The influence of soil series on cereal grain yield
by Michael Herbert Larson

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Soils
Montana State University

Abstract:
Knowledge of the productivity potential of each soil in a field can assist land managers in making management decisions. Producers can realize greater returns on their investments if they use soil performance data to set realistic yield goals, recognize yield limiting soil properties, and learn to farm soils instead of fields.

We collected and compared soil performance data for twenty-one important agricultural soils in Montana. Within a given field, five plots were located for each of two or three different soil series. Each plot was evaluated for grain yield and selected chemical, physical, and morphological, characteristics.

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Fertilizer recommendations based on soil test values were made for individual soil series compared to the entire field, This analysis provides evidence of the benefit of managing individual soil series according to their potential. Soil performance data can be applied to soil survey maps, aerial photographs, and other types of yield maps to assist the producer in managing soils according to their potentials.

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MICHAEL HERBERT LARSON

A thesis submitted in partial fulfillment
of the requirements for the degree

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APPROVAL

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Michael Herbert Larson

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

Knowledge of the productivity potential of each soil in a field can assist land managers in making management decisions. Producers can realize greater returns on their investments if they use soil performance data to set realistic yield goals, recognize yield limiting soil properties, and learn to farm soils instead of fields.

We collected and compared soil performance data for twenty-one important agricultural soils in Montana. Within a given field, five plots were located for each of two or three different soil series. Each plot was evaluated for grain yield and selected chemical, physical, and morphological characteristics.

Yield differences between soil series in the same field ranged from 0.07 to 1.88 Mg/ha (1 to 28 Bu/A). Following harvest, soils were analyzed to a depth of 120 cm for nitrogen, phosphorus, potassium, organic matter, electrical conductivity, and pH. Morphological properties measured included depth to calcium carbonate, available water holding capacity, water use, and clay content. Depth to calcium carbonate, organic matter content (0-15 cm), and soil pH (0-15 cm) proved to be the most yield-limiting soil properties according to stepwise regression analysis ($r^2 = .83$). It appears that these properties in turn are related to available soil phosphorus (0-15 cm) and available water holding capacity of soil profiles.

Fertilizer recommendations based on soil test values were made for individual soil series compared to the entire field. This analysis provides evidence of the benefit of managing individual soil series according to their potential. Soil performance data can be applied to soil survey maps, aerial photographs, and other types of yield maps to assist the producer in managing soils according to their potentials.

INTRODUCTION

To realize optimum crop production for a crop-soil system, it is necessary to characterize soil and plant growth relationships. The influence of soil nutrients, water and other soil characteristics on crop production have been studied for decades. Recently, the importance of the interrelationships among plant characteristics and population, soil moisture and fertility, soil morphological properties, temperature, topography and many other variables which can influence crop yield and quality has been recognized.

Only a limited number of quantitative investigations of cereal grain yield in relation to soil series have been undertaken. This kind of information can help farmers make decisions about cropping systems, tillage, and fertilizer application based on each soil's yield capabilities and properties.

Collecting soil performance data makes it possible to set realistic crop yield goals for important agricultural soils. The data can become an integral part of soil survey reports, providing farm managers a means for improving their management decisions. Overall usefulness of a soil survey will be increased from an agronomic standpoint.

The objectives of this study were to: 1) obtain soil performance data for 21 agricultural soils in Montana, 2) identify soil properties related to yield performance of soil series occurring in sequence in a single field, and 3) evaluate opportunities for managing soil series differently.

LITERATURE REVIEW

This section reviews research findings of four areas: 1) soil performance studies, 2) topographical influence on crop yield, 3) calcium carbonate influence on crop yield and, 4) soil variability.

SOIL PERFORMANCE STUDIES

Soil performance studies are directed toward two objectives simultaneously: 1) to provide crop yield data for representative soils and 2) to determine soil properties related to yield. Although some soil performance studies have been completed, most fail to provide adequate information on the yield of the same crop on different soils and few attempt to identify yield-limiting soil properties.

Difficulties that arise in quantifying soil productivity are partially due to crop yields being a product of various management, genetic, and climatic factors as well as soil properties. In Montana and other dryland production areas, yearly moisture differences have the greatest influence on year-to-year differences in soil productivity.

Odell (1958) suggests that most soil performance studies are based on one of three methods which include: 1) producer surveys, 2) experiment station or farm record data and, 3) small plot experiments. The third method is the most precise method of gathering soil performance data.

Sampling crop yields on various soil series within the same field eliminates the variability associated with management and climatic factors so that yield differences can be attributed to soil properties associated with specific soil series. This type of experiment reduces the number of experimental variables. Management and climatic interactions and differences can be removed, so that the important chemical and morphological soil properties can be examined.

Many studies have been conducted to relate soil and crop productivity to soil type (Rennie and Clayton, 1960; Bennett, et al., Munn, et al., 1982; and Webb, et al., 1983).

Rennie and Clayton (1960) studied the significance of four local soil types to soil fertility in Saskatchewan. The criteria used to assess soil productivity included grain yield with and without fertilization, uptake of applied phosphorus fertilizer, and extractable phosphorus. Their data showed variability in yield and response to phosphorus even within small distances in a single field due to the soil variability. They suggested that differences in productivity were closely associated with pedogenic differences used to classify soils.

Bennett et al. (1980) found that soils distinguished by differing depths of fine textured material over gravels produced significantly different yields of spring barley under dryland conditions.

Munn et al. (1982) studied the effectiveness of the paired design compared to nonpaired sampling to establish yield differences between two soils developed on glacial till in northern Montana. Their findings showed that percent calcium carbonate was highly negatively correlated with spring wheat yields on the Scobey-Kevin complex, but more so on the Kevin soil than the Scobey soil.

Webb et al. (1983) concluded through regression analysis that available water holding capacity increased with depth of fine textured material over gravels ($r^2 = .92$). Consequently, a strong linear relationship ($r^2 = .90$) exists between yield and depth to gravels. They suggest the practice of mapping and defining soils according to their depth to underlying gravels.

TOPOGRAPHICAL INFLUENCE ON CROP YIELDS

Many of the agricultural soils in northern Montana were formed from calcareous glacial till parent material. An undulating to strongly rolling topography with slopes of 2% to 15% is characteristic of soils formed in glacial till. A catena or toposequence contains a continuum of soil profiles which have developed under a range of micro-environments caused by localized changes in relief (Bushnell, 1942). To a great extent, soil properties are influenced by landscape position. Lower slope positions are usually associated with better moisture, greater plant growth, increased water infiltration and percolation, greater organic matter content, and increased degree of horizon differentiation. On the other extreme, soils located at knoll positions are usually shallow, droughthy, and much more prone to severe erosion. In this study, the effect of soil properties and associated micro-climate was examined by sampling toposequences in each of several fields.

According to Larson (1981) erosion reduces productivity through the loss of plant-available water capacity. This subjects the crops to more frequent and severe water stress. He also states that erosion reduced root zone depth and is partially responsible for plant nutrient losses, degradation of soil structure, and ineffectiveness of pesticides.

Malo and Worcester (1975) noted the relationships of crop growth to landscape position in North Dakota. Sunflower response was studied at various landscape positions under uniform management. The shoulder and footslope positions showed decreases in plant heights, later blossoming dates, lower yields and smaller seed sizes when compared to the responses of the toeslope. Barley responses showed similar relationships to landscape position in 1973. They suggested the responses observed on the shoulder slope reflect the erosional and moisture stress conditions at this landscape position. They concluded that differences in plant responses to landscape position exist primarily because of changes in soils and their associated properties.

Webb (1983) used regression analysis to show that for every 1 cm increase in depth of fine material there was, on the average, a 36 kg/ha increase in the yield of oats and a 31 kg/ha increase in the yield of wheat.

In a study on the growth of winter wheat on a toposequence, in Washington, Ciha (1984), found differences in mean grain yield ranging from 0.45 to 1.90 Mg/ha when compared across slope positions. He concluded that in the Palouse, slope steepness can influence soil temperature, levels of soil erosion within a single year, quantity of snow present on the surface for protection against winter injury, and available soil moisture. He noted that it may become important in the future to identify specific cultivars for a slope position.

Ferguson and Gorby (1967) report that 15 kg of fertilizer P was needed for optimum production on well-drained soils but twice as much was needed for poorly drained soils. They thought this was due to the changes in microclimatic factors as affected by the slope shape, size and aspect.

Spratt and McIver (1972) initiated a study in Saskatchewan to determine whether fertilizer recommendations, based on soil tests, should be modified for various soils due to their topographical characteristics. They reported that, with or without fertilizer, the grain yields were lower at the crown of the hill and increased progressively down slope. Fertilizers did not increase the yield potential of the crown and midslope positions to the level of the lower slopes. They reported that basic soil factors of the soil catena affect yields of wheat more than the soil fertility and that fertilizers would not eliminate the large yield variation.

CALCIUM CARBONATE INFLUENCE ON CROP YIELD

The mineral calcite ($CaCO_3$) is present in soils that have developed in arid to humid climates. It may occur either in the original soil parent material or as a result of pedogenic processes. With increasing rainfall, soil parent material is the important factor in determining geographic distribution. Harper (1957) reports that with increasing rainfall, the presence of calcic horizons are more confined to areas with strongly calcareous parent materials.

Many of Montana's soils have strongly calcareous parent material and limited moisture. Soil series are commonly distinguished by soil scientists on the basis of depth to calcium carbonate. Where soil moisture deficits occur in most seasons, soils with greater depth to calcium carbonate (higher water holding capacities) will usually support higher yielding crops.

The longer a parent material has been exposed to processes of soil formation, the greater the soil profile development. The estimated time for development of a calcium carbonate enriched Ck horizon is approximately 10,000 years (Buol, et al., 1973).

Calcium carbonate horizons are thought to roughly indicate the average annual depth of water penetration, that is, the depth to which salts are leached. Although water sometimes passes through $CaCO_3$-enriched horizons, these are the layers that tend to dry out last and therefore become the place where relatively insoluble calcium carbonate precipitates from the soil solution.

Soils with shallow carbonate depth are common in semiarid regions especially where they have been subject to severe erosion due to cultivation. Erosive sites are prone to a number of environmental and soil factors that reduce productivity. They include high soil temperature, lower available soil moisture, low organic matter content, and shallow depth of mineral horizons (A and B horizons).

Plant nutrient availability is often suppressed by an abundance of free calcium carbonate in the soil (Larsen, 1967; Spratt and McIver, 1972; Mortvedt, 1976; Karathanasis et al., 1980; Webb, 1983; Munn et al., 1982).

Larsen (1967) suggests the P labile pool is constantly transferred to non-labile pools in the presence of $CaCO_3$. He postulates that as P fertilizer is added to the soil in the monocalcium phosphate form, it moves as a concentrated solution of dicalcium phosphate. As it moves, soluble P may react with $CaCO_3$ to form a precipitate of phosphate minerals.

Spratt and McIver (1972) studied crop response to P fertilizer on eroded sites in Manitoba. They suggested that soils high in Ca content may either limit plant nutrient uptake or rooting tendency. Their findings also indicate that basic pedological and microclimatological factors of the soil catena affect yields of wheat more than soil fertility and fertilizers.

Mortvedt (1976) postulates that shallow depth to $CaCO_3$ may cause stunted plant growth as a result of P and micronutrient immobilization. Karathanasis et al. (1980) studied grain yields at international sites. Their results showed low yields on highly calcareous soils.

In evaluating selected soil and climatic variables in Montana Burke (1982) reported depth to calcium carbonate as positively correlated with cereal grain yield. Dry consistence of the Ck horizon was also positively correlated with yield, due to its positive correlation with greater depth to Ck and fine texture.

SOIL VARIABILITY

Commonly, in fields one observes plant responses to soil differences. Such "spots" in fields are a problem for farmers, because these areas need different management than other parts of the field.

Soil surveyors attempt to group similar soil areas together as mapping units, in which the soil is expected to be homogenous or is at least easily recognized from slope position or other features. However, many inclusions of other soils cannot be shown in standard soil survey reports because areas smaller than about 5 acres are too small to show on standard aerial photographs and maps.

An important consideration for any soil-site study is the physical and chemical variability, either within a soil series (Wilding et al., 1965; Cipra et al., 1972; Lee et al., 1975), or within a soil cartographic unit (mapping unit) (Adams and Wilde, 1976; Beckett and Webster, 1971; Bascomb and Jarvis, 1976).

Wilding et al., (1965) and Adams and Wilde, (1976) discussed that with the increasing variety of uses which soil surveys now serve in both urban and rural areas, a greater emphasis must be placed on more accurate and quantitative definitions of the basic interpretative elements of surveys.

In a study of the Richfield silt loam, Cipra et al., (1972), determined soil fertility variation among pedons separated by 3 m, 90 m, and from 8 to 145 km. They report that variation among pedons 3 m apart contributed only slightly to total variation while pedons 90 m apart contributed substantially to total variation within the soil series.

They contend that to estimate the soil series mean by ±10%, some fertility tests would require as many as 175 fields; others only two fields.

Assessment of the soil factor can be complicated by variations in climate, fertility levels, and rotation effects according to Lee et al., (1975) when studying wheat yields from four soil series. They concluded that for more accurate predictions of soil cropping potential, a subdivision into soil types and phases would be desirable.

Beckett and Webster (1971) studied the variability of soil properties within mapping units. They separated soil properties into three groups: 1) Those which are only slightly affected by management, such as sand, silt, and clay, plastic and liquid limits, thickness of horizon, and total P, 2) properties such as organic matter, cation exchange capacity, and nitrogen and 3) properties most affected by management such as available P, Mg, Ca, and K. Those properties most affected by management were consistently more variable than the others.

Bascomb and Jarvis (1976) examined the variability in three areas of the Denchworth soil map unit in England. They also reported that the properties influenced by management were the most variable. They suggested that Denchworth soils can be managed uniformly for land uses dependent upon physical properties of soil. But, the variability of soluble phosphorus precluded the use of a soil map as a guide to fertilizer application and little was achieved for that aspect of management. They suggested mapping soluble phosphorus distribution within fields.

MATERIALS AND METHODS

LOCATION

The study sites are located in Chouteau County, in north central Montana (Fig.1). It is presently being mapped under the National Cooperative Soil Survey program and is scheduled for completion in about 1990. Most of the economy is based on cereal grain agriculture. This county was selected for study because 1) there were many fields with at least two contrasting soil series within its boundaries 2) the area ranks within the top two counties in the state for wheat and barley production, and 3) the soil survey crew was particularly interested in assisting with the initial mapping and interpretation of the respective soil series.

SOIL FORMING FACTORS

The factors affecting soil formation in this area include: 1) geologic parent material, 2) climate, 3) topography, 4) plants and animals, and 5) time.

Parent materials of the study sites in Chouteau County were deposited by the Laurentide continental ice sheet. The resultant glacial till is derived from the soft black shale unit of the Colorado Shale. The till is predominately calcareous loam and clay loam.

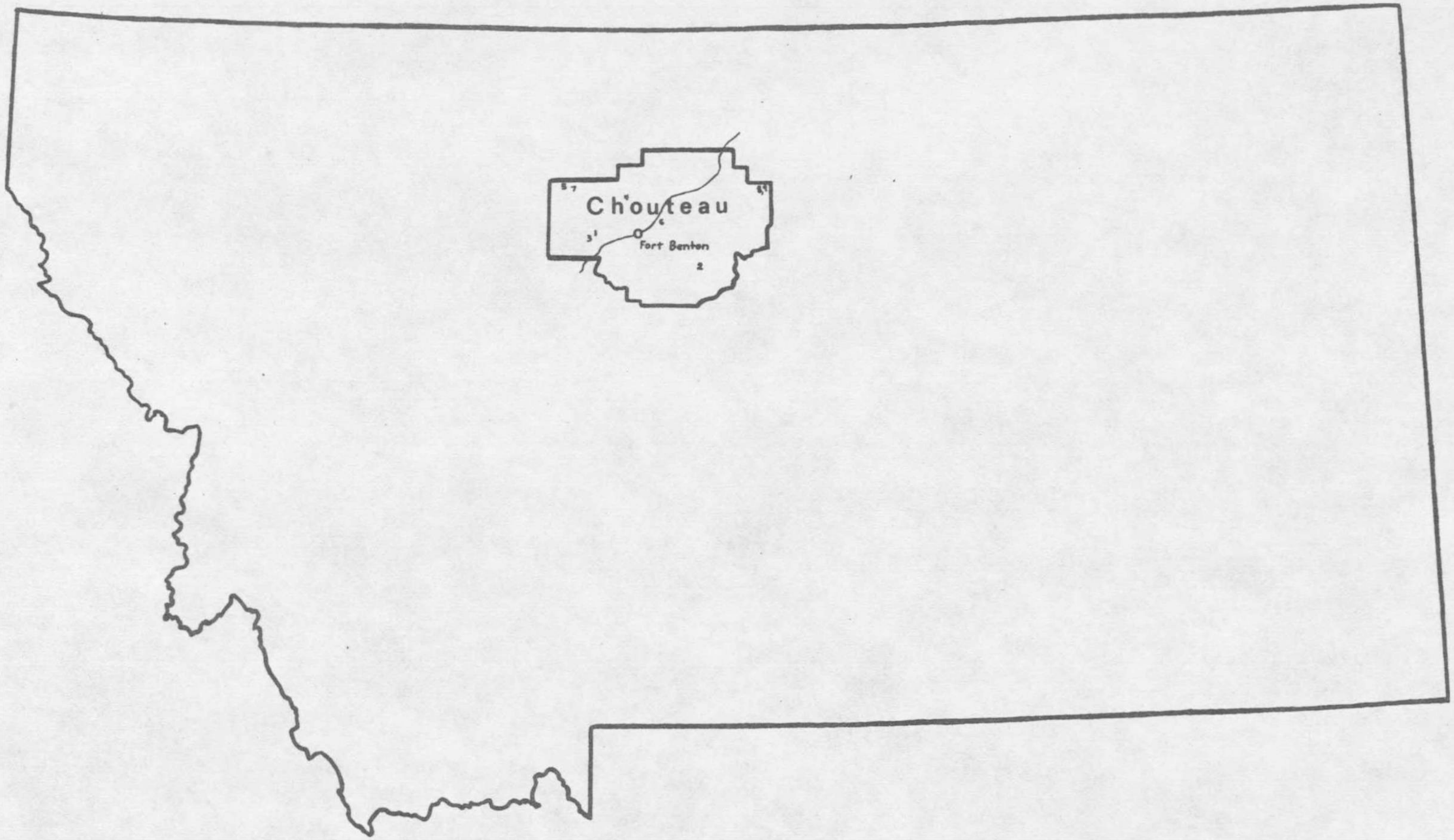


Figure 1. Location of Study Sites.

The climate of Chouteau County is continental characterized by long, cold winters and warm summers although warm chinook-like winds are common during the winter months. The average annual precipitation ranges from 30 to 40 cm (12-18 inches). The mean annual temperature ranges from 6^{o} C to 7^{o} C (42^{o}-45^{o} F). The length of growing season averages 125 days during which time 60% of the total annual rainfall falls (Caprio et al., 1980).

The topography of Chouteau County results from the glacial advance of the Laurentide Continental ice sheet. The ice rounded the topography, smoothing hills, leaving depressions, and burying former valleys. During the past century, intensive agriculture and resultant soil erosion, have further influenced the natural topography.

Native climax vegetation was dominated by green needlegrass, western wheatgrass, needleandthread, blue gramma, and little bluestem (Soil Conservation Service, 1976). Vegetation influences soil properties in several ways. Organic acids reduce soil pH and increase chemical weathering. Organic matter increases with amount of vegetation undergoing microbial decomposition.

Parent materials of the study soils were deposited about 15,000 years ago as glacial till, outwash, and lake sediments (Klages and Montagne, 1985). The minerology of glacial deposits is determined by the kinds of rock formations from which they have been derived. Many of the northern Montana deposits are calcareous, which indicates that limestone has been one of the important source rocks.

DESCRIPTION OF SOIL SERIES STUDIED

Soil series are soils that are grouped together because they have similar profile characteristics with the exception of Ap texture. The primary use of soil series in the classification system is to relate the polypedons represented on detailed soil maps to soil taxa and to the interpretations that may follow (Soil Taxonomy, 1975). This and the following sections describe the soil series used in this study. Appendix A contains the complete Soil Conservation Service Soil Interpretation Record for each soil series. Table 1 shows the soil series studied and their classification according to Soil Taxonomy, 1975.

Soils at sites 1-4 were studied in detail whereas sites 5-8 were examined less intensively to provide a larger data base for yield comparisons between soil series. Sites 5-8 provide excellent opportunities for future related research.

The following groups of associated soils were studied in detail and will be discussed by site. Information about each soil association is based on field observation and personal communication with SCS Soil Survey party leader, Neal Svendsen.

Site number	Soil Association
1	Ethridge - Lonna
2	Bearpaw - Vida - Zahill
3	Scobey - Kevin - Hillon
4	Telstad - Joplin - Hillon

Table 1. Classification of Soil Series Studied.*

Site	Soil Series	Subgroup	Family
1	Ethridge	Aridic Argiborolls	fine, montmorillonitic
	Lonna	Borollic Camborthids	fine-silty, mixed
2	Bearpaw	Typic Argiborolls	fine, montmorillonitic
	Vida	Typic Argiborolls	fine-loamy, mixed
	Zahill	Typic Ustorthents	fine-loamy, mixed (calcareous)
3	Scobey	Typic Argiborolls	fine, montmorillonitic
	Kevin	Aridic Argiborolls	fine-loamy, mixed
	Hillon	Ustic Torriorthents	fine-loamy, mixed (calcareous)
4	Telstad	Aridic Argiborolls	fine-loamy, mixed
	Joplin	Aridic Argiborolls	fine-loamy, mixed
	Hillon	(see site 3)	
5	Kobar	Borollic Camborthids	fine, montmorillonitic
	Marvan	Ustertic Torriorthents	fine, montmorillonitic (calcareous)
6	Chinook	Aridic Haploborolls	coarse-loamy, mixed
	Yetull	Ustic Torripsamments	mixed, frigid
7	Ethridge	(see site 1)	
	Marias	Udorthentic Chromusterts	fine, montmorillonitic (calcareous) frigid
8	Attewan	Aridic Argiborolls	fine-loamy, mixed
	Telstad	(see site 4)	
9**	Attewan	(see site 8)	
	Telstad	(see site 4)	

* Classification according to Soil Taxonomy (Soil Survey staff, 1975).
**Irrigated site

Site 1 soils are not as extensive in North-Central Montana as the glacial till soils of sites 2-4. Ethridge and Lonna were chosen to compare soils with differences that are primarily related to morphology instead of topography.

Sites 2-4 include glacial till soils that are very extensive in cereal grain producing areas of Montana. Figure 2 illustrates a block diagram of a typical glacial till landscape. Topography and landscape position play a major role in the development of these soils. Soil morphological expressions of development include differences in water holding capacity, depth to calcium carbonate, and clay content.

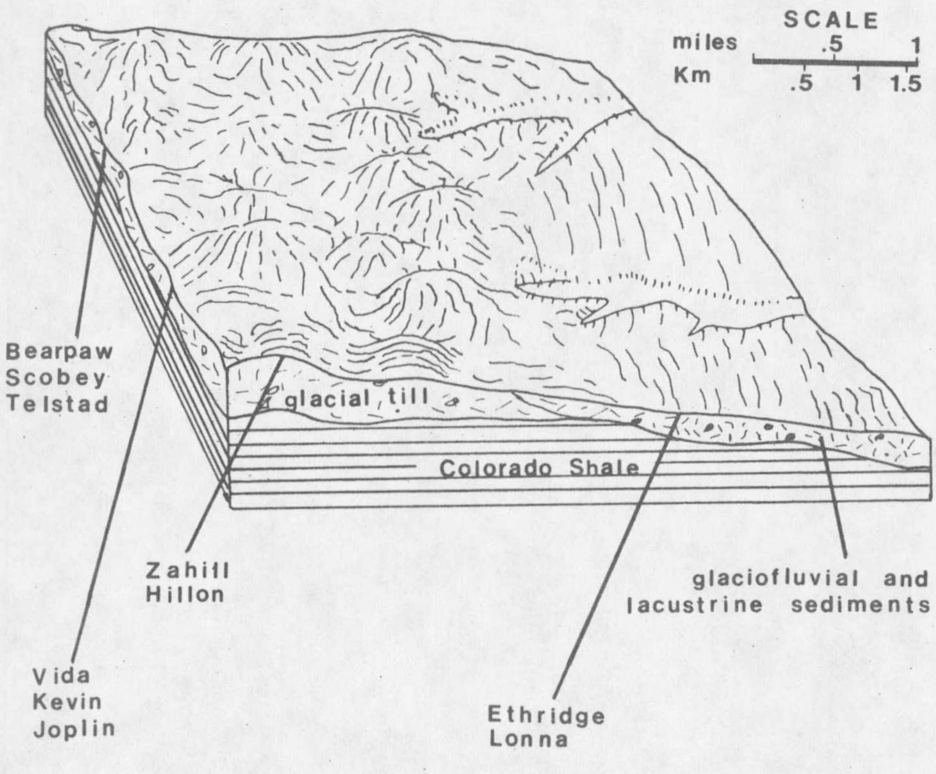
Ethridge-Lonna (Site 1)

The Ethridge-Lonna soils are primarily in the southwest part of the county. The average annual precipitation is about 30 cm (12 inches), the frost free period averages 120 days, and the mean annual air temperature (MAAT) is 44° F. The Ethridge samples were from an area of Ethridge silty clay loam, on 0-2% slopes. The Lonna was sampled in an adjacent area of Lonna silty clay loam with similar slope. Both soils formed in glaciofluvial or glaciolacustrine deposits quite possibly associated with glacial lake Great Falls.

Ethridge soils are deep, well-drained, fine, montmorillonitic Aridic Argiborolls. They are generally silty clay loam throughout with a well-developed argillic horizon. Calcium carbonate accumulations are typically at depths of 25 to 35 cm (10 to 14 inches).

Lonna soils are deep, well-drained, fine-silty, mixed Borollic Camborthids. They are also silty clay loams throughout but have a

Figure 2. Typical Glacial Till Landscape.



calcareous cambic horizon rather than an argillic horizon.

The morphological differences in these soils are difficult to explain. They are both on smooth, nearly level and stable landscapes, about the same age and formed in the same parent material, yet the Ethridge soil has a mollic epipedon and argillic horizon while the Lonna soil is ochric with a cambic horizon. Erosion processes combined with mixing of the Bk horizon may have changed the Lonna from a Mollisol to the present calcareous Camborthid. The Lonna soils are significantly lower in organic matter and do not have the desirable soil structure of the Ethridge soils.

Bearpaw-Vida-Zahill (Site 2)

These soils were sampled in the south-central part of the county near Geraldine, Montana where the average annual precipitation is about 40 cm (16 inches), the frost free season is about 125 days, and MAAT is about 45° F. The parent material is undulating and gently rolling clay loam continental glacial till. The samples were taken from areas of Bearpaw and Vida clay loams, 0-4% slopes and 4-8% slopes respectively. The Zahill soil is an important inclusion in these mapping units, particularly where slopes range from 4-8%.

Bearpaw soils are deep, well-drained, fine, montmorillonitic Typic Argiborolls. They occur in low-lying smooth, depositional areas. Calcium carbonate accumulations are at depths of 25-40 cm (10-16 inches).

Vida soils are deep, well-drained, fine-loamy, mixed, Typic Argiborolls. They occur on intermediate to upper slope positions. Calcium carbonate accumulations are at depths of 15-25 cm (6-10 inches).

Zahill soils are deep, well-drained, fine-loamy, mixed (calcareous), frigid, Typic Ustorthents. They occupy the knoll and ridge positions of the landscape. Calcium carbonate is present at the soil surface and throughout.

The Bearpaw-Vida-Zahill association is very similar to the Scobey-Kevin-Hillon association except the latter occurs in higher rainfall areas (Ustic moisture regime vs. Aridic).

Scobey-Kevin-Hillon (Site 3)

These soils were sampled in the southwestern part of the county. Climatic conditions are similar to the Ethridge-Lonna site. These soils developed in clay loam continental glacial till. The plots were selected from an area of Scobey-Kevin clay loams, with 0-4% slopes. Hillon is an inclusion in this mapping unit.

Scobey soils are deep, well-drained, fine, montmorillonitic, Aridic Argiborolls. They are on the lower, depositional slopes. Depth to calcium carbonate ranges from 25-40 cm (10-16 inches).

Kevin soils are deep, well-drained, fine-loamy, mixed, Aridic Argiborolls. Its landscape position ranges from lower to intermediate slopes. Calcium carbonate accumulates below the 15-25 cm (6-10 inches) depth.

Hillon soils are deep, well-drained, fine-loamy, mixed (calcareous), frigid, Ustic Torriorthents. They occur on the knoll positions and eroded upper sideslopes. Hillon soils are calcareous at the surface.

Telstad-Joplin-Hillon (Site 4)

These soils were sampled in the west central part of Chouteau county. The average precipitation is about 33 cm (13 inches), the frost free period about 120 days, and the MAAT is about 44° F. The parent material is loam or clay loam continental glacial till on an undulating to gently rolling landscape. Sample plots were in areas mapped as Telstad-Joplin loams with 0-4% and 4-8% slopes. Much like Site 3, Hillon soils are major inclusions in this mapping unit.

Telstad soils are deep, well-drained, fine-loamy, mixed, Aridic Argiborolls. They are on lower slopes and smooth areas. Calcium carbonate accumulations are at depths of 25-40 cm (10-16 inches).

Joplin soils are deep, well-drained, fine-loamy, mixed, Aridic Argiborolls. They occur on upper side slopes of knolls and occasionally on knoll tops. Calcium carbonate accumulations are at depths of 15-25 cm (6-10 inches).

Hillon soils are similar to those described for site 3 except they are mainly loams rather than clay loams throughout the soil profile.

FIELD METHODS

Field Selection

Four key soil performance sites (sites 1-4), plus four additional sites (sites 5-8) were selected in April of 1984 with the assistance of SCS soil survey party leader for Chouteau County, Neal Svendsen and retired soil scientist, June Haigh.

A single field-single producer approach was used to ensure uniform management of each soil performance site. At the time of field selection, management data questionnaires were filled out for each cooperator. A sample questionnaire appears in Appendix B. Management questionnaires are summarized in Appendix C. All sites were commercial cereal grain production fields that received recommended fertilizer rates, crop varieties, plant population, and pesticides. Crop rotation was generally winter wheat-fallow-spring wheat or barley with an occasional crop of sunflower or safflower. Management and climate were assumed to be constant throughout the respective fields so that soil effects on crop yields could be examined.

A goal of this study was to discover an efficient and effective method of collecting soil performance data. The method must accurately assess soil series' yield performance under Montana conditions. The method must also allow for collection of chemical and morphological data so that the yield-limiting properties of a particular soil series can eventually be understood.

Plot Selection

Following verification of the soil series by field investigation, small plots were staked out along transects. Plots were chosen by selecting an area of the designated soil series that was apparently within the range of characteristics defined by SCS. Morphological properties such as depth to calcium carbonate, presence of an argillic horizon, and clay percentage of the Ap and B horizons were important means of identification.

For each soil series, five plots (replications) were marked with dimensions dependent on row width. Plot size was 100 cm wide x 240 cm long, for 25 cm row width, 120 cm wide x 240 cm long for 30 cm rows, and

140 cm wide x 240 cm long for 35 cm rows. Plot size was measured with a steel tape. Figure 3 illustrates plot locations for sites 1-4.

Field Measurements

At the beginning of the growing season, depth of spring soil water was determined for all plots using the Brown soil moisture probe. Measurements of slope percent, aspect, and landscape position (concave or convex) were made for each plot.

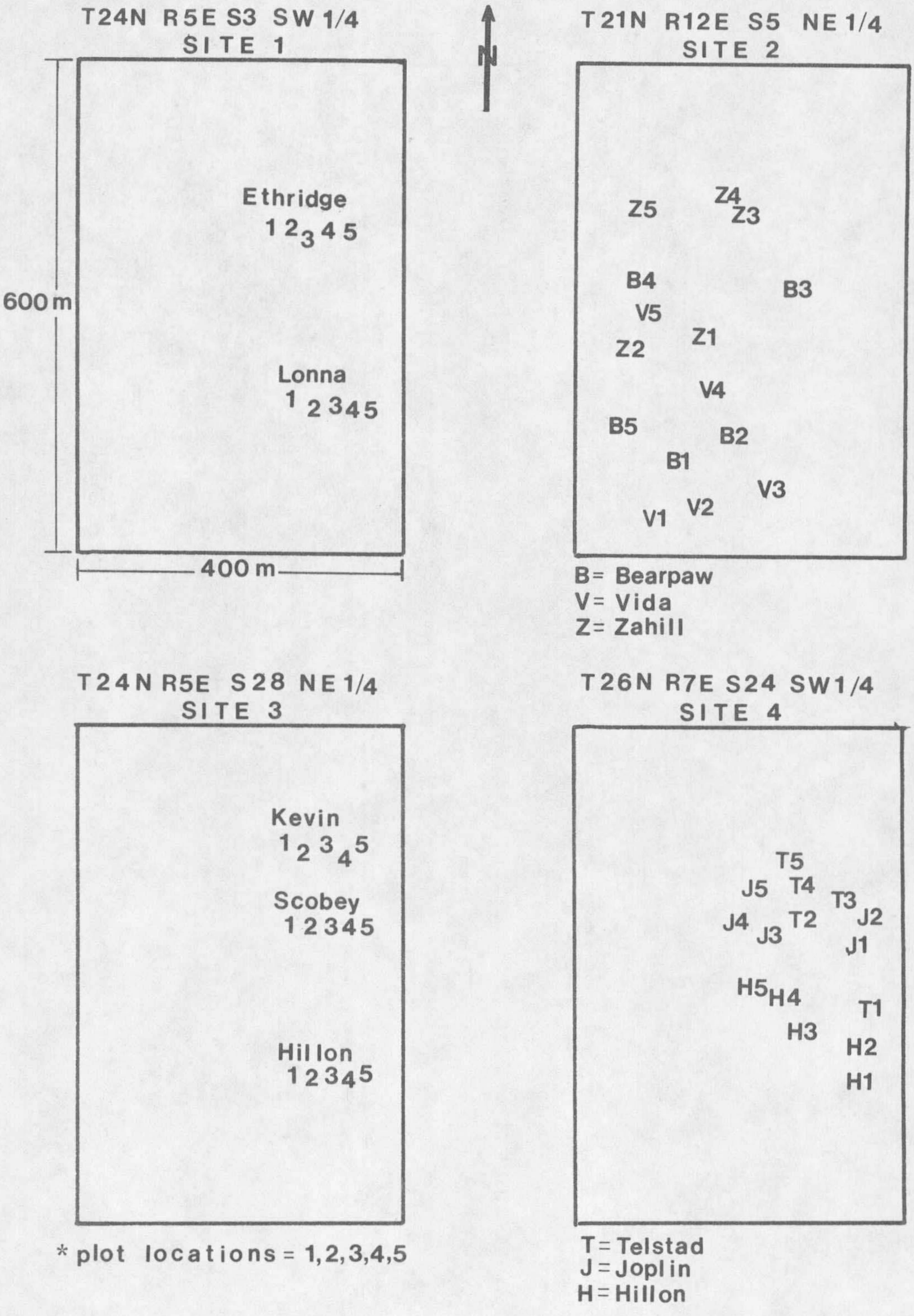
Crop Sampling

Crop samples were collected to study the influence of soil series on crop yield. In most cases, differences in crop density and overall vigor were observable in the field and reflected influences of the contrasting soil series.

Wheat samples were collected in late July of 1984 to determine yield differences between soils. Percent protein, test weight, and number of plants per plot were also measured. Test weight for individual samples was used to calculate yield. These data are presented in Appendix E for general information and future reference.

The entire plot area was hand-harvested with an electric clipper. Samples were bagged for each respective plot, tagged, and returned to Montana State University storage. After allowing the grain to dry, it was threshed, cleaned, and weighed to determine grain yield for each plot.

Figure 3. Plot Locations* for Sites 1-4.



* plot locations = 1,2,3,4,5

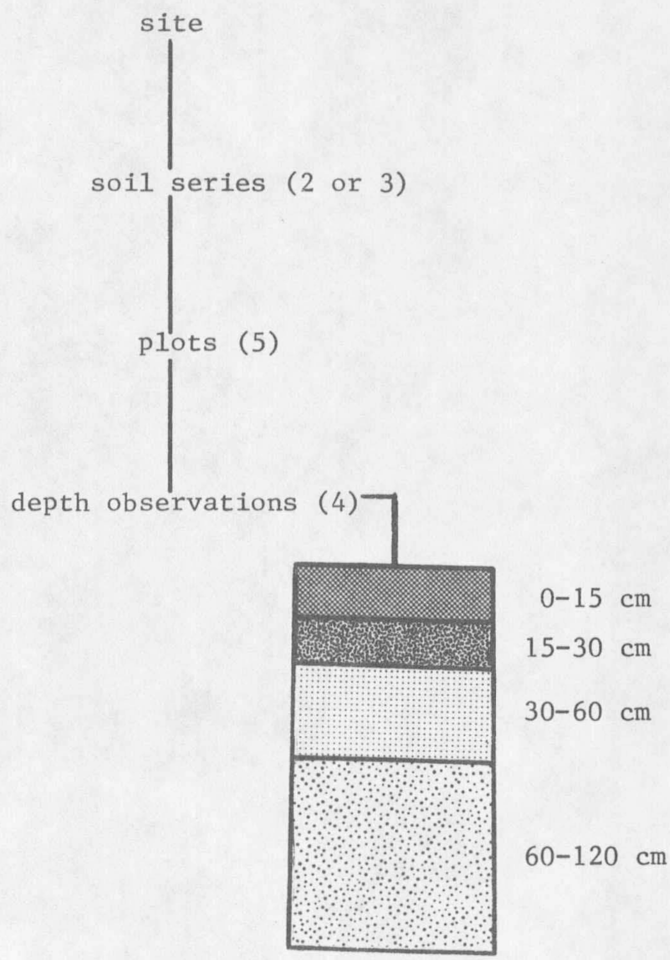
Soil Sampling

Following crop harvest of all plots, the sites were revisited and soil samples were taken with a Giddings soil hydraulic probe to a depth of 120 cm, using a 7.5 cm diameter probe. The probe was inserted at several locations within each plot to obtain a composite sample.

For chemical analysis, composite samples (1 quart) were taken from each of four depth increments of 0-15 cm, 15-30 cm, 30-60 cm, and 60-120 cm. Thus, there were samples from five plots, with four depth increments per plot totaling 20 samples for each soil series (Figure 4). Samples were bagged, and returned to Montana State University soil testing lab for chemical analysis including pH (2:1), organic matter, Olsen-phosphorus, extractable potassium, nitrate-nitrogen, and electrical conductivity.

Soil morphological properties were measured for each plot at the time of soil sampling. Measurements included depth to calcium carbonate as determined by effervescence with a ten percent solution of hydrocholoric acid (HCl), depth of respective soil horizons, and estimated clay percentage of the Ap and B horizons. Additional analysis of clay percentage and gravimetric water content was carried out at the Montana State soil classification laboratory.

Figure 4. Soil Sampling Design.



LABORATORY METHODS

Soil Chemical Analysis

All soil samples were air dried in a forced-air oven at 55°-60° C for 48 hours. Samples were crushed with a mechanical mortar and passed through a ten mesh sieve. Standard Montana soil testing laboratory procedures for field soils were used in determining soil pH, extractable phosphorus, extractable potassium, nitrate, organic matter, and electrical conductivity. Brief descriptions of each analysis follow:

Soil pH. Soil reaction was measured in a 1:2 soil to water paste after a 30 minute equilibration. The determination was made by glass electrode.

Electrical Conductivity. Filtrate from the soil reaction test was used for electrical conductivity measurement by conductivity bridge. Results were converted to saturated paste values by the equation: $Y = 3X + .07$ for X above 7 mmhos/cm and $Y = 4X$ for X below 7 mmhos/cm; Y = estimated saturated paste value and X = EC values.

Soil Phosphorus. Extractable phosphorus was determined by the Olsen method as described by Olsen et al. (1954). This method consists of extracting soil samples with 0.5 N $NaHCO_3$ buffered at pH 8.5. The extract was treated according to the phosphomolybdate blue method of Murphy and Riley (1962).

Soil Potassium. The determination of extractable potassium was made by extracting soil samples with 1 N acetate solution buffered at pH 7.0. The sample was shaken for 30 minutes and the filtered extract is analyzed by flame emission on an atomic absorption spectrophotometer (Bower et al., 1952).

Soil Nitrogen. Nitrate-nitrogen was determined by cadmium reduction and colorimetric analysis as detailed by Sims and Jackson (1971).

Soil Organic Matter. Soil organic matter was determined by the modified Walkley-Black method as described by Sims and Haby (1970).

Soil Physical Analysis

At the time of oven drying, soil samples from the 30-60 cm and 60-120 cm depths were analyzed for gravimetric water content. This measurement provides some indication of any plant available water remaining in each soil profile after harvest. The 0-15 cm samples were not weighed because all were clearly too dry to contain available water. In addition, clay contents for each depth increment were determined by hand texturing and hydrometer method as described by Bouyoucos, (1936). This information was necessary to estimate available water holding capacity (AWHC) and water use for each profile.

Available Water Holding Capacity. The Decker equation as described by Decker (1972) was used to estimate AWHC. The equation is as follows:

$$\text{AWHC (weight)} = 2 + 0.33\ (\text{clay }\%) + 0.5\ (\text{organic matter }\%)$$

Total AWHC for the 120 cm profile was then adjusted by adding growing season precipitation and subtracting 10 cm for plant emergence. AWHC by weight was converted to a volume basis using estimated bulk densities reported by Evans (1982).

Water Use. Water use was defined as profile AWHC minus water in the same profile at harvest according to gravimetric water measurements, plus growing season precipitation. The profile depth was assumed to be 120 cm at all sites.

Plant Analysis

Percent Protein. Grain samples taken at harvest were used to determine percent protein in grain by Technicon Near Infrared Analyzer (Infra Analyzer 400) method.

MANAGEMENT RECOMMENDATION PROCEDURE

To determine possible advantages of fertilizing by soil rather than on a field basis, fertilizer recommendations for winter wheat were taken from the Montana Small Grain Guide (Extension Bulletin 364). Recommendations of phosphorus (P_2O_5), potassium (K_2O), and nitrogen (N) are given in Tables 12-14 (page 55). These data make it possible to determine if soil series require different fertility levels to achieve their respective yield goals.

Soil series yield goals from SCS Soil Interpretation Records (10 year estimates) are reported in Appendix A. The author also communicated with SCS State Soil Scientist Staff concerning their yield value determinations. For comparison, actual average crop yields obtained during this project for the 1983-84 growing season were included.

STATISTICAL METHODS

Analyses of data were accomplished using Montana State University Statistical Analysis Program (MSUSTAT) (Lund, 1985) and Statistical Analysis System (SAS) (Helwig, 1978).

Soil Analysis

The experimental design for the soil properties measured was a nested design. There were four fields, two or three soil series per field, five sampling plots (replications) representing each soil series, and four depth observations at each sampling plot. Soil pH, extractable phosphorus, extractable potassium, nitrate-nitrogen, organic matter, and electrical conductivity were analyzed at 0-15, 15-30, 30-60, and 60-120 cm depths giving rise to 20 observations per soil series. Morphological properties described by depth increment include: estimated clay percentage available water holding capacity, and water use. Depth to calcium carbonate was determined for each soil during field plot selection.

Means, standard deviation, range, mean difference, standard error difference, and t-statistics were obtained from the MSUSTAT T-Grouped program. A one way analysis of variance was used to determine if there were significant differences in the means of soil properties between soil series within a single field.

To determine which of the soil variables contribute most to the dependent variable, yield, SAS stepwise multiple regression procedures were used for all eleven soil series combined and for individual soil series. Apart from this procedure, SAS maximum correlation coefficient (Max R) and Pearson's correlation matrix (Proc Corr) were conducted for all soil series to measure strength of relationship and multicollinearity effects between the means of all 29 soil variables studied. Significance levels were based on tables in Statistical Methods (Snedecor and Cochran, 1980).

Plant Analysis

To identify significant differences in the means of the crop yields among soil series pairs, a one way analysis of variance was used. The experimental design for crop yields was based on the assumption that the mean yield from five plots represents the soil series.

A T test (MSUSTAT T GROUPED) was used to determine if significant differences occurred between soils for crop yield.

Sample Number

In order to establish the number of experimental plots needed, one would need a preliminary study to determine the amount of variability within individual soil properties .

Sample number (n) is then calculated from the standard statistical equation: $n = \frac{t^2 s^2}{d^2}$ where n is the number of samples required; t is the tabulated t value for the desired confidence level; s is the standard deviation; and d is the allowable error.

For purpose of this study, it was decided that five plot areas per soil series would provide statistical significance for major variables and would be a workable sample size for the number of soil series examined.

Standard Statistics

To measure the variability of soil properties within a soil series, the mean, standard deviation, range and coefficient of variation of the properties measured was calculated. The mean is a measurement of central tendency, an average of all plots analyzed. The range includes the minimum and maximum value for each determination. Standard deviation (Snedecor and Cochran, 1980), is defined as:

$$sd = \sqrt{\frac{1}{n-1} \sum_{1}^{n} (xi - \bar{x})^2}$$

The coefficient of variation is the sample standard deviation expressed as a percentage of the sample mean.

$$cv = \frac{sd}{\bar{x}}$$

While the standard deviation is in the same units as the observations, coefficient of variation is a relative measure of variation (%).

RESULTS AND DISCUSSION

Results and discussion of the influence of soil series on cereal grain yield are presented in three sections; 1) soil performance data, 2) soil properties related to yield and 3) management opportunities. Cereal grain yield differences for all soil series are presented. A statistical evaluation of soil chemical and morphological data to determine the most important yield-limiting properties is given for Sites 1-4. The third section describes management opportunities for farming soils instead of fields based on soil test and fertilizer recommendations for Sites 1-4.

SOIL PERFORMANCE DATA

Crop Yield Comparisons Between Soil Series

One of the greatest benefits of a soil peformance study is that it provides a summary of actual cereal grain yields on various soil series. Yield differences between soil series for wheat (Triticum aestivum L.) and barley (Hordeum vulgare L.) are presented in Table 2. Yield differences ranged from only 0.04 Mg/ha (0.6 Bu/a) between the Bearpaw and Vida soil series, to a high of 1.86 Mg/ha (27.6 Bu/a) between Kobar and Marvan.

Of a total of 15 soil series comparisons, eight had significant differences at the 0.01 level with one additional soil series comparison being significantly different at the 0.05 level. Six of the total nine

Table 2. Grain Yield Differences Between Soil Series for All Sites.

Site	Soil Series	Yield Mg/ha	Yield Bu/a	Significance
1	Ethridge	2.85	42.3	**
	Lonna	2.49	36.9	
2	Bearpaw	4.05	60.2	**Z
	Vida	4.01	59.6	**Z
	Zahill	2.34	34.8	
3	Scobey	2.65	39.3	*K, **H
	Kevin	2.26	33.5	**H
	Hillon	1.92	28.5	
4	Telstad	2.49	37.0	
	Joplin	2.40	35.7	
	Hillon	2.17	32.2	
5	Kobar	2.66	39.5	**
	Marvan	0.80	11.9	
6	Chinook	2.29	34.1	
	Yetull	1.99	29.6	
7	Marias	2.45	36.2	
	Ethridge	2.36	35.1	
8	Telstad	1.67	24.9	**
	Attewan	0.69	10.2	
9¶	Telstad	6.54	97.2	**
	Attewan	6.08	90.4	

*, ** Significant differences between means at the 0.05 and 0.01 levels, respectively; letter indicates soil series comparison were significantly different.

¶ = irrigated site

soil performance sites had significantly different yields at the 0.05 level between soil series in the same field.

Compared to average growing season (May-July) rainfall data for these sites (20 to 30 cm), rainfall was approximately 12 cm below normal. Visual observations indicated greater water stress for soils occupying the shoulder and knoll positions of the landscape where the soil water regime is influenced by slope, runoff, and wind.

Figures 5 and 6 show the plot locations and soil profile characteristics in relation to crop yield for site 1 and sites 2-4 respectively.

Crop Yield Variability Within Soil Series

The variation in yield for a particular soil series may have been affected by microclimatological factors. Some of the variability may be due to variations in slope, aspect, and shape of plot area (concave or convex). Table 3 presents the mean yields with their standard deviation, range, and coefficient of variation for soil series at sites 1-4.

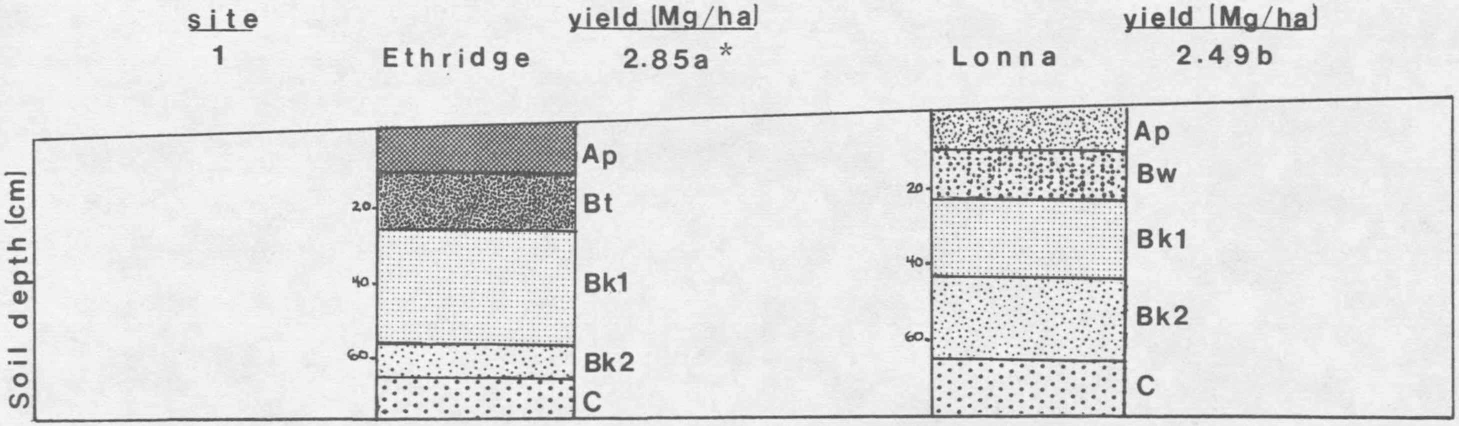
The Bearpaw, Scobey and Telstad glacial till soils occupying the toeslope landscape positions showed little plant water stress. On the other hand, plants on the Zahill and Hillon soils expressed plant water stress even though post-harvest soil water content determinations indicated they had greater subsoil water content (30-120 cm depth) than the depositional and midslope soil series. This suggests that plants grown on knoll positions may be incapable of taking up subsoil water, even though it exists.

Table 3. Means, Standard Deviations, Range, and Coefficient of Variation for Crop Yields at Sites 1-4.

Site	Soil Series	X	SD	Range	CV
		----------Mg/ha--------------			%
1	Ethridge	2.85	0.19	2.64-3.07	6.66
	Lonna	2.49	0.23	2.21-2.65	9.24
2	Bearpaw	4.05	0.30	3.62-4.43	7.41
	Vida	4.01	0.61	3.37-4.71	15.21
	Zahill	2.34	0.56	1.88-2.96	23.93
3	Scobey	2.65	0.39	2.17-3.02	14.72
	Kevin	2.26	0.16	2.02-2.46	7.07
	Hillon	1.92	0.13	1.80-2.13	6.77
4	Telstad	2.49	0.31	2.10-2.83	12.45
	Joplin	2.40	0.23	2.15-2.73	9.58
	Hillon	2.17	0.37	1.66-2.51	17.05

X = mean
SD = standard deviation
Range = minimum and maximum values
CV = coefficient of variation (%)

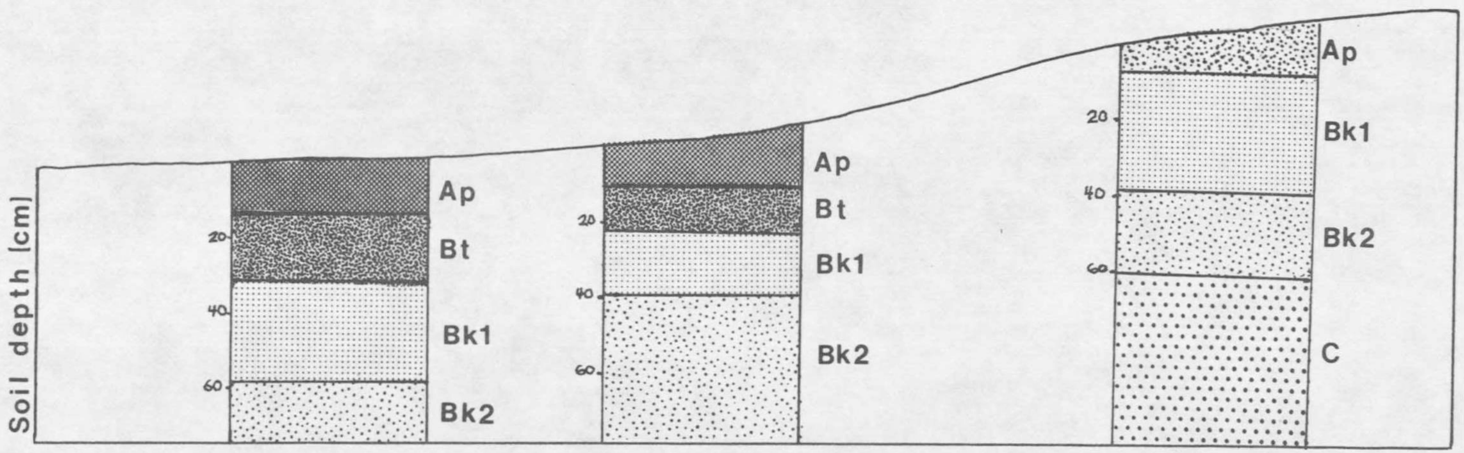
Figure 5. Wheat Yield at Site 1 in Relation to Soil Depth and Characteristics of Toposequence.



* Yield values followed by the same letter are not significantly different at p = 0.01.

Figure 6. Wheat Yield at Sites 2,3, and 4 in Relation to Soil Depth and Characteristics of Toposequence*.

site		yield (Mg/ha)		yield (Mg/ha)		yield (Mg/ha)
2	Bearpaw	4.04a**	Vida	4.01a	Zahill	2.34b
3	Scobey	2.65a	Kevin	2.26a' †	Hillon	1.92b
4	Telstad	2.49	Joplin	2.40	Hillon	2.17



* Soil series found at sites 2,3, and 4 have similar soil depths and landscape positions; see Appendix A for more detailed descriptions.

** Yield values followed by the same letter are not significantly different at p = 0.01.

† Yield values followed by the same letter ' are significantly different at p = 0.05.

Percentage yield differences were surprisingly similar between the Ethridge and Lonna (16%), Kevin and Hillon (19%), and Joplin and Hillon (13%). This may suggest that given similar landscape position and parent material, soils with calcium carbonate accumulation at or near the surface will yield about 16% less than soils with noncalcareous plow layers. This shows the importance of keeping the top 15-25 cm of a noncalcareous soil in place.

An evaluation of yield differences within individual soil series is beyond the scope of this study. However, more accurate assessment of soil series yield potentials may require closer examination of microclimatological factors. For example, soil series plots could be selected according to similar hydrological characteristics (slope, aspect, plot shape). Analysis of these characteristics might help explain yield differences within the same soil series.

Soil Performance Data Collection Methodology

The collection of soil performance data in this study systematically provided 1) realistic yield goals for soils, 2) information on the effects of soil properties on crop yield, and 3) a basis for management according to soil conditions.

Data collection plots were located across landscapes (toposequential testing) for which grain yield was measured and soil properties evaluated at each plot. Plots can be set up along a transect deliberately traversing soil boundaries.

To effectively measure soil performance data, uniform procedures are essential. The methodology used for this study proved to be an accurate and effective means of assessing crop yields across varying soil conditions. Although it was designed specifically for Montana conditions (Appendix B), the data can be implemented into the USDA Soil-Crop Yield Data Base (National Bulletin 430-3-12).

It may become important in the future to identify other important soil and crop variables that will improve the overall usefulness of this data.

SOIL PROPERTIES RELATED TO GRAIN YIELD

The second objective of this study was to determine the most important soil properties related to grain yield. This section uses two statistical methods of identifying soil properties related to yield differences between soil series at sites 1-4.

The means, standard deviations, ranges, coefficients of variation, and significance levels for soil chemical and morphological properties are presented in Appendix F. Soil factors that probably limited yield were selected on the basis of logic and common knowledge gained from the literature and personal communication. Although factors other than those discussed were also significantly different they are not discussed here because their roles as yield-limiting factors are not understood.

Selected Yield-Limiting Soil Properties

Ethridge - Lonna

Table 4 shows five soil properties related to yield differences between the Ethridge and Lonna soil series. Solum thickness is a soil feature which indicates a degree of profile development and/or weathering. Ethridge has a greater solum thickness and has undergone more development of profile and soil structure than Lonna. Lonna is subject to high wind erosion hazard whereas the hazard is moderate for Ethridge (Lonna is in wind erodibility group 4L, Ethridge in group 7). Ethridge soils have deeper depth to $CaCO_3$ and an argillic horizon (Bt) development which provides greater AWHC and water retention in the profile.

Ethridge has more favorable nutrient conditions for wheat growth. As shown in Table 4, Ethridge has three times more available phosphorus and double the extractable potassium in the Ap horizon. As previously mentioned, calcium carbonate is known to limit the availability of soil phosphorus in calcareous soils. Although the depth to $CaCO_3$ for Lonna was about 14 cm, field evidence of some $CaCO_3$ mixing within the Ap horizon by cultivation, may have further influenced nutrient availability. Differences in extractable potassium might be attributed to clay fixation or available water characteristics.

The significant differences in pH at the 0-15 cm depth reflect the addition of some $CaCO_3$ to this layer.

Table 4. Selected Factors (5 of 14*) Related to Yield Differences Between Ethridge and Lonna Soil Series at Site 1.

Soil Properties	Depth(cm)	Ethridge	Lonna
AWHC (cm)	0-120	23	18
$CaCO_3$ Depth (cm)		23	14
Olsen-P (mg/kg)	0-15	18	6
Extr-K (mg/kg)	0-15	596	287
pH 2:1	0-15	7.9	8.5
Yield (Mg/ha)		2.85	2.49
(Bu/a)		42.3	36.9

*minimum significance level = 0.05
N = 5
AWHC = available water holding capacity

Bearpaw - Zahill

Table 5 shows four soil properties related to yield differences between the Bearpaw and Zahill. Site 2 is a good example of rolling glacial till topography with approximately a 15 m variation in relief and with steepness of slope exceeding 15% in some areas.

Bearpaw occupies depositional areas and has a deep mollic epipedon. It is among the top yielding cereal grain producing soils in Montana. Bearpaw's high productivity potential is influenced by high Ap clay content, high phosphorus and potassium availability in the Ap, and depth to $CaCO_3$. In high rainfall years, runoff of soil and nutrients from the upper slope positions is likely to have a positive influence on Bearpaw's productivity.

Table 5. Selected Factors (4 of 12*) Related to Yield Differences Between Bearpaw and Zahill Soil Series at Site 2.

Soil Properties	Depth(cm)	Bearpaw	Zahill
Clay (%)	0-15	26	21
$CaCO_3$ Depth (cm)		41	0
Olsen-P (mg/kg)	0-15	21	11
Extr-K (mg/kg)	0-15	278	174
Yield (Mg/ha)		4.1	2.3
(Bu/a)		60.2	34.8

*minimum significance level = .05
N = 5

Zahill soils are calcareous and occupy knoll landscape positions. Fertilizer phosphorus in calcareous soils can precipitate to form relatively insoluble compounds that deposit on surfaces of $CaCO_3$, or phosphate can be retained by clays saturated with $CaCO_3$ (Tisdale and Nelson, 1975). Under native conditions, the Zahill soils have shallow depth to $CaCO_3$ and low organic matter content in the Ap horizon. With cultivation of these erosion-prone areas, calcareous C horizon is mixed into the Ap horizon. This is probably detrimental to plant nutrient relationships. Whether yields are reduced by gains in $CaCO_3$ or the associated losses in soil organic matter is still unknown. Larson