Use of soil parameters to assess crop yield potential in Gallatin Valley, Montana : a study of soil quality

by Arsil Saleh

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Soils
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Abstract:
Soil survey and inventory activities involve collecting a variety of soil and environmental data and information which are subsequently available for numerous uses and applications. Some soil parameters have been identified to strongly influence quality of the soil, a term which has gained numerous definitions. Knowledge of using soil performance data in relation to crop yield may be a good learning process in approaching the study of soil quality. Understanding soil quality and its relation to dependent factors is, perhaps, helpful in making soil information more useful, especially in developing countries. The intent of the present investigation was not to develop yield estimate models based on soil parameters but rather to undertake a desktop exercise that would provide experience with the process of investigating soil quality and soil data.

The main purpose of this study was to investigate important soil parameters which influence crop yield in Gallatin Valley. Variability in environmental conditions affecting crop yield was limited by taking a relatively small geographic area, Gallatin Valley, Montana for this study. Data and information about soils were primarily obtained from Natural Resources Conservation Service's URL Websites. Twenty nine soil pedons (with 162 horizons) representing eleven soil series were involved in this study. Soil data and information were obtained only for A and B horizons ; these data were used to calculate weighted-average values, which were used in subsequent analysis. Lack of available crop yield data was addressed by applying five different approaches to obtain crop yield estimates for winter and spring wheats (Triticum aestivum L.), and alfalfa (Medicago sativa L.). Eight soil variables from the entire soil survey database were used in conjunction with estimates of crop yield to assess the role of soil properties in soil quality characterization. Statistical Analysis System (SAS) programming was used for variable selection and regression analysis.

Six 'best' regression equations were developed from this study. Two regressions predicting yield on the basis of soil properties were fit for each crop. Soil water holding capacity (WHC) proved to be the 'best' predictor of crop yield. Models involving WHC were defined as the first 'best' regressions for each crop. This independent variable was able to explain 91 percent of the variability in winter and spring wheat yields (models 1.1 and 6.1), and 87 percent of the yield variability in alfalfa (model 11). A combination of WHC and soil clay content (clay) comprised the second 'best' regression equations for each crop. This combination accounted for 64 percent variation in winter wheat yield (model 5.3), 56 percent yield variation in spring wheat (model 10.2), and 53 percent ofyield variation in alfalfa (model 15.2). _ Soil survey inventory results have been shown to be very useful for assessing yield potential of winter and spring wheats, and alfalfa on a limited basis. Of the five sources of dependent variables, yield estimates from NRCS-USDA were the most significantly correlated with soil parameters. Best guess yield estimates by experienced producers were very closely correlated with the estimated yields by the NRCS-USDA. By applying further manipulations, MAPS Atlas database proved useful for characterizing soil quality.

The reader should be cautioned that the models developed here are clearly limited in their application

to yield estimation, due to the fact that the approach used was somewhat circuitous, i.e., using NRCS yield estimates based on soil water holding capacity, as the foundation for model development.

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Arsil Saleh

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

Soil survey and inventory activities involve collecting a variety of soil and environmental data and information which are subsequently available for numerous uses and applications. Some soil parameters have been identified to strongly influence quality of the soil, a term which has gained numerous definitions. Knowledge of using soil performance data in relation to crop yield may be a good learning process in approaching the study of soil quality. Understanding soil quality and its relation to dependent factors is, perhaps, helpful in making soil information more useful, especially in developing countries. The intent of the present investigation was not to develop yield estimate models based on soil parameters but rather to undertake a desktop exercise that would provide experience with the process of investigating soil quality and soil data.

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1. INTRODUCTION

Soil survey and mapping is a process of inventorying information about soil and the related environmental factors. The results are soil survey reports containing information on soils, relief/topography, vegetation, geology, and climate. An integral part of soil survey is a detailed list of soil characteristics and nomenclatures.

In developed countries, soil survey inventory is an integral part of land resource management. Soil maps and taxonomic information resulting from soil surveys have been put to a number of agricultural interpretive uses (Buol et al., 1989). Besides agricultural purposes, soil survey data can also be extensively used for non-farm activities such as land use planning, environmental quality protection, highway location, real estate development, tax assessment purposes, and siting of recreation facilities and septic tank filter fields.

Following the developed countries, some developing countries have also been adopting the practice of characterizing and mapping their soils. Indonesia is one example of a country actively engaged in soil survey. Its researchers and surveyors have been reporting and documenting numerous soil inventory reports to be used publicly. However, most of the results are still "under utilized". Simultaneous to the soil survey process, many other efforts have been undertaken to improve the usefulness and to better explain soil inventory reports to users. One of these efforts is that in 1988 researchers declared the US soil classification system, Soil Taxonomy (Soil Survey Staff, 1975) to be used for classifying and reclassifying Indonesian soils.

Assessment of soil potential or quality based on soil characteristics obtained from soil survey and mapping activities in Indonesia is one way to increase the usefulness of soil survey information. The importance of relationships among soil properties, plant characteristics and populations, and environmental variables has been recently recognized (Larson, 1986).

In order to build and develop models defining soil-crop relationships, it is first necessary to collect information on soil characteristics along with crop variables. Because adequate data or crop yield records which can be used to study soil-crop relationships are not always available for most farm fields, numerous research efforts have articulated mathematical models to correlate soil characteristics with yield potential.

The current study used several approaches to gain data and information about soil and crop variables. Independent variables (in the present study those being soil parameters) were obtained from the soil survey inventory of Gallatin County, Montana conducted by the Natural Resources Conservation Service - US Dept. of Agriculture (NRCS-USDA). The soils information was made available publicly through a URL website. Dependent variables (crop yield estimates) were estimated using the Brown and Carlson (1990) equations for winter and spring wheats, and an equation by Bauder et al. (1978) for estimating alfalfa yield potentials.

This study was conducted in a relatively small geographic area with a diversity of soils. This was done to partition soil parameters from other external environmental factors which influence crop performance. Assuming "homogenous" external factors, variability in crop performance occurring in the Gallatin Valley area was expected to represent the effect of differences in soil characteristics. Winter wheat, spring wheat, and alfalfa were used for conducting the analysis of soil-plant relationships. These crops are well suited to the environment of the Gallatin Valley.

The objectives of this study were to undertake an exercise which would investigate approaches of studying soil quality by looking at relationships between soil data and information from soil survey inventory and crop yield potentials. The ultimate goal was to gain an appreciation for methods of utilizing soil inventory data to assess soil quality. In this thesis, this was done by determining if there were identifiable soil factors which consistently or significantly influence crop performance and yield potential. Hypotheses to be tested in this study were : (1) can we use soil survey and inventory data for assessing yield potential and approaching the study of soil quality; (2) can we define soil quality using soil survey data; and (3) can a model to assess soil quality be developed using soil survey data ?

In this regard, the reader is advised to utilize and make application of the resultant models for the estimation of crop yield potential with significant apprehension. The models which have been developed here were not intended to be "stand alone" estimators and have, in fact, been developed and validated totally on the basis of similarly derived estimates. The primary focus of this investigation was to undertake an exercise which would illustrate one approach to assessing soil quality and familiarize the investigator with the potential uses of soil inventory data.

2. LITERATURE REVIEW

Soil Quality and Soil Health

Soil quality and soil health are terms of similar meaning. Soil scientists frequently refer to 'soil quality' when assessing or characterizing soil functions in the environment. On the other hand, farmers and land managers commonly consider soil health for expressing similar purposes of their soils. Rhoton and Lindbo (1997) evaluated soil quality as a means of defining the suitability of a soil for crop production purposes and environmental control.

Some soil scientists believe that soil quality is an abstract characteristic and one that can not be defined. From their perspective, soil quality is strongly dependent on external factors such as land use and soil management practices, ecosystem and environmental interactions, and socio-economic and political priorities (NRCS-USDA, 1996).

NRCS-USDA (1996) determined that the soil can and does serve many purposes, both to humans and the environment. These roles are best defined as soil function. Soil functionally provides a physical matrix, a chemical environment, and a biological setting for living organisms. Hydrologically, soil may regulate and partition water flow and storage. Moreover, it can control crop nutrient retention and cycles.

Definition of Soil Quality

A definition of soil quality may involve soil productivity, which can include an accounting of major chemical, physical, and biological characteristics of the soil. Soil productivity may be utilized to quantify soil quality in relation to soil characteristics. One way to define soil quality is by characterization of a selection of specific soil components. For example, soil quality can be assessed by an evaluation of soil morphology, soil physical characteristics, soil chemical properties, and soil microbiological conditions (Turco et al., 1994). To define soil quality, the Soil Science Society of America (1987) takes into account attributes of soils that are inferred from soil characteristics or indirect observations (e.g. compatibility, erodibility, and fertility).

A broader definition of soil quality considers the capacity of a soil to function productively in a sustainable manner. Larson and Pierce (1991) define soil quality as the capacity of a soil to function within the ecosystem boundaries and interact positively with the environment external to that ecosystem. In addition to the 1991 definition, Pierce and Larson (1993) simply state that soil quality is fitness of soil for use, while Gregorich et al. (1994) state that soil quality is degree of fitness of a soil for a specific use. More specifically, NRCS-USDA (1996) claims soil quality as the fitness of a specific kind of soil to function within its surroundings, support plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation.

Parr et al. (1992) propose the definition of soil quality as the capability of soil to produce safe and nutritious crops in a sustained manner over the long-term, and to enhance human and animal health, without impairing the natural resource base or harming the environment. In addition, Harris et al. (1996) propose that quality of a soil is determined by the fitness of the soil body to protect water and air quality, sustain plant and animal productivity and quality and to promote human health.

Some other scientists define soil quality by looking at its function and behavior. Doran and Parkin (1994) consider soil quality as the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health. The National Soil Survey Handbook (Soil Survey Staff, 1992) observes that soil quality is the performance of soil attributes which serve as criteria to make predictions of soil response and behavior. The attributes are inferred from observation and soil properties.

In general, researchers consider the relationship between soil and intended uses in order to evaluate soil quality. One common theme persists throughout this varied selection of definitions of soil quality. It (soil quality) is reflected in the ability of a specific soil to sustain or support a prescribed or defined use for an extended period of time.

Why is it Difficult to Define Soil Quality ?

The difficulty in defining soil quality arises from the complexity of pertinent soil properties which one attempts to assimilate into a single term or numeric value that will account for soil characteristics appropriate to a variety of uses (Rhoton and Lindbo, 1997). The complexity in the nature of soils makes this integration difficult. Doran and Parkin (1994) stated that soil quality is an abstract characteristic of the soil which is impossible to define, because it is dependent upon numerous external factors. An interpretation or perception of good soil also varies from person to person and with intended use of the soil.

Why do we Need to Define Soil Quality ?

The value of defining soil quality is that it provides a standard for whether or not a soil is managed and maintained in an acceptable states for future generations. Consequently, any definition of soil quality must be broad enough to be able to cover a number of facets of soil function (Doran and Parkin, 1994). In addition, an objective assessment or characterization of soil quality can serve as a valuable tool for soil management decision-making.

The criteria commonly used as indicators for soil quality/health are also used for assessing soil productivity. Since soil quality is still difficult to define, many people approach assessment of soil quality by trying to find some closely related factors. Rhoton and Linbo (1997) reported that effective soil depth has been highly correlated with adverse changes accompanying the modification in soil properties. Variation in effective soil depth and/or soil thicknesses due to either erosion or continual production processes may determine variability in the quality of soil. Therefore, soil depth can be used to explain differences in soil properties and accurately estimate soil productivity and erosion. At locations where soils are limited in thicknesses, effective soil depth may be a reasonable way of assigning an index of soil quality.

Soil productivity and soil erosion can be considered critical indicators in the study of soil quality because of their significant relationship to soil quality. Concepts of both soil productivity and soil erosion reflect the impacts of most soil and environmental characteristics. Soil productivity and soil erosion reflect many major soil properties and the soil's environmental condition; hence these two measurements may be adequate enough to be primary indicators of soil quality for many purposes.

Indicators for Assessment of Soil Quality

In order to assess the quality of soil, all properties that directly or indirectly determine soil function should be considered as part of the process (Visser and Parkinsons, 1992). These two scientists identified that carbon and nitrogen cycles are essential indicators of soil quality. In addition, Doran and Parkin (1994) identified pH, P_2O_5, and K_2O as other soil factors to be considered for defining quality of a soil. They also considered soil physical properties (such as texture, rooting depth, permeability, and soil moisture), soil temperature, and microbial activity when assessing soil quality. A study by Entry et al. (1996) determined that the ratio between organic carbon and nitrogen is a poor predictor of annual crop yield but it may be an accurate indicator of soil health and a good predictor of long-term crop yield. Crop yield can be an important indicator of soil quality (Granatstein and Bezdicek, 1992), however, productivity individually is not enough to be a complete measure.

To improve Soil Quality

Quality of a soil can be improved in many different ways. Cropping diversity is a way of enhancing it. Research by Franco-Vizcaino (1996) revealed that increasing diversity of crop residues incorporated into the soil through rotations has been associated with better condition of agricultural land. This is because the soil gains improvements in soil tilth, nutritional status, and biological activity, which are indicators of soil quality. Any improvement in soil physical, chemical and biological conditions can be used to indicate changes in soil quality.

Soil Function and Soil Productivity

Soil is an integral part of the environment. It can play an important role influencing many different processes within the soil and/or in adjacent areas. NRCS-USDA (1996) identifies four roles of soil in the environment : a) to facilitate living organisms, b) to control water flows, c) to regulate changes among phases in the soil, and d) to filter, buffer, degrade, immobilize, and detoxify organic and inorganic materials.

Soil-Crop Relationships and Soil Productivity

Soil is a dynamic and living natural body that plays many important functions in terrestrial ecosystems (Doran and Parkin, 1994). Specific characteristics of the soil should be given consideration when use of the soil is intended for farm purposes (producing foods). Soil thickness, texture, and structure are among the important soil physical parameters relating to crop production through their influences on soil hydraulic properties, aeration, and nutrient holding capacity.

Soil and plant systems are very complicated. There are many variables influencing the soil properties that affect crop performance. Advances in computer technology have helped create means of considering soil variables to be combined in various interactions (Hanks and Ritchie, 1991). The combination of variables may be used to predict soil-crop relationships. A number of models with varying complexity have been proposed. The more complicated of these relationships may be less practical to farmers but may be useful to better understand the complexity of nature.

Many researchers have tried to simplify the relationships between soil and crop yield by developing models. The purpose of this model development is to organize what is known about a subject. Crop yield estimate models should be focused on growth rate, growth duration, and the extent of stresses (Ritchie, 1991). Such models should consider variables that determine root distribution in the soil (Jones et al., 1991). Hanks and Ritchie (1991) look at models as a simplification or imitation of the real thing or as a system of postulates.

Bauder (1998, personal communication) proposed evaluating soils originating from similar environments (but not necessarily the same parent material) in relation to crop yield potential to identify numerous combinations of soil variables which influence soil productivity. The significance of such an approach to the study of soil quality is the potential it lends to identifying influencing factors which frequently appear in the analysis of soil quality. He further suggested that one approach to identifying specific soil properties which can be considered synonymous with soil quality is to count the frequency with which various soil factors significantly correlate with crop yield within a reasonably confined geographic area. This would provide one approach or initial stage of evaluating soil productivity on a regional basis, based on the premise that soil quality is reflected in site yield potential.

Another method for assessing soil quality is to account for many different kinds of soil and environmental data or information (Halvorson et al., 1996). This would also allow evaluation of soil quality based on alternative uses of soil and provide a mechanism to estimate soil quality for un-sampled locations.

Brown and Carlson (1990) pointed out that water has been the most limiting factor in agricultural production in Montana. They successfully developed models for estimating yield potentials of five different crops and the models have been expected to be applicable at a number of locations in north central Montana. Their equations consist of three main estimated values : plant available water (PAW), initial yield level (IYP), and a slope value (available water - yield relationship) for each crop. The PAW was based on stored soil water and rainfall during the growing season (May 1 through July 31). Amount of water provided by the soil was estimated by converting depth of soil wet to field capacity on the basis of soil textural classes. The other component of PAW is the amount of precipitation during the growing period. Seventy five percent of precipitation during the growing period was considered to contribute to stored soil water. Both estimation and calculation produced total amount (inches) of water available to the plant (total plant available water, PAW). IYP parameter was required to make the model more complete and rational.

Two of Brown and Carlson's equations are :

$$Ys = 5.1\ (ET - 3.8)\ \text{bushels/acre} \qquad [\text{Eq. 2-1}]$$

This equation is proposed to be useful for assessing yield potential of spring wheat (Ys) and the equation prepared for winter wheat (Yw) is as follows :

$$Yw = 5.8\ (ET - 3.9)\ \text{bushels/acre} \qquad [\text{Eq. 2-2}]$$

Brown and Carlson (1990) initially proposed a relationship between a variable ET (which they defined as evapotranspiration) and estimated plant yield. Inspection of the detail and approach of the Brown and Carlson models reveals that the ET term expressed in their models is, in fact, more accurately, an estimates of "plant available water" during the growing season. In as much as no attempt was actually made to either measure or estimate ET, the author has taken liberty to modify the Brown and Carlson equations in this investigation, substituting the term PAW where ET was initially used. This has been done for the purposes of clarity and correctness of expression.

The Importance of Soil Organic Matter

Organic matter is a significant and controlling substance in the soil. It can influence significant properties of the soil. Doran and Parkin (1994) stated that, in general, soil organic matter can control biological, physical, and chemical characteristics of the soil. Moreover, organic matter plays a major role in determining the soil's ability to store and transmit soil water, regulate the availability of water to plants, and transport environmental pollutants up to the soil surface and into groundwater.

Calcic Horizon

Calcic horizons are subsurface horizons in which secondary carbonates have been precipitated to a significant extent (Soil Survey Staff, 1994). The high content of lime in the horizon may be derived from soil parent materials or as a result of pedogenic processes. To fulfil the criteria of calcic horizon, the accumulated carbonates should indicate an illuviation process. In more detail, Soil Survey Staff (1994) states that the layer should be at least 15 cm thick and contain not less than 15 percent $CaCO_3$ equivalent. High concentration of carbonates with no indications of cementation and/or induration distinguishes this horizon from a petrocalcic horizon.

Position of the lime from the soil surface has also been related to the topographic condition. The depth to the lime from the soil surface is generally shallower in soils located on rolling to undulating areas than those of valley floor or flat areas. This phenomenon is strongly related to the erosion condition in the area. Montagne (1998, personal communication) drew a relationship between topographic condition and depth to calcareous layer in soil profile. The steeper the slopes and the more eroded the land is the shallower the depth to the calcic horizon from the soil surface.

The presence of and depth to the calcic horizon may be related to the amount of precipitation. Calcic horizons are considered to roughly indicate the average depth of water penetration into soil profile annually (Larson, 1986). Harper (1957) identified a strong relationship between the presence of calcic horizon and the amount of rainfall. Higher amounts of rainfall generally result in deeper depth to calcic horizon from the soil surface. In dry climates, the calcic horizon indicates the depth of rainfall penetration in the soil.

In terms of soil - crop relationships, the presence of calcium carbonate ($CaCO_3$) in rooting zones of calcareous soils can influence plant growth. Depth to calcium carbonate was found to be significantly correlated with crop production, especially cereal grain yields, in Montana (Burke, 1982). Medium level of calcium carbonate (less than 15 % $CaCO_3$ equivalent) in the soil column can have a positive effect on crop production, while medium to high levels of lime content can cause an imbalance of soil nutrients hence reducing the amount of crop production. Dry consistence of the calcic horizon was also positively correlated with yield.

In the field, the presence and depth of calcic horizon can be directly determined. Soil surveyors usually test this characteristic by looking at whether or not the horizon effervesces upon addition of HCl. If this characteristic is present when characterizing soil profiles, the surveyors usually indicate it by affixing “k” or “ca” following primary horizon designations (eg. Bk, Cca, etc.).

3. MATERIAL AND METHODS

Soil and environmental variables of Gallatin Valley area were compared with respect to their relationships to crop yield estimates. The significance of the relationships was expected to show the level of importance among soil variables which influence predicted crop yields. Moreover, this project was an attempt by myself to gain a better understanding of soil quality.

Values for independent variables were obtained from the Natural Resources Conservation Service - U.S. Department of Agriculture (NRCS-USDA) soil databases by accessing URL addresses of NRCS housed in Iowa and Nebraska. Data for dependent (crop yield potential) variables were obtained from application of three algorithms and from interviewing experienced producers from the Gallatin Valley area.

Study Site and General Characteristics

The study sites were located in Gallatin Valley, Gallatin County, south western Montana (Figure 1). The study area is covered by seven sheets of topographic maps with a scale of 1:62,500 (USGS, 1947 through 1952). Geographically, the whole area is located between longitude 110°48' to 111°48' West and latitude of 45° 31' to 46°04' North. Legal positions of the area were between Township T4S to T4N and Range R2W to R7E (DeYoung and Smith, 1931).

The soils of the study area were surveyed by NRCS-USDA personnel of Bozeman office and a final soil survey report is presently in the process of being completed. This

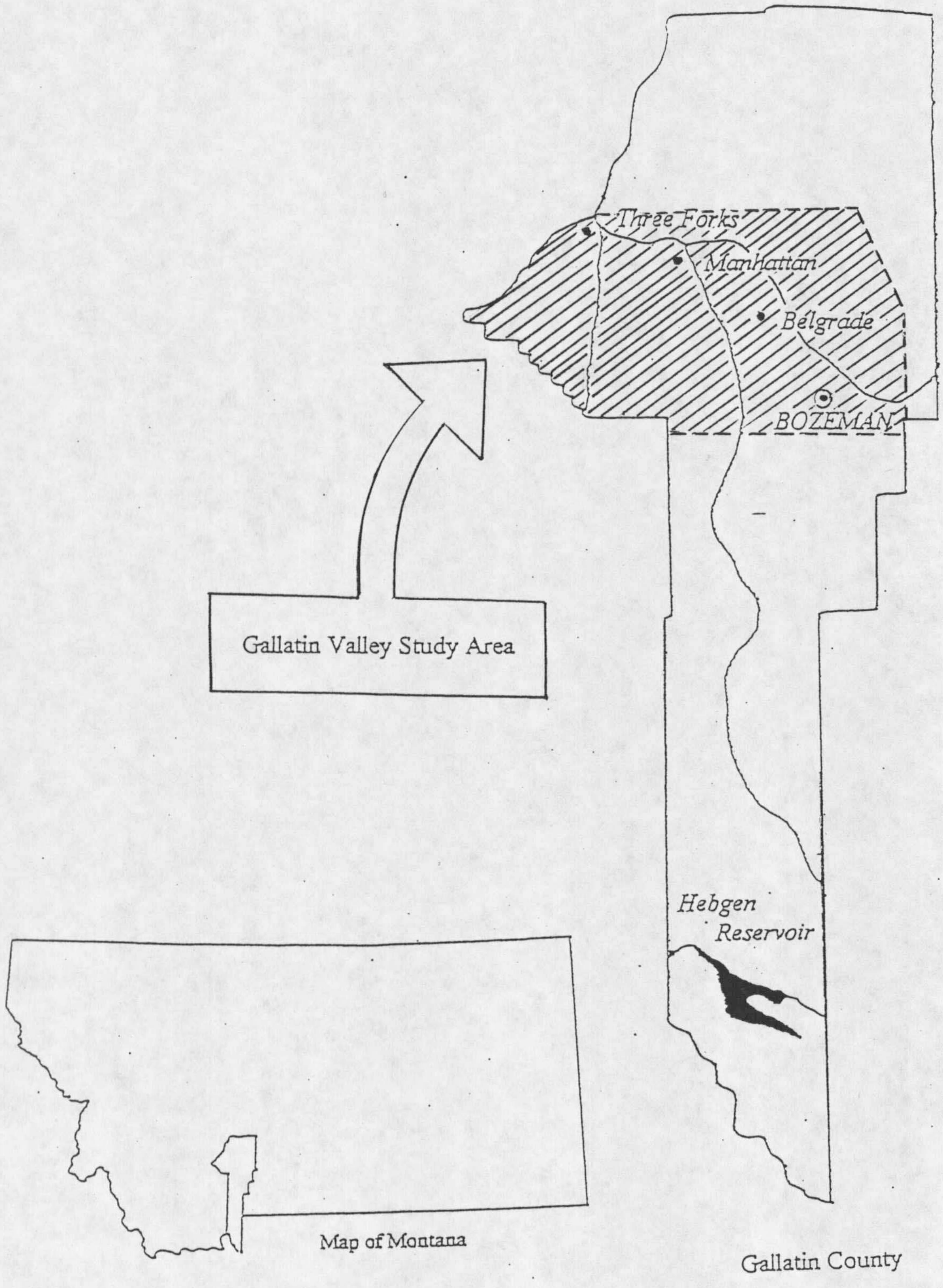

Figure 1. Study Location

location was chosen for study because it represented a relatively small geographic area with a diversity of soils having developed under a condition of "homogeneous or less variable" soil forming factors. Other reasons were that this area is well suited for cereal grains, and within the area there were many farm fields in which a number of soil series exist.

The Gallatin Valley area is characterized as receiving annual precipitation ranging from 38.1 to 55.9 cm (15 - 22 inches) and mean annual air temperature varying from 3.8 to 8.3°C (39 to 47°F) (NRCS-USDA, 1998). Physiographically, landforms of this area are commonly relict stream terraces and alluvial fans. Relief and topography of the area vary from flat to rolling plains with slope gradients up to 45 percent. Elevations vary from 1330 to 1930 m (4000 to 5800 ft) above sea level (DeYoung and. Smith 1931; USGS 1947-52). Geologic parent materials of the soils in the Valley are loess, alluvial, and alluvio-colluvial (NRCS-USDA,1998).

Soils of the Gallatin Valley area are commonly deep (greater than 100 cm thick), well drained, and moderate to moderately-slowly permeable. Top soils are somewhat thick (10 to 25 cm) and dark in color. Thicknesses of subsoils are greater than 75 cm. Some of the soils contain coarse fragments in the upper horizons and calcic horizons within the soil profiles (NRCS-USDA, 1998). Currently, land utilization of the soils included in this study is farm fields.

Selection of Soil Series

The soil series of the study, described in a semi-detailed (scale of 1:24,000) soil survey inventory in the Gallatin County (in the process of finalization), were selected based on specific criteria. The selection process was initiated with a study of locations, geologic parent materials, climatic conditions, and slope gradients. In addition, the selection also considered capabilities of the soils for agricultural purposes, especially cereal grains. The third criterion was the availability, access to, and completeness of the data for selected soils.

Initially the data for essentially all the soils of Gallatin Valley area were listed. A check was then made of the geologic parent materials. Parent materials included loess, alluvial, and alluvio-colluvial. Soils derived from these three parent materials were selected for this study. Limited climatic information was obtained from narrative soil series descriptions. Information on slope gradients was obtained from the soil mapping units or soil morphological descriptions. Furthermore, evaluations by NRCS-USDA on the soil series capabilities for general agriculture were also taken into account. The emphasis of this project was on the mapping units having slope classes of A, B, and C. The objective of this approach (taking "similar" soil geologic parent materials, relatively small area, and certain ranges of slope gradients) was to focus as much as possible solely on 'soil' factors in further analyses.

Eleven soil series in total originating from Gallatin Valley area were selected for this study. The selected soil series were : Amsterdam, Beanlake, Beaverton, Blackdog, Bozeman, Kelstrup, Martinsdale, Meagher, Sawicki, Turner, and Windham (Table 3-1, and Appendices A and B). Each soil series was represented by the data from at least one 'representative' pedon (Appendix D). In total, twenty nine soil pedons, having 162 horizons along with soil laboratory data, were included in the analysis (Table 3-2).

Table 3-1. Soil series, parent material, and family level classification of representative pedon used as source of independent variable data.

No	Soil Name	Parent material	Classification (Family Level)
1.	Amsterdam	Loess	Typic Haploborolls, fine-silty, mixed, sup.
2.	Beanlake	Alluvium	Typic Calciustolls, fine-loamy, mixed, sup., frigid
3.	Beaverton	Alluvium	Typic Argiustolls, loamy-skeletal over sandy or sandy skeletal, mixed, sup., frigid
4.	Blackdog	Loess	Typic Argiborolls, fine-silty, mixed, sup.
5.	Bozeman	Loess	Argic-Pachic Cryoborolls, fine-silty, mixed
6.	Kelstrup	Loess	Aridic Haploborolls, coarse-silty, mixed, sup.
7.	Martinsdale	Alluvio-colluvial	Typic Argiustolls, fine-loamy, mixed, sup.
8.	Meagher	Alluvio-colluvial	Typic Argiborolls, fine-loamy, mixed, sup.
9.	Sawicki	Alluvio-colluvial	Typic Argiustolls, loamy-skeletal, mixed, sup., frigid
10.	Turner	Alluvium	Typic Argiustolls, fine-loamy over sandy or sandy skeletal, mixed, sup., frigid
11.	Windham	Alluvio-colluvial	Typic Calciustolls, loamy-skeletal, carbonatic, frigid

Note : Si = silt, L = loam, Cob = cobbly, C = clay, Gra = gravelly, sup. = superactive.
Soil names include the texture class of the Ap horizon.

The majority of the selected soil series were defined/described as loamy families of Typic Argiustolls. Others were Argiborolls, Calciborolls, Cryoborolls, and Haploborolls. All of the soils were classified as Mollisols (Soil Survey Staff, 1994). The selected soil series were assumed to have developed under "relatively homogenous" geological and climatic conditions based on inspection of the soil parent materials, and temperature and moisture

Table 3-2. Statistics of soils data and information obtained from URL Website.

No.	Soil Series	Independent Variables								
		pdn	horiz	thick	clay	BD	WRD	OC	pH	DCH
		Number of representative data points								
2.	Amsterdam	7	42	42	42	29	18	42	42	7
3.	Beanlake	2	8	8	8	8	8	8	8	2
4.	Beaverton	2	9	9	9	-	N/A	9	9	2
5.	Blackdog	3	11	11	11	-	N/A	11	11	3
6.	Bozeman	1	9	9	9	9	5	9	9	1
7.	Kelstrup	2	10	10	10	-	N/A	10	10	2
8.	Martinsdale	4	32	32	32	17	13	32	25	4
9.	Meagher	1	4	4	4	4	4	4	4	1
10.	Sawicki	2	11	11	11	11	11	11	11	1
11.	Turner	3	13	13	6	19	19	13	19	3
12.	Windham	2	7	7	7	7	7	7	7	2
	Total	29	162	162	150	104	93	157	155	28

Note : pdn = pedon; horiz = horizon; thick = thickness; BD = bulk density; WRD = water retention depth; OC = organic carbon; DCH = depth to calcic horizon; N/A = not available.

regimes. Based on evaluations by NRCS-USDA, the capabilities of the soils were classified into class 3E for general irrigated and non-irrigated farm uses. Agricultural potentials of the soils were rated as low, medium, and high.

Selection of Independent Variables

Independent variable data were obtained from profile descriptions and laboratory data of the selected soil series. Each soil horizon in the initial database was defined by 61 types of soil information. This information can be grouped into two general categories : morphological data (10 parameters or descriptors) and laboratory data (51 parameters). The laboratory data can be further divided into 3 groups : physical, chemical, and mineralogical data consisting of 28, 19, and 4 parameters, respectively.

Some of the soil morphological information was difficult to analyze quantitatively because of the data characteristics. For instance, soil consistence, rooting condition, level of effervescent, and soil structure are described qualitatively. Soil colors, coded as a combination of alpha numeric and characters, were also difficult to analyze with respect to their linear relationship with other parameters. This is because hue values of soil color charts are designed to follow cylindrical coordinates geometrically (Zelenak, 1995). In addition, although useful from interpretive perspective, soil profile descriptions were found to be ineffectual for quantitative analysis. Discussions of soil profile characteristics are included in Appendix C.

Type of soil clay mineral was disregarded in this study. Although this information was available for use, clay type was reported qualitatively in the database and the data were not available for all soil horizons. This information might be useful to help explain some properties of the soil and to make further interpretation about the soil in future studies.

Inspection of the entire database revealed that the database was incomplete with respect to some variables. Variables with incomplete data sets were eliminated from the database. After reducing the list of above soil parameters and considering completeness of the laboratory data, 19 soil physical and 8 chemical variables were then analyzed with respect to their correlation to each other. The 27 soil variables were subjected to a correlation analysis using the Pearson coefficients with a significance level of 0.05 as the selection criteria for further inclusion in the study.

Based on Pearson coefficients, six soil variables obtained from the soils laboratory data were then selected for further study. A seventh and eight variable, depth to calcic horizon (calcic) and soil erodibility (Kf), were subsequently added to the list. Values for depth to calcic horizon were determined from soil morphological information and horizon designations, and from soil pH laboratory data. Information on soil erodibility was provided by the NRCS field office at Bozeman. In total, eight independent soil variables were involved in the analysis (Table 3-3).

Table 3-3. Independent variable, code, and dimension of unit included in subsequent analyses.

No	Parameter	Code	Unit
1.	Soil thickness	thick	cm
2.	Soil clay content	clay	g/100 g
3.	Soil bulk density	BD	g/cm^3
4.	Soil water holding capacity	WHC	cm/cm
5.	Soil organic carbon content	OC	g/100 g
6.	Erodibility	Kf	
7.	Soil pH	pH	pH unit
8.	Depth to calcic horizon	calcic	cm

Weighted and Averaged Value of Independent Variables

Laboratory data for each soil profile were simplified to obtain single values where appropriate. The laboratory data values for clay content (clay), bulk density (BD), soil water holding capacity (WHC), organic carbon content (OC), and pH from each horizon were weighted using a method by Rhoton and Lindbo (1996) to produce single values representing soil profiles. The weighting method took into consideration thickness and variable value of the corresponding horizon. By summing the product of horizon thickness and the corresponding variable value for all horizons of the profile, and then dividing the sum by the total profile thickness, a single value for the independent variable was derived for subsequent analysis. The arithmetic weighted values for replicate soil pedons were then averaged to obtain single values for each soil series. The average weighted values of the soils data are present in Table 3-4. The formula used for weighting the variable values is as follows :

$$I = (\Sigma(t * i))/T$$ (Rhoton and Lindbo, 1996) [Eq. 3-1)

where I = weighted average value, t = thickness of the horizon (cm), i = value of independent variable, and T = total thickness of the soil profile (cm).

Table 3-4. Average weighted value of the soil characteristic defined as independent variable for subsequent analyses.

No.	Soil Series	Independent Variable							
		thick	clay	BD	WHC	OC	Kf	pH	calcic
		cm	g/100g	g/cm^3	cm/cm	g/100g			cm
1.	Amsterdam	103	20.5	1.33	0.18	1.00	0.42	7.9	41.7
2.	Beanlake	152	21.5	1.48	0.14	1.23	0.37	8.2	15.2
3.	Beaverton	66	13.8	1.58	0.06	0.53	0.19	7.7	52.0
4.	Blackdog	104	22.2	1.28	0.18	1.31	0.35	7.8	61.0
5.	Bozeman	145	22.8	1.50	0.15	1.08	0.35	8.4	51.0
6.	Kelstrup	152	21.5	1.49	0.11	0.39	0.36	8.3	39.0
7.	Martinsdale	67	23.2	1.53	0.13	0.82	0.37	7.7	35.8
8.	Meagher	152	21.9	1.47	0.11	1.00	0.36	7.8	48.3
9.	Sawicki	116	18.8	1.56	0.07	1.36	0.27	6.9	> 152.4
10.	Turner	61	12.7	1.40	0.12	0.63	0.27	7.9	47.0
11.	Windham	91	22.7	1.47	0.09	0.69	0.42	8.1	53.3

Note : Soil thickness was calculated as the weighted average thickness of the A and B horizons using the method described in equation 3-1.

Obtaining Yield Estimates

Development of crop potential data (or dependent variables) was approached through calculations and estimations. Three algorithms were employed to calculate yield estimates for the study sites. Equations by Brown and Carlson (1990) for estimating winter and spring wheat yield potentials, and an equation by Bauder et al. (1978) for predicting alfalfa crop yield were used. The algorithms used were based on PAW and/or ET (inches) values as follows :

for winter wheat : $Yw = 5.8 * (PAW - 3.9)$ bushels/acre [Eq. 3-2],

for spring wheat : $Ys = 5.1 * (PAW - 3.8)$ bushels/acre [Eq. 3-3],

and for alfalfa hay : $Y_A = 0.2 * (ET)$ tons/acre [Eq. 3-4].

For purpose of this study and for development of these three models, PAW is defined as stored soil water and additional water (inches) during the growing season. PAW estimates were equated with ET for use in equation 3-4. The PAW values which were substituted into equations 3-2, 3-3, and 3-4 were generated from two sources of data, NRCS-USDA and MAPS Atlas.

Five different databases of yield estimates were developed for subsequent analysis with the independent soil variables. These databases were identified as 1) NRCS, 2) MAPS-1, 3) MAPS-2, 4) MAPS-3, and 5) Producers' survey.

NRCS

The lack of reliable long-term actual crop yield records for each soil series of the study necessitated use of previously documented yield estimation models to obtain dependent data. One source of yield estimates was that the NRCS-USDA. The NRCS-USDA utilizes soil survey results to predict crop-yields based on estimates of plant available water.

MAPS

Data from the MAPS Atlas database (Caprio et al., 1994) were used in conjunction with equations 3-2, 3-3, and 3-4. Information about soil water holding capacity (WHC), mean monthly precipitation (Ppt), and potential evapotranspiration (PET calculated using

Penman method) were generated from this database. The extracted information was then used to produce three different PAW or potential water use values.

- MAPS-1

MAPS-1 utilized the information on soil water holding capacity - WHC (variable number 104 of the MAPS Atlas database) and precipitation - Ppt during the growing season to calculate PAW values as follows :

$$PAW = WHC + Ppt \qquad \text{[Eq. 3-5]}$$

where Ppt (precipitation) for alfalfa was taken from March through September (variables 89 through 95); for spring wheat from May through August (variables number 91 to 94), and for winter wheat from April through July (variables number 90 to 93).

- MAPS-2

The method referred to as MAPS-2 considered PAW values were similar to PET values calculated by the Penman method from April through September (variables number 37 through 42). PET (potential evapotranspiration) for winter wheat = PET values from May through July + 1/3 PET in August, for spring wheat, PET = 1/2 PET in May + PETs of June and July, and 1/3 PET in August (Schaff, personal communication); and PET for alfalfa = PET from April to August + 1/2 PET in September (Bauder, personal communication).

- MAPS-3

Considering the MAPS-2 method, Bauder (personal communication) suggested making an adjustment to derive an additional PAW estimate. The adjustments combined the MAPS-1 and MAPS-2 methods to include PET, WHC and Ppt data for calculation. The adjuster - X value was calculated as follows :

$$X = (WHC + Ppt)/PET \quad \text{[Eq. 3-6]}$$

and the PAW was approached using the following equation :

$$PAW = PET \times X \quad \text{[Eq. 3-7].}$$

Ideally, if PAWs were equal to PET, then this X values would equate to 1.0. Otherwise, the X value would be a proportionality less than 1.0, thereby reducing the Ppt contribution to PAW. The climatic data used in equations 3-6 and 3-7 were similar to those in equations 3-5. Based on PAW values obtained from application of equations 3-5 and 3-7, and the data from MAPS Atlas (Caprio et al., 1994), crop yield estimates were calculated using equations 3-2, 3-3, and 3-4 for estimating yield potentials of spring and winter wheats, and alfalfa, respectively. A summary of the PAW values calculated using the procedures defined as MAPS-1, MAPS-2, and MAPS-3 is presented in Table 3-5.

Table 3-5. Summary of the estimated PAW or potential water use value from the three MAPS methods.

No.	Soil Series	Estimated PAW value								
		MAPS-1 method			MAPS-2 method			MAPS-3 method		
		W	S	A	W	S	A	W	S	A
		inch								
1.	Amsterdam	14.3	14.1	17.8	20.5	18.2	30.2	19.8	19.7	20.0
2.	Beanlake	17.9	17.5	20.8	20.0	17.7	29.6	19.1	19.0	19.4
3.	Beaverton	17.3	17.0	21.1	20.9	18.4	30.7	20.0	19.9	20.2
4.	Blackdog	17.6	17.2	21.4	20.9	18.4	30.7	20.2	19.9	20.2
5.	Bozeman	16.3	15.7	20.5	21.1	18.6	31.0	20.2	20.1	20.4
6.	Kelstrup	18.2	17.8	22.1	21.1	18.6	31.0	20.2	20.1	20.4
7.	Martinsdale	17.6	17.2	21.5	19.9	17.6	29.2	19.1	19.0	19.3
8.	Meagher	12.7	12.5	16.2	20.4	18.0	29.9	19.7	19.7	19.9
9.	Sawicki	18.6	17.5	24.4	19.0	16.8	27.4	18.0	17.9	18.2
10.	Turner	17.0	16.7	20.3	21.1	18.7	31.0	20.3	20.2	20.5
11.	Windham	15.6	15.5	20.2	18.2	16.1	26.7	17.3	17.2	17.5

Note : W = winter wheat, S = spring wheat, A = alfalfa.

Producers' Survey

Another method used to obtain yield potentials was by direct estimation. Seven experienced crop producers (Morgan et al., personal communication) from the Gallatin Valley were asked to provide estimated yield potentials at seven of the eleven sites. The predictions were based on their experiences, a data set of soil and climatic conditions at each site, and an actual field site inspection where the producers discussed limitations and potentials before providing yield estimates.

Dependent Variables

Dependent variables in this study were yield prediction estimates of three indicator crops corresponding to the eleven selected soil series. The indicator crops were spring and winter wheat *(Triticum aestivum L.)*, and alfalfa (*Medicago sativa L.).* Yield estimates from NRCS, application of MAPS-1, MAPS-2, and MAPS-3 data to equations 3-2, 3-3, and 3-3, and from producer estimates were the primary sources of data used in the dependent variable analysis. A summary of the various yield estimate abbreviations, by method of derivation, is presented in Table 3-6.

All of the yield data were treated as dependent variables. For purposes of statistical analysis, crop names (dependent variables) were abbreviated W (winter wheat), S (spring wheat), and A (alfalfa). Numbers following these three letters in Table 3-6 indicate sources of data or information. For example, A-1 means the yield estimation for alfalfa (A) was based on NRCS estimates (1).

Table 3-6. Dependent variable, code, and dimension of unit included in subsequent analysis.

Dependent Variable by method	Code	Unit
Alfalfa Hay NRCS	A-1	Mg/ha
Alfalfa Hay MAPS-1	A-2	Mg/ha
Alfalfa Hay MAPS-2	A-3	Mg/ha
Alfalfa Hay MAPS-3	A-4	Mg/ha
Alfalfa Hay Producers	A-5	Mg/ha
Spring Wheat NRCS	S-1	Mg/ha
Spring Wheat MAPS-1	S-2	Mg/ha
Spring Wheat MAPS-2	S-3	Mg/ha
Spring Wheat MAPS-3	S-4	Mg/ha
Spring Wheat Producers	S-5	Mg/ha
Winter Wheat NRCS	W-1	Mg/ha
Winter Wheat MAPS-1	W-2	Mg/ha
Winter Wheat MAPS-2	W-3	Mg/ha
Winter Wheat MAPS-3	W-4	Mg/ha
Winter Wheat Producers	W-5	Mg/ha

Note : 1 = NRCS, 2 = MAPS-1, 3 = MAPS-2, 4 = MAPS-3, 5 = Producers.

Statistical Methods

Independent and dependent variables used in the statistical analysis were all coded and are listed in Tables 3-2 and 3-6, respectively. Values for the independent variables used in the analysis were those listed in Table 3-4. Values for the dependent variables determined by the five estimation procedures are presented in the Results and Discussion (Tables 4-2 through 4-6). Analyses were conducted using Statistical Analysis System (SAS Inc., 1994) procedures.

Correlation Analysis

Correlation analysis was conducted using SAS Process Correlation (SAS Proc Corr) procedure, with the strength of relationships indicated by Pearson's correlation coefficient, commonly known as r (small r). The p-values (probability of significance due to treatment effect) at the 0.05 and 0.01 probability levels were determined using a t-test.

Initial analysis was completed to determine relationships among the independent variables. The eight independent variables from 11 soil series were assessed to determine correlation with each other. Any strong relationship among independent variables was inspected and subsequently assessed for possible collinearity. SAS procedures were also used to diagnose collinearity relationships among the selected independent variables. The independent variables were subsequently-correlated with the dependent variables to identify variables having strong associations with independent variables.

Regression Analysis

SAS stepwise linear regression analysis (SAS Inc., 1994) was conducted to identify soil parameters (independent variables) which were associated with estimated yields (dependent variables). This procedure worked in forward selection and assessed the significance of each independent variable sequentially. The process added variables one by one, depending on calculated F-statistic values. Variable having the highest F-statistic value was included first. Variables with successively lower F-statistic values were sequentially considered. The NRCS soils data/information was the source of the independent variables.

This procedure helped produce regression models. Besides that, this procedure was also expected to help identify the "best" fit independent variables for regression model development. The best variables were then used to develop predictive models for estimating yields.

4. RESULTS AND DISCUSSION

The primary intent of this investigation was to design, conduct and assess a study that would provide an experience of utilizing soil survey and inventory data in an assessment of soil quality. Admittedly many approaches to soil quality have been proposed in the scientific literature and no single method has received universal acceptance. The approach used here was designed to investigate assessment of soil quality and soil potential based on a very limited set of data. Soil quality was not, in fact, defined specifically at any point in the design of this investigation. This was a concerted decision of the design, in as much as it was recognized that soil quality is dictated by the intended use of the soil resource.

Specifically for this study, the notion of soil quality was transposed with site potential for growth and agricultural production of three crops, i.e., spring and winter wheat and alfalfa. Hence, the underlying premise of this investigation was as follows : the experience of defining soil quality or potential, assessing available soil inventory data, and utilizing soil inventory data and other available resource information would expose the researcher to the diversity of approaches available for utilizing soil inventory data in the process of assessing soil quality or site capability.

Slope Impacts on Soils and Estimated crop yields

Soil mapping units (SMU) with which the soil series were associated are shown in Appendix E. The SMUs were coded with a combination of numbers and characters.

Numbers indicate the order of the soil mapping units, and characters affixed to the numbers represent slope classes of the mapping units. For instance, SMU 53B equates to mapping unit 53, slope class B. The mapping unit descriptions are part of Soil Survey Inventory Report of Gallatin County, Montana being processed by the NRCS-USDA of Bozeman. The slopes of the study sites were grouped into A, B, and C classes, which represented slope gradients of 0-4, 4-8, and 8-15 m/100 m, respectively.

NRCS yield estimates of a single soil series located on slope classes of A, B, and C were similar (Appendix E) (NRCS-USDA, 1997). In fact, yield estimates for soils of a single series with multiple slope classes did not differ significantly. The lack of significant differences in yield due to variation in slope might be the consequence of the narrow range of slope gradients of the selected soils used in this analysis. All of the selected soil series were located on slope classes of less than 15 m/100 m. One would expect some degree of significance in variation in yield among similar soils with extreme variations in slope gradient. These variations would be due to differences in solar radiation, rainfall interception, runoff, erosion, and drainage.

Crop Yield Estimates

NRCS

Table 4-1 shows crop yield estimates reported by NRCS-USDA for the eleven soil series of this study. The yield estimates for winter wheat ranged from 2.08 Mg/ha (31 bu/ac) to 4.43 Mg/ha (66 bu/ac), for spring wheat from 1.81 Mg/ha (26.9 bu/ac) to 3.94 Mg/ha (58.5 bu/ac), and for alfalfa from 1.68 Mg/ha (0.8 t/ac) to 4.49 Mg/ha (2.0 t/ac). Beaverton series had the lowest estimated winter wheat and alfalfa yields, and essentially the same estimated spring wheat as Windham series, which had the lowest spring wheat yield. The greatest yields occurred with the Bozeman series for the three crops. Estimated alfalfa yield was relatively high in the Amsterdam and Blackdog series. Based on evaluations by NRCS-USDA, the capabilities of the soils were classified into class 3E for general irrigated and non-irrigated farm uses (NRCS-USDA, 1998). Agricultural potentials of the soils were rated as low, medium, and high (Rolfes, personal communication).

Table 4-1. Agricultural potential rating and yield estimate of winter wheat, spring wheat, and alfalfa on selected soil series, based on NRCS-USDA evaluation.

No.	Soil Series	APR	Estimated Yield					
			Winter Wheat		Spring Wheat		Alfalfa	
			Mg/ha	bu/ac	Mg/ha	bu/ac	Mg/ha	t/ac
1.	Amsterdam	high	4.30	64.0	3.82	56.8	4.49	2.0
2.	Beanlake	med	3.43	51.0	3.05	45.4	3.37	1.5
3.	Beaverton	low	2.08	31.0	1.87	27.8	1.68	0.8
4.	Blackdog	high	4.17	62.0	3.70	55.0	4.49	2.0
5.	Bozeman	high	4.43	66.0	3.94	58.5	4.49	2.0
6.	Kelstrup	med	3.63	54.0	3.22	48.0	3.37	1.5
7.	Martinsdale	med	3.43	51.0	3.05	45.4	4.04	1.8
8.	Meagher	med	3.16	47.0	2.81	41.8	3.37	1.5
9.	Sawicki	low	2.28	34.0	2.04	30.4	2.24	1.0
10.	Turner	med	2.89	43.0	2.58	38.3	3.37	1.5
11.	Windham	low	2.02	30.0	1.81	26.9	2.24	1.0

Note : Conversion from Mg/ha to ton/acre, multiply the value by 0.4457, and from Mg/ha to bushel/acre, multiply the table value by 14.881.
APR = agricultural potential rating; bu/ac = bushel/acre; t/ac = ton/acre; med = medium.