	7.0
$PH_{1:1\text{-water}}$	01	**Grass**	**5.72**	**6.81**	**6.41**	**6.31A**	**0.43**	**6.8**
(15 – 30cm)	02	Corn	4.70	6.42	5.25	5.40B	0.50	10.4
	03	Corn	4.89	6.76	5.28	5.41B	0.55	10.2
	04	Corn	4.83	5.79	5.24	5.30B	0.31	5.9
	05	Corn	4.93	7.17	5.15	5.63B	0.80	14.2
$EC_{1:1\text{-water}}$	01	**Grass**	**0.09**	**0.20**	**0.16**	**0.15a**	**0.05**	**29.7**
dS m^{-1}	02	Corn	0.14	0.23	0.17	0.17a	0.03	18.0
(0 – 15cm)	03	Corn	0.14	0.22	0.17	0.17a	0.03	15.2
	04	Corn	0.14	0.28	0.16	0.18a	0.04	22.2
	05	Corn	0.13	0.22	0.15	0.17a	0.04	22.6
$EC_{1:1\text{-water}}$	01	**Grass**	**0.10**	**0.21**	**0.13**	**0.14A**	**0.04**	**27.2**
dS m^{-1}	02	Corn	0.11	0.28	0.15	0.17A	0.06	35.1
(15 – 30cm)	03	Corn	0.12	0.37	0.18	0.19A	0.07	37.2
	04	Corn	0.12	0.25	0.15	0.16A	0.04	25.4
	05	Corn	0.12	0.35	0.16	0.20A	0.08	39.0
BD_m	01	**Grass**	**1.32**	**1.49**	**1.44**	**1.43a**	**0.06**	**4.3**
g cm^{-3}	02	Corn	1.37	1.58	1.50	1.49a	0.07	4.5
(0 – 15cm)	03	Corn	1.45	1.55	1.49	1.49a	0.04	2.7
	04	Corn	1.36	1.63	1.44	1.47a	0.09	6.1
	05	Corn	1.32	1.61	1.48	1.46a	0.10	7.1
BD_m	01	**Grass**	**1.37**	**1.71**	**1.50**	**1.54A**	**0.11**	**7.4**
g cm^{-3}	02	Corn	1.60	1.85	1.76	1.74B	0.08	4.6
(15 – 30cm)	03	Corn	1.40	1.86	1.74	1.71B	0.12	7.0
	04	Corn	1.55	1.94	1.73	1.74B	0.13	7.3
	05	Corn	1.43	1.91	1.72	1.70B	0.16	9.6
SOM	01	**Grass**	**30**	**63**	**41**	**43a**	**12**	**27.0**
Mg ha^{-1}	02	Corn	20	37	21	25b	7	26.0
(0 – 15cm)	03	Corn	21	39	29	29b	6	19.0
	04	Corn	21	41	31	31b	6	19.0
	05	Corn	18	44	25	29b	11	38.0
POM	01	**Grass**	**13**	**27**	**19**	**19a**	**5**	**24.2**
Mg ha^{-1}	02	Corn	9	13	11	11b	1	12.4
(0 – 15cm)	03	Corn	10	14	12	12b	1	11.7
	04	Corn	7	15	12	11b	3	22.0
	05	Corn	7	14	11	11b	2	19.0

† EC = electrical conductivity in a 1:1 soil/water mixture, SOM = soil organic matter, POM = particulate organic matter. ‡ Means followed by the same letters do not present significantly differences at 5% level by t-test.

The pH of the area under natural grass for both depths averaged (6.0), one unit higher than the field planted in corn (pH = 5.0) and indicating soil acidification due to conventional management. Presumably, the main factor causing acidification is associated with application of ammoniacal fertilizers. The significant negative correlation between pH and inorganic-N (r = - 0.40) supports this and is related in part to the lower buffer capacity of sandy soils.

Bulk density of surface soils (0 to 15 cm), were similar for both grass and corn areas (Table 3.19), but at the 15 to 30 cm depth, bulk densities were higher with corn, suggesting subsoil compaction. The negative correlation (r = - 0.76) observed between bulk density and grain yield, suggests a detrimental association of this property with corn growth and development. The average bulk density of 1.74 g cm^{-3} measured for the 0 to 30 cm depth in the area in corn, is close to the threshold values of 1.75 to 1.80 g cm^{-3} given by Arshad et al. (1996) as restricting for root growth on sandy soils. Bowen (1981), suggests values of 1.80 and 1.85 g cm^{-3} can impede root growth in sandy soils.

Soil organic matter contents also differed greatly between grassed and corn areas. The area with grass has an average of 34% (15 Mg ha^{-1}) more organic matter than the area cultivated in corn. Although residue additions to the soil occur every year in area annually cropped to corn, multiple cultivation reduces soil aggregate size, destroys residue, and hastens carbon oxidation and mineralization. Also, nitrogen application through irrigation water contributes to increased residue decomposition.

SUMMARY AND CONCLUSIONS

Spatial variability of soil physical and chemical properties and its relationships with corn growth and development was assessed in a sandy soil cultivated with corn in central Nebraska. Field studies involved extensive soil sampling, measurement of plant population, leaf tissue composition, and grain yields during the 1997 and 1998 growing seasons. Classical statistics, geostatistics, factor analysis, and multiple linear regressions were used as the principal techniques to explore soil and crop variability, the nature of interactions that might affect crop yield, and to classify and map status of soil properties in the field.

Spatial distribution of grain yields was similar in both years. Grain yields ranged from 11 to 14 Mg ha^{-1} and averaged 12.5 Mg ha^{-1}. Plant populations varied from 62 to 73 thousand plants per hectare across the field but were not consistently related to grain yield.

Factor analysis was found a useful tool in analyzing associations of systematic soil variation within the experimental field. Most of the soil variation as related to crop growth was described by five factors, which collectively explained 85% of the total soil variability. Regression models based on these factors were associated with 50% of the corn yield variation. The results suggest that soil physical-chemical factor, as related to organic matter, texture, bulk density, and pH has a large effect on the variation of corn yield. Soil inherent fertility and fertilizers factors had little relationship with grain yield mainly due to high levels of measured nutrients in the field and fertilizers applied by the farmer. Contour maps based on the score of each factor were useful in displaying the pattern of soil variation in the experimental field.

The beginning of soil degradation associated with corn production was assessed by comparing field soil properties under corn management to those under perennial grass. Loss of organic matter, due mainly to intensive tillage and input of fertilizers, mainly nitrogen, acidification associated with application of ammoniacal fertilizer, and subsoil compaction were some indicators of this degradation. As indicated by some soil properties measured in field, the actual systems of soil and crop management used by the farmer resulted in reduced soil quality and increased environmental degradation. Additional inputs of fossil fuel derived energy in irrigation and fertilizers will be necessary to sustain the high levels of corn production which will likely lead to further soil and environmental degradation.

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