Evaluating selected soil morphological, classification, climatic, and site variables that influence dryland small grain yield on Montana soils
by Thomas Harold Burke

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Soils
Montana State University

Abstract:
Rating soils based on their crop productivity capabilities is a potentially useful tool that can allow researchers to predict crop yields on a regional basis. Unfortunately, rating systems or indices have been hindered by (1) difficulties in quantifying soil properties and (2) by interference from outside variables such as management, climate, and site variables.

In order to address these problems, 184 field experiments conducted from 1 968 to 1 982 were selected throughout the dryland plains of Montana for evaluating selected soil morphological, classification, climatic, and site variables in relation to small grain yield. All sites chosen for study were at "optimal" management conditions in terms of fertility, weed and pest control. Data were analyzed by multiple stepwise linear regressions to identify variables related to yield.

Important soil morphological variables that were related to small grain yield included available water holding capacity (r=+), deep depth to Cca horizon, generally coarse, subangular blocky structure in the Cca horizon, and to a lesser extent, fine texture. Dry consistence of Cca was also positively correlated with yield in most cases, due to its positive correlation with deep depth to Cca, fine texture, and well developed structure in the Cca horizon. Other variables that were important to small grain yields in Montana included rainfall Cr=+) and spring soil water stored from 0 to 120 cm (r = +). Rainfall, available water holding capacity, Cca dry consistence, and spring soil water from 0 to 122 cm accounted for 44% of yield variation, statewide.

Data were also subdivided by crop type (winter wheat, spring wheat, and barley) and by geographic location (north-central, southeastern, northeastern Montana, and Gallatin-Madison county area) for regression analysis. For crop subfiles, all yields depended on rainfall (r=+); spring wheat to the greatest extent and barley the least. For location subfiles, southeastern Montana was the only area without soil morphological variables appearing in its regression, suggesting that water factors were more limiting for this area.

A soil productivity index (SPI) was generated for 52 soil series considered in the study, with the "best" yielding soils in Montana (such as the Bozeman silt loam) having high available water holding capacity and relatively deep depths to Cca horizon. When SPI values were combined with water variables and crop type, 45% of yield variation was explained. Further soil productivity studies are needed to explain more yield variation.

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

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ABSTRACT

Rating soils based on their crop productivity capabilities is a potentially useful tool that can allow researchers to predict crop yields on a regional basis. Unfortunately, rating systems or indices have been hindered by (1) difficulties in quantifying soil properties and (2) by interference from outside variables such as management, climate, and site variables.

In order to address these problems, 184 field experiments conducted from 1968 to 1982 were selected throughout the dryland plains of Montana for evaluating selected soil morphological, classification, climatic, and site variables in relation to small grain yield. All sites chosen for study were at "optimal" management conditions in terms of fertility, weed and pest control. Data were analyzed by multiple stepwise linear regressions to identify variables related to yield.

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CHAPTER 1

INTRODUCTION

Researchers in Montana, as well as other parts of the world, have recognized a need for determining relationships between gross soil physical properties and crop production. By knowing how various soil variables influence crop production, soil scientists can determine the "soil productivity" or how much a crop can physically yield for a specific soil type. Once productivity factors are known for many soil series, researchers can then construct a soil productivity index (SPI) of soils for their particular area.

Soil productivity index values are a potentially useful tool that can allow researchers to predict crop productivity on a regional basis. This transfer of "agricultural technology" can in turn allow growers to tailor their crops to their particular soils. Other applications for using SPI values include aiding economists in determining potential values of soils and aiding in identifying productive lands for general land use planning and agricultural preservation policies.

SPI values can be determined for most dryland small grain production areas of Montana since soil properties are well documented in county soil surveys for a majority of

Montana's grain production areas. However, quantification of soil properties is essential in order to derive SPI values and consequently compare one soil type to another. Since many soil characteristics do not easily lend themselves to quantitative interpretations, researchers and SCS personnel have had difficulty in quantifying soil productivity for Montana's dryland grain production areas.

Specific problems of quantification that have faced researchers involve the qualitative nature of soil properties themselves. Many soil parameters can influence yields in subtle, indirect ways and are interrelated, making cause and effect relationships of soil properties to yield difficult to determine. Difficulties in quantifying soil productivity are also partially due to crop yields being a product of various management, genetic, and climatic factors as well as soil properties. In Montana, where the dryland production areas are semi-arid, yearly moisture differences become especially critical characteristics that can influence soil productivity values.

This study addresses these problems of quantifying soil productivity. Specific objectives of this study include:

(1) to identify a few selected soil morphological, soil classification, field site, and soil-climatic parameters that may be important to small grain yields in Montana.

(2) to take into account management variability of growers by using existing yield data from experiments with

"highest attainable yields" in terms of fertility, weeds, and pest management.

(3) to employ an existing information base (from county soil surveys and field experiments) to ascertain soil properties that may influence grain yield.

(4) to quantitatively examine cause and effect relationships between important variables and small grain yields, employing multiple regression techniques and correlation matrices.

(5) finally, to determine if these quantitative relationships can be useful for constructing a "soil productivity index" model for Montana's dryland grain production areas.

CHAPTER 2

LITERATURE REVIEW

Approaches of Quantifying Soil Productivity

One of the first attempts to quantify soil productivity was made by Storie in 1933. In his original index scheme, he chose a multiplicative model, examining surface texture, slope, profile morphology (depth), and other modifying factors such as pH and degree of wetness. Although Storie's model presented quantitative relationships between soil properties and crops, his ratings were based soley on soil characteristics. Huddleston (1983) called this approach an "inductive method" of indexing soil productivity; that is, soil productivity ratings" are constructed based entirely on inferences about effects of soil properties on the yield (and growth) of plants". This approach was commonly taken during the 1930's and early 1940's by researchers.

After World War II however, Huddleston notes that the "deductive approach" became more popular among researchers. This method is currently used in every modern SCS soil survey in the form of yield tables. Unlike the inductive method, the deductive approach bases soil productivity entirely on comparisions of yield data from different soil types. Presently, researchers employ three methods of collecting data for determining soil productivity: (1) using questionnaires to survey producers, (2) compiling existing data from farm records or experiment station results, and (3) actually collecting yield data on a small plot basis (Odell, 1958). By far, small plot data collection is the most precise method but perhaps the most costly.

One major limitation in using the deductive approach however is that crop yields not only reflect soil properties but climatic, management and biological variables as well. In order to account for these variables, researchers have tried sequential sampling (Olsen, 1981). When using sequential test plots, the experimenter deliberately samples plots on different (or sequential) soils within the same field (usually in a moisture catena). This method can essentially hold climatic, management, and biological variables fairly constant.

In Montana, Burke (unpublished data, 1982) sampled sequentially on three different soil series in order to show yield differences of winter wheat on no-till, minimum till and conventional summer fallow tillage in northcentral Montana. Results indicated that the Ernem series yielded much less (33 bu/ acre) than either Tanna or the Linnet-Acel complex regardless of tillage practice (see Figure One). Since the Ernem soil was much shallower than either Tanna or Linnet-Acel, lower yields were possibly influenced by Ernem having the lowest water holding capacity.

On a more quantitative basis, Munn and others (1982) randomly plotted samples sequentially between Scobey-Kevin soils in northern Montana within the same fields in order to detect yield differences in spring wheat. Using a paired t test, they observed that Scobey out-yielded Kevin in the same field at 7 different sites. In addition, more variation was detected between Scobey and Kevin than plots taken all within the same soil, indicating that soil series deliniation may be useful in detecting yield differences.

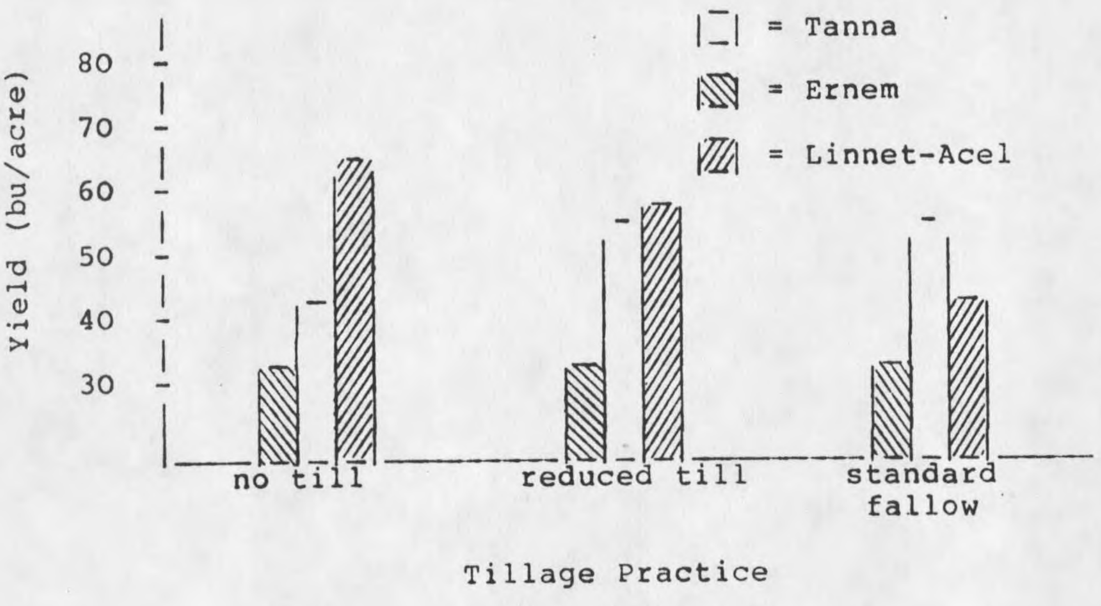

Figure 1. Yield Differences of Winter Wheat on No-Till, Minimum Till, and Standard Fallow on Three Soil Series.

For more than two soils (or populations), Duncan Range test comparisions have been successfully used by Peters

(1977) over a large area (western Alberta). For a large data base or a large area, multiple regression techniques have also been employed in determining important soil properties that influence yield and in evaluating how soil properties interact with each other (Allgood and Gray, 1978). Using a multiple regression model, Karathanasis et al. (1980) noted that 17 to 74% of the variation of grain yield was explained by soil variables on plots distributed worldwide.

Sopher and McCracken (1973) have cautioned, however, that multiple regression analysis can produce models that are unrealistic. They stressed that misuse of regression models can occur in two forms: "(1) drawing conclusions from a sample not representative of the population studied, and/or (2) literally interpreting the values of regression coefficients that are derived from highly correlated independent variables". The first misuse can be eliminated by replicating samples adequately in time and space. The second misuse is harder to alleviate since "independent" variables in soil-plant relationships are usually highly correlated, forcing coefficients to be correlated (not additive) also. This is of no consequence, Sopher and McCraken state, if the model is used soley as a predictor tool but should not be used to make cause and effect interpretations of variables unless correlations are taken into account. They suggest constructing a correlation matrix and eliminating (or combining) those variables that are highly correlated. This technique is used in the present study. More will be said about these "multicollinearity effects" in the Materials and Methods section.

Soil Morphological, Climatic, and Site Influences on Yield

Soil Morphological Variables

The state of soil physical factors, such as texture, structure, bulk density and consistence can affect small grain yields in various ways. Soil texture indicates the relative proportions of the primary soil separates (sand, silt, and clay) in a soil. In terms of crop growth, soil texture can affect yields indirectly by affecting soil strengh, pore size, air, water and soil temperature (DeJong and Rennie, 1967). Sopher and McCraken (1973) reported that an increase in clay for North Carolina soils correlated negatively with corn yield, while sand correlated positively with corn yield and silt correlated negatively (although only slightly) with yield. The negative response of increased clay to yield was attributed to higher clay amounts occurring in areas with poorer drainage. For drier areas, Allgood and Gray (1978) reported that clay in Oklahoma soils had a positive correlation with wheat yield while sand was negatively correlated (although only slightly), suggesting that finer textures may be more beneficial to grain yield in that semi-arid area. In general, the Soil Survey Staff (1971) has rated sandy loams, loams, and silt loams as being the best textures for growing crops while coarser and finer textured soils rate lower.

Soil structure denotes the arrangement or the orientation of primary particles into secondary particles, thus indicating the distribution of micropores and macropores. In terms of crop growth, structure influences yield since roots penetrate partially by growing through existing voids and partially by moving aside soil particles (Taylor, 1974). Thus, roots tend to find structural weaknesses following voids even in rigid soil systems. With soils that are not highly structured and have high soil strength (i.e. few pores), roots must move substantial quantities of soil in their path which can reduce the plant's growing capacity.

Similar to structure, bulk density is a direct measurement of the amount of pore space that is available for water and air movement. Plant response to increased bulk density (compaction) can vary with soil type, plant species, climate and stage of development (Rosenburg, 1964). Specifically, Ferguson (1983) notes that the greatest compaction can occur in systems in which: (1) the soil particles cover a broad spectrum of sizes so that small particles can fit nicely between larger particles, (2) high surface areas and swelling clays (montmorillonite) dominate,

(3) swelling type cations (Na+) dominate, (4) a water content that minimizes cohesion and friction exists.

In terms of soil productivity, Rosenberg (1964) noted that increasing bulk density may increase mechanical impedance, reduce aeration, and alter water availability and heat flux by decreasing pore space.

High bulk densities, however, may be beneficial to crops, particularly on sandy soils. For sandy loam soils, Rashid et al. (1976) reported that increased bulk density actually raised the water retention capacity of the soil by presumably reducing macropores (which do not strongly hold gravitational water). Excessive compaction may be harmful however. Veihmeyer and Hendrickson (1948) demonstrated that all plants tested couldn't penetrate soils with bulk density values of 1.9 g/cc or more. In Montana, bulk density problems due to compaction of cropland are not apparent up to 1.7 g/cc (Hayden Ferguson, personal communication).

Soil consistence is essentially an integrated measurement of bulk density, structure, and texture of a particular soil. It is determined by measuring soil resistence to crushing and its ability to be molded or changed in shape. Soil Survey Staff (1971) has chosen a moist consistency of "very friable" as the most suitable consistence for crop production. A firm or hard dry consistence is rated as poor and commonly implies slow permeability (Veeh, 1981).

In addition to soil physical aspects, gross morphological properties such as soil depth, available water holding capacity and depth to calcium carbonate horizon also are important factors of soil productivity. Bennet and others (1980) noted that deep soils correlated highly with high wheat yields, apparently due to increased available water holding capacity. Rapid stress to plants occurs on shallow soils with low water holding capacities which are subjected to greater climatic evapotranspiration demand than deeper soils (Richie, 1981). Soil Survey Staff (1971) recommends that a soil depth of 30 inches or greater is needed for good overall crop productivity.

In Montana, most agricultural soils have calcium carbonate accumulation, or calcic horizons, within their profiles (Montagne et al., 1982). This accumulation of free lime may negatively affect plant growth. Mortvedt (1976) postulated that high free lime levels may cause stunted growth as a result of P and micronutrient immobilization as well as serious ammonia volitalization losses in cases of improper N fertilizer management. On a worldwide scale, Karathanasis et al (1980) noted that the lowest grain yields were oberved on highly calcareous soils (and on soils with a pH lower than 6.0). In northern Montana, Munn and others (1982) observed that percent $CaCO_3$ was highly negatively correlated with spring wheat yields on Scobey-Kevin complex, but more so on the Kevin soil than the Scobey soil. This was explained by the fact that Kevin had its calcic horizon closer to the surface. They also postulated that the shallower calcic horizons may have induced P deficiency and thus lowered yield for Kevin soils compared with Scobey soils.

Soil-Climatic Variables

Variables that affect soil water and soil temperature can affect crop production as well. Lack of soil water, for example, can critically stress plants and result in less growth and yield. Richie (1981) states that plant stress can be caused by either (1) a deficiency of water in the root zone within the soil and/or (2) excessive atmospheric water demand from leaves.

Researchers have measured water stress of plants indirectly by estimating potential evapotranspiration (PET) which is primarily determined by weather factors such as temperature, net radiation, humidity and wind velocity (Penman, 1956). As a result, PET can essentially be used as a measure of water use where soil water is not limiting (i.e. irrigated wheat). In general, a higher PET rate occurs when weather is warm and dry which can deplete available soil water and decrease root penetration (Hsiao and Acevado, 1974).

In Montana, a semi-arid state, dryland grain production areas are often subjected to limited water situations during the growing season. Thus, PET estimates are not appropriate for estimating water under these conditions and, instead, researchers have measured or estimated actual evapotranspiration (or AET) for semi-arid soils. For estimating AET, one needs to understand how the water-dynamics of the soil-plant-atmosphere system relates to the available water holding capacity of the soil, its depletion and replenishment (Richie, 1981). Generally, as AET decreases, soil water decreases.

To take into account both atmospheric demands and soil water supply, Denmond and Shaw (1962), using PET and AET in an equation, calculated the relative ET as follows:

$$\frac{AET}{PET} = \text{relative ET.}$$

When AET/PET < 1, there is a general decline in relative ET with time. If either AET decreases (soil water decreases) and/ or PET increases, relative ET slows down and the plant ceases to assimilate CO_2. Richie (1981) has noted that when relative ET is less than one, PET becomes less important in semi-arid areas as factors affecting water transport from soil to plant become more important. He also states that variations in soil water deficiences (AET) are the major cause in year to year variations in yield.

Precipitation during the growing season usually is beneficial to crop yield in that it increases soil water available for plant use. Runge and Odell (1958) found that water above normal precipitation was especially beneficial on corn in Iowa approximately one month before anthesis. In contrast, Karathanasis etal. (1980) found that seasonal rainfall had a low significance or a slightly negative effect on wheat yield on a worldwide scale (apparently due to leaching of nutrient anions). For semi-arid areas, however, precipitation has positive effects on small grain yields. Brengle (1982) noted that for eastern Colorado, all land types that produce wheat yields well above the cost of production were found in areas that receive more than 380 mm precipitation annually. Thus, total amount of precipitation becomes more critical perhaps up to a point. Karathanasis did note that wheat yields increased with increased water up to 350 mm and then decreased on a worldwide basis. Apparently, Karathanasis concluded, the distribution of rainfall during the critical growth stages appeared to be more important than total amount of precipitation except at the lower end of the precipitation scale.

Soil temperature also can influence plant yield. Willis and Power (1975) reported that increasing soil temperature decreases water viscosity and surface tension while increasing hydraulic conductivity. Thus an increase in soil temperature can increase the water flow in a particular soil.

Soil temperatures can also affect crop growth and yield directly. Nielsen (1974) notes that optimal yields for barley usually occur at 18 C, while wheat yields are optimized at 20 C. Power et al. (1970) however noted that yield potential of barley may decrease with an increase in root temperature due to higher temperatures hastening maturity.

In terms of crop yields, Black (1970) observed on eastern Montana soils that winter wheat yields were very dependent on soil temperature and soil water during May, suggesting that higher early temperatures are critical for producing good yields. Runge and Odell (1958) found that both precipitation and maximum daily temperature 50 to 74 days before and 14 to 30 days after full tassel on corn explained up to 67% of the yield variability from 1903 to 1956.

Site Variables

Site characteristics or local topography can influence crops indirectly by affecting soil properties or conditions which influence yield. Soils with south-facing aspects, for example, receive greater solar energy, resulting in higher soil temperature and a drier overall growing season than soils with north-facing aspects. The latter have more soil water during the growing season, greater organic matter, and generally thicker soil depth (Montagne et al., 1982).

Slope angles and slope positions by themselves also affect soil properties which can influence yields. Soils on convex positions tend to be shallower (due to more erosion influence) than concave-position soils which tend to accumulate more soil water (Montagne et al., 1982). In terms of slope angle, Furley (1971) reported that high correlations exist between soil properties and slope angle on convex portions of slopes but relationships of soil angle and properties on concave areas were much poorer. On calcareous soils studied, Furley reported that convex slope angles were directly positively related to pH while negatively related to organic carbon, nitrogen, and silt and clay on convex slopes. Consequently, slope angle does affect values of certain soil properties with most of the changes occuring on convex slopes as opposed to concave slopes.

CHAPTER 3

MATERIALS AND METHODS

Plot Selection and Sampling

One hundred and eighty four field experiments were conducted between 1968 and 1982 on 123 sites throughout the state of Montana (see Figure 2). Of these 184 experiments, 182 were fertility field plots conducted by researchers from various Montana State Agriculture Experimental Field Stations (MAES) and recorded in MAES Annual Reports. In addition, these field experiments were utilized in Veeh's thesis (1981) for predicting K response based on selected soil properties. The two remaining field experiments were conducted in 1982 by the "Integrated Pest Management" team (Nissen and Juhnke, 1983). Appendix A lists the locations of each site and the number of experiments per site.

Plot selection for this thesis was based on the criteria that (1) weeds and disease problems were adequately controlled so as not to influence grain yields and, (2) that fertility levels of N, P and K were adequate so as to not limit yields. Thus the highest yields recorded by researchers that corresponded to a particular plot were considered "highest attainable yields" in terms of

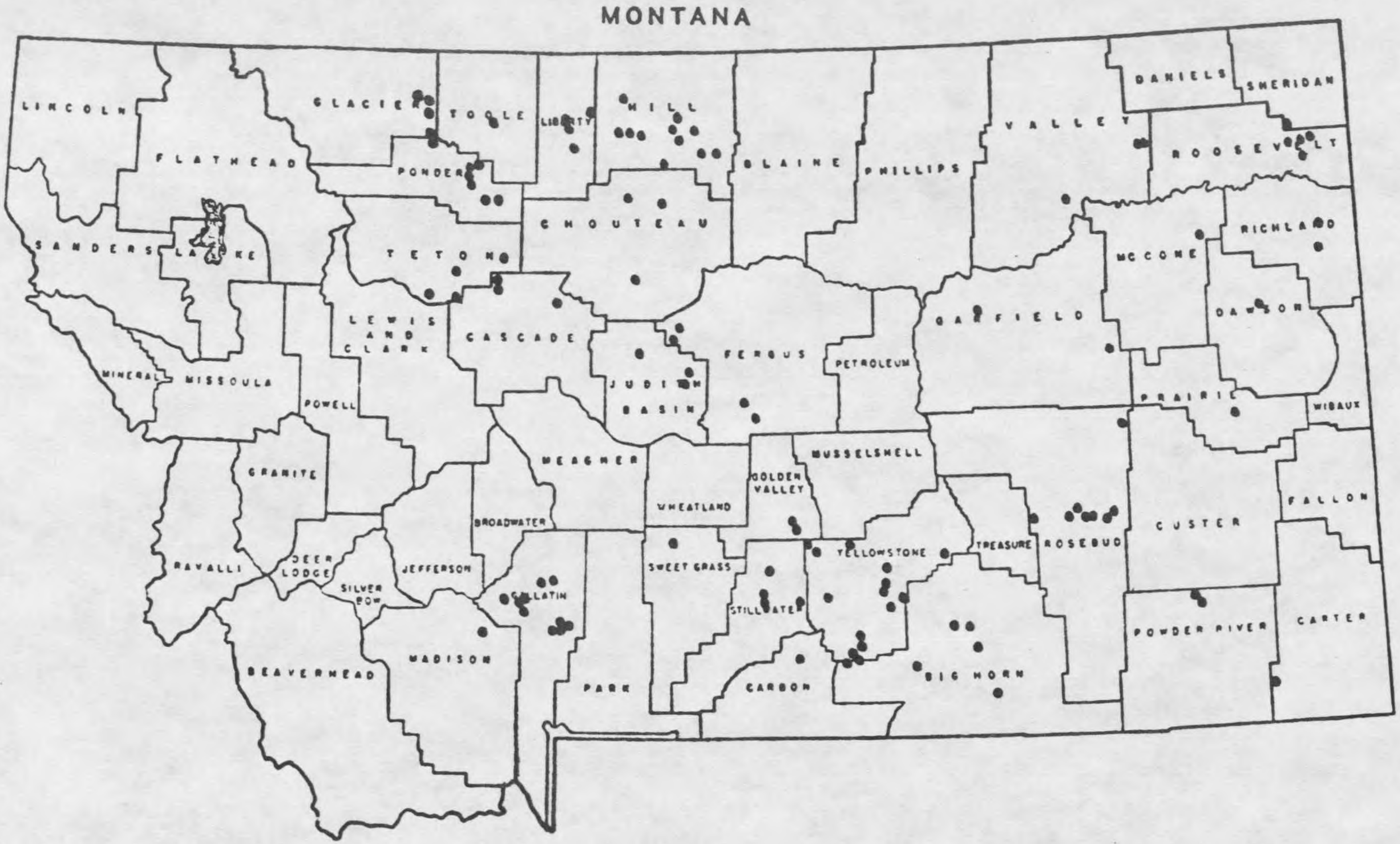

Figure 2. Location of Study Sites.

fertility, weed, and disease control. Field experiments where severe drought was apparent were also included in this study if water data were recorded for that particular site. In this way, management and climatic variables were at least partially accounted for.

For collecting physical soil data, soils were sampled as near the center of the old experiment sites as possible, as explained by Veeh (1981). Core samples, from a Giddings probe, were divided into plow layer (Ap) horizon, B horizon (based on structural and textural differences induced by clay accumulation) and a "Cca" horizon where strong reaction occurred with dilute hydrochloric acid. For the IPM sites, one pit was dug on the convex slope and one for the concave slope for each site, and analyzed separately. Since yield data for the IPM sites were averaged on both convex and concave slopes, soil sample data were likewise averaged for each site.

Variable Selection and Measurement

Listed in Table 1 are the variables considered in this study and used in multiple regression and correlation analyses. This section will explain in detail how variables were measured and, where appropriate, how variables were coded.