Evaluating the performance of the soil productivity index (PI) model in Cascade County, Montana
by Kristin Elva Sorensen Gerhart

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

Abstract:
The Productivity Index (PI) model developed by Pierce and associates at the University of Minnesota for initial use in the Corn Belt is evaluated for application in the northern Great Plains. In the project's first phase, the PI model is used in conjunction with the USDA Soil Conservation Service SOILS-5 data base to generate soil productivity ratings for agricultural soils in Cascade County, Montana. These PI values are regressed against small grain yield data from SOILS-5 and the Cascade County Area Soil Survey to test the model's ability to estimate actual soil productivity. The regression results indicate that the existing model is not as successful as it was in the Corn Belt, explaining only 40% (average r2 = .40) of the variation in Cascade County barley, spring wheat and winter wheat crop yields. The project's second phase explores potential additions to the PI model. Four factors known to be important yield determinants are examined in conjunction with PI values using multiple regression analysis to investigate how well they improve the explanation of crop yield variations. These analyses did improve the r2 values to greater than .50 for spring wheat and barley.

Several aspects related to the quality and consistency of input data, the model's current design and the need for model extensions are discussed. However, from the results of the multiple regression analyses it is concluded that the model's success in the northern Great Plains requires the addition of other parameters to account for climatic, topographic, and calcium carbonate effects on soil productivity. Overall, the PI model appears to be a promising tool for extensive soil productivity and soil erosion studies in Montana and the northern Great Plains.

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APPROVAL

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ABSTRACT

The Productivity Index (PI) model developed by Pierce and associates at the University of Minnesota for initial use in the Corn Belt is evaluated for application in the northern Great Plains. In the project's first phase, the PI model is used in conjunction with the USDA Soil Conservation Service SOILS-5 data base to generate soil productivity ratings for agricultural soils in Cascade County, Montana. These PI values are regressed against small grain yield data from SOILS-5 and the Cascade County Area Soil Survey to test the model's ability to estimate actual soil productivity. The regression results indicate that the existing model is not as successful as it was in the Corn Belt, explaining only 40% (average $r^2 = .40$) of the variation in Cascade County barley, spring wheat and winter wheat crop yields. The project's second phase explores potential additions to the PI model. Four factors known to be important yield determinants are examined in conjunction with PI values using multiple regression analysis to investigate how well they improve the explanation of crop yield variations. These analyses did improve the r^2 values to greater than .50 for spring wheat and barley.

Several aspects related to the quality and consistency of input data, the model's current design and the need for model extensions are discussed. However, from the results of the multiple regression analyses it is concluded that the model's success in the northern Great Plains requires the addition of other parameters to account for climatic, topographic, and calcium carbonate effects on soil productivity. Overall, the PI model appears to be a promising tool for extensive soil productivity and soil erosion studies in Montana and the northern Great Plains.

CHAPTER ONE

INTRODUCTION

Scope and Purpose

Soil erosion represents the disturbance and transport of surface soil by wind and/or water. Rates of soil formation match the pace of surface soil removal (about 3-4 cm per 1,000 years) and soil depth is maintained in environments free of human disturbance over long periods of time (Beckman and Coventry, 1987). Although rates of erosion fluctuate over shorter time scales in these undisturbed environments, rates of soil formation show little change, and periods of net loss are offset by periods of net gain. However, many types of human land use cause accelerated erosion rates several times greater than the natural rates of soil displacement and soil formation. Hence, the balance between rates of soil formation and removal is lost, leading inevitably to shallow and less productive soils.

Accelerated erosion rates are cause for concern because productive soil is an essential resource which contributes to the nation's economic development and the general well-being of its people. Our modern agricultural activities make intense demands on our soil resources, and in doing so, lead to the removal of valuable topsoil faster than it can be replaced. These losses of topsoil are accompanied by losses of organic matter, favorable soil structure, water holding capacity, nutrients and rooting depth, and they often produce soils which are less productive. Thus farmers are presented with the problem of maintaining or increasing soil productivity, or yield per unit area, over extended periods of time. Although it is possible for erosional processes to alter the soil profile in a positive manner, most commonly the effect is negative. The farmer then must choose between accepting lower crop yields or replacing lost nutrients in order to maintain previous productivity levels. The result, through either product scarcity and/or higher food production costs, is higher food prices.

Crosson (1983, p. 41) defines the concept of productivity as "ratio of output of product or services to the input of resources used per unit of time to produce the output." However, in a specifically soil-related study such as this one, a more precise statement defines productivity as "the capacity of a soil in its normal environment for producing a specified plant or sequence of plants, under a specified system of management" (Meyer et al., 1985, p. 219).

Several approaches toward quantifying the effect of soil erosion on soil productivity have been formulated over the past fifty years. The United States Department of Agriculture (USDA) has been the most consistent sponsor of this research, and the Soil Conservation Service (SCS) recently named quantification of the erosion/productivity relationship as its top priority (Sharpe, 1984). In 1980, the Secretary of Agriculture appointed a National Soil Erosion - Soil Productivity Research Planning Committee to investigate and define the factors, issues and methods involved with this relationship.

A number of scientists have described the deficiencies of past and present studies and have also argued the need for more rigorous and conclusive assessments (Flach and Johannsen, 1981; Meyer et al., 1985; Larson, 1986; Daniels et al., 1987). For example, Crosson (1983, p. 44) states that the earlier studies "do not permit valid general statements of how much national agricultural productivity has been, or is being, lost to erosion." Similarly, Poincelot (1986) notes that while yields and profits have continued to be adequate, they are based on an increase in technological inputs which support high yields, and thus yield decreases due to erosion tend to be overlooked.

Dudal (1981) suggested that research on achieving high levels of biologic productivity and on the land's ability to recover and maintain its productivity is necessary to guarantee the stability of our agriculture systems for future generations. The study presented here responds to Dudal's suggested research directions requiring investigations into the effects of erosion on long-term soil productivity. One approach involves the use of models to estimate soil productivity change over time. The Productivity Index (PI) model developed by Pierce and associates at the University of Minnesota (Pierce et al., 1983; 1984a; 1984b; 1984c) is precisely such a tool, and thus its application to Montana's soils and grain crops will be critically examined in this study. Although the Minnesota PI model investigations were performed using the soils and crops of the Corn Belt, their tentative conclusions regarding the PI model's performance with small grain crops provided cause for optimism when applying the model to a northern Great Plains environment.

The major objective of this project is to evaluate whether or not the PI model can be used to quantify the effects of erosion on soil productivity for the soils and crops found in Cascade County, Montana. The overall outcomes of this study will assist with the evaluation, and targeting of soil conservation efforts, as well as continued study of the agricultural soils that are vulnerable to erosion. Specifically, there are four reasons for evaluating the PI model's performance in Cascade County. First, because the PI values calculated by the model provide estimates of current soil productivity as well as future productivity conditions following simulated rates of soil loss, successful use of the model will provide a systematic, consistent method of identifying soils most susceptible to erosion-induced soil productivity losses. Second, the model becomes an "analytical tool" useful in locating land areas where it is most urgent and efficient to adopt conservation efforts (Runge et al., 1986, p. 46). Third, the model results will help with the compilation of erosion risk assessment maps as urged by Daniels et al. (1985), who criticized the current method of mapping erodible soils using small numbers of rainfall intensity measurements. Finally, soil vulnerability indices similar to those developed by Pierce et al. (1984b) could be produced from analyses of soil data using the PI model, perhaps in conjunction with the soil vulnerability maps.

Quantifying the Effect of Erosion on Soil Productivity

Assessments of soil erosion/soil productivity relationships require experimental designs based on complex considerations. First, studies must encompass soils of all productivity levels because erosion affects deep, shallow, rich and poor soils in different ways. This is because individual and combined soil horizons present different combinations of texture, structure, temperature, water storage, nutrients, salts, unweathered material, and physical impedance to root growth. For example, a study performed only on deep loess soils may not produce useful conclusions since productivity on such a soil will nearly always be high. The productivity of these soils is not sensitive to soil profile changes which occur during the erosion process. Thin, less favorable soils, being more sensitive to a loss of depth, would produce quite different results. Finally, soils of average depth and productivity fall somewhere between the two extremes. Therefore, research must incorporate a design which evaluates both deep, medium and shallow soils.

The problem of quantifying the effect of erosion on soil productivity is difficult for two additional reasons. First, studies must consider the complex interrelationships between soil productivity and variation in landscape positions, growing seasons and moisture availability regimes, as well as those between landscape position and erosion rate (Daniels et al., 1985). Second, rates of productivity losses may not be constant over time, meaning that a similar amount of erosion during the second ten years may reduce productive potential more than during the first ten years (Meyer et al., 1985). Experiment design thus presents a perplexing and intricate problem.

The first studies designed to explore the connection between erosion and soil productivity were carried out in the first half of this century (Crosson, 1983). These studies occurred at the time when incentives to boost crop yields were widespread, and the use of new technology in the form of fertilizers, pesticides and machinery disguised the actual effects of erosion on the soil itself. These complicating factors, combined with the problems of research expense, collection of large amounts of high quality data and the popular belief that farmers had largely succeeded in stabilizing soil movement through new tillage practices, limited the number of studies examining the productivity effects of erosion (Crosson, 1983). Most of the early research tested the effects of erosion on the soil's rooting environment in small simulation plots or actual field situations (e.g., Daniel and Langham, 1936; Finnel, 1948; Stallings, 1950).

Unfortunately, the limited scope of these microstudies did not provide an adequate basis for comprehensive deductions. Specifically, the results were derived from small scale, controlled environments and they required field verification (Meyer et al., 1985, p. 222). Additionally, Langdale and Schrader (1982, p. 44) warned that the results are outdated and cannot be used either for predicting modern crop yield responses to eroded soils or for comparison with the results of current studies. Nevertheless, the microstudies did uphold the important concept that repairing soil erosion damage depends on both the type of erosion and the characteristics of the damaged soil (Crosson, 1983).

The concept of soil loss tolerance (T) values also arose from the newly gathered information and study results of the 1940s (Crosson, 1983). Expressed in tons per acre per year, a T value represents the amount of soil which can be removed from the soil profile before a loss in productivity becomes evident. Soil scientists generally concur that there is little scientific basis for the T values which are assigned to soils according to their topsoil depths and depths to restrictive layers (Gibbon, 1984; Nowak et al., 1985). Indeed, Wischmeier and Smith (1962, p. 156) explain that the assignment of T values is "largely a matter of judgement based on observations." From a more current perspective, Larson et al. (1983) suggest that the rate of soil formation is commonly used to determine T values. However, McCormack and Young (1981) concluded that the criteria now used to determine T values are unsound, mainly because the effects of erosion on productivity are not well understood. Successful application of the PI model to Great Plains environments would increase knowledge of such effects and establish more valid criteria for specifying tolerable soil loss under Great Plains soil and crop conditions. Substitution of PI model results in place of T values has already been investigated for soils in the Corn Belt (Pierce et al., 1984a).

The discovery from these early studies that erosion adversely impacted soil productivity partly explains why research in the 1960s began to shift away from productivity effects of erosion to related aspects of soil erosion such as the measurement of erosion rates, minimizing wind and water energy over field surfaces, and formulating erosion control strategies (Meyer et al., 1985). In addition, further improvements in agricultural technology, which served to increase crop yields again, caused the soil erosion/soil productivity problem to lose urgency.

Soon it was recognized that better quantification and prediction of soil erosion effects were needed. This new interest was spurred by the improved availability of data on erosion rates, soil properties and yield, as well as by rising fuel and other farming costs. Research turned again to the soil erosion/soil productivity problem and focused upon a variety of new approaches. One procedure involved the removal of topsoil to examine the influence of shallower rooting zones (e.g., Tanaka et al., 1986). Another approach employed newly collected information on land capability subclasses and erosion rates (Krauss and Allmaras, 1982). A third method relies upon regression analysis of past yields and past erosion rates in an effort to predict how current erosion rates will affect future crop yields (e.g., Crosson, 1985).

During this period, the first U.S. National Resources Inventory (NRI) was completed in 1977 as required by the Soil and Water Resources Conservation Act (RCA), Public Law 95-192 (USDA-SCS, 1984a). It is reasonably suggested by Crosson (1983) that the enormous volume of data collected for the NRI and made available through computers spurred the creation of macrostudies. Two significant advances in research strategy were thus made possible by the NRI. First, it enabled a considerable extension in the geographic scope of research. Second, and more importantly, the NRI made it possible to incorporate analysis at the fundamental level of individual soil properties. None of the microstudies had the capability of assessing as much diverse information over such large geographic areas.

The first of the macrostudies, thoroughly described by Crosson (1983), was the Yield-Soil Loss Simulator or Y-SLS. Crop yields were predicted with the Y-SLS equation, as functions of the combined depths of topsoil and two subsoil horizons, average slope, land capability subclass, soil texture and use of irrigation. Separate Y-SLS equations were developed for the 1977 NRI to assess soil erosion/soil productivity relationships for ten major crops and 21 water resource regions throughout the nation. The results were viewed skeptically because the input data were thought to be questionable and the model itself had been developed under a very strict time schedule. Essentially, the Y-SLS was considered a learning experience and it has indeed served as "the point of departure" for two more comprehensive and sophisticated modeling efforts (Crosson, 1983, p. 45).

The first and more substantial of these efforts consists of the Erosion/Productivity Impact Calculator (EPIC) model. The development of EPIC was prompted by the USDA National Soil Erosion -- Soil Productivity Research Planning Committee and its completion was rushed in order to report on the impact of erosion on long-term soil productivity in the 1985 RCA Appraisal (Williams et al., 1984; 1985). The nine sets of inputs required by the EPIC model incorporate weather, hydrology, erosion and sedimentation, nutrient cycling, plant growth, tillage, soil temperature, economics and plant environmental control (Williams et al., 1984). The model is capable of simulating hundreds of years of erosion on a daily basis and, unlike much soil erosion/soil productivity research, it incorporates the effects of crop management changes and economic impacts. Its authors claim that EPIC has produced "reasonable results under a variety of climatic conditions, soil characteristics and management practices", and has also demonstrated "sensitivity to erosion in terms of reduced crop production" (Williams et al., 1984, p. 141). However, EPIC's data requirements are formidable and the model is perhaps best used as it is now, by government agencies which possess the necessary data and personnel resources for national scale assessments.

The second successful modeling effort following the Y-SLS has seen development and testing of the PI model by Larson, Pierce, and their associates at the University of Minnesota (Larson et al., 1983; Pierce et al., 1983; 1984a; 1984b; 1984c). Their model was derived from an earlier equation constructed by Kiniry et al. (1983) at the University of Missouri. Most of the modifications to the original model were made in order to take advantage of the USDA-SCS SOILS-5 data base (which supplies most of the input data) and to accommodate additional concepts relating to variable soil conditions (Pierce et al., 1984a).

Underlying the PI approach is the premise that crop yields are closely related to the rooting environment provided by the soil. The model focuses, therefore, on inherent soil properties and based on these variables, it calculates the productive capability of the soil represented by Productivity Index (PI) values ranging from 0.0 to 1.0. The model is capable of predicting future PI values as the soil profile is affected (lowered) by erosion over time, because it analyzes the different horizons in the soil profile.

It is necessary, however, to recognize the effect of site-specific factors which may strongly skew the calculated PI values. These factors, which are not evaluated by the PI model, include steeply sloping, depressional or frequently flooded lands, and soils with high organic contents. The University of Minnesota study (Pierce et al., 1984a) demonstrated that the relationship between PI and yield (measured by the coefficient of determination, r^2) is much improved by excluding these special cases from the regression analyses used for model verification. Therefore, the impact of these factors (and perhaps additional environmental factors) must be carefully considered, especially when applying the PI model to locations other than the Corn Belt.

The model has other limitations related to three basic assumptions made in order to hold a number of factors constant. First, climate variability within a study region and between study regions (i.e., the Corn Belt and Cascade County) was presumed to have no effect on the model's performance. This assumption means that PI values generated in dissimilar climatic regions cannot be compared with each other since regional climatic conditions exert different influences on soil productivity. Second, it was assumed that a high level of farming technology (machinery, biocides, fertilizers, etc.) was used in crop production and therefore, that farming technology could not account for variations in crop yields. Third, the NRI erosion rates were accepted as estimates of future erosion in the next 50 to 100 years. These assumptions might be viewed as model limitations since they introduce generalization.

The initial development and testing of the model by Pierce and his associates took place in the U.S. Corn Belt (Pierce et al., 1983). They found that high PI values correlated strongly with high crop yields and low PI values with low yields. The productivity indices generated by the model represented productivity loss per centimeter of soil and thus, when combined with a known rate of soil removal (in cm yr^{-1}), a rate of productivity loss or gain could be calculated. Pierce et al. (1984c) used their PI values in conjunction with the 1977 NRI soil erosion rates to estimate the productivity changes of individual Corn Belt soils after 25, 50, and 100 years of simulated erosion. Following these first tests on soils supporting corn crops, Pierce and his associates demonstrated that their model may perform well for soybeans, barley, spring wheat, sunflower and oat crops in Minnesota (Pierce et al., 1984b).

The relatively simple and explicit nature of the PI formula prompted the International Federation of Institutes for Advanced Study (IFIAS) to evaluate model performance in Nigeria, India, Mexico and Hawaii (Rijsberman and Wolman, 1985). The model lends itself to application in diverse regions since it is designed without a complicated equation and does not require complex data inputs and computations. Therefore, possible model modifications and deficiencies are more easily identified. Although IFIAS' international applications of the PI model might best be considered tentative, mainly because data quality and availability were not equivalent to the data used by the University of Minnesota researchers, Rijsberman and Wolman (1985, p. 354) did conclude that "the PI approach appears to be a promising tool" for areas other than the Corn Belt. As soil resource agencies extend and refine their data bases and data management systems, it is desirable to develop models such as the PI model to complement these agencies' efforts. Expanding the use of these data bases using models results in improved and more efficient management of soil resources.

Overall, the PI approach would appear to satisfy several important requirements for improved assessment of the soil erosion/soil productivity problem. As stressed by Meyer et al. (1985, p. 215) it uses "appropriate quantitative data" in "pertinent experiments" which produce quantitative rather than qualitative results. Further, major variables are "experimentally evaluated to determine their relative importance." It was against this background (and these advantages) that this model was chosen for this study, which examines the suitability of using the model to evaluate soil erosion/crop productivity in the northern Great Plains.

Description of Study Area

Situated in northcentral Montana, Cascade County is centered approximately on latitude 47°22'N, longitude 111°20'W and borders the eastern slopes of the Rocky Mountains (Figure 1). In general, the topography ranges from nearly flat or rolling plains in the north to benchlands and mountainous areas in the southwest and southeast.

Approximately the northern two thirds of the study area lies within the Brown Glaciated Plains Major Land Resource Area (MLRA 52), and the other one third is classified as Northern Rocky Mountain Foothills, MLRA 46 (USDA-SCS, 1982a; 1982b) (Figure 1). MLRAs are defined by the USDA as large land areas (i.e., geographic units) having similar soils, climate, water resources and land use characteristics (USDA-SCS, 1984a). Land use in both MLRA 52 and MLRA 46 is characterized by the production of small grains and livestock forage. MLRA 52, with lower elevations (650 to 1,300 m) and less rugged terrain than MLRA 46 (1,200 to 2,000 meters elevation), is more extensively farmed. In both areas most grain is dry-farmed, but many river valleys are irrigated. Rangeland supports short and mid-height grasses as well as some shrubs, while some of the

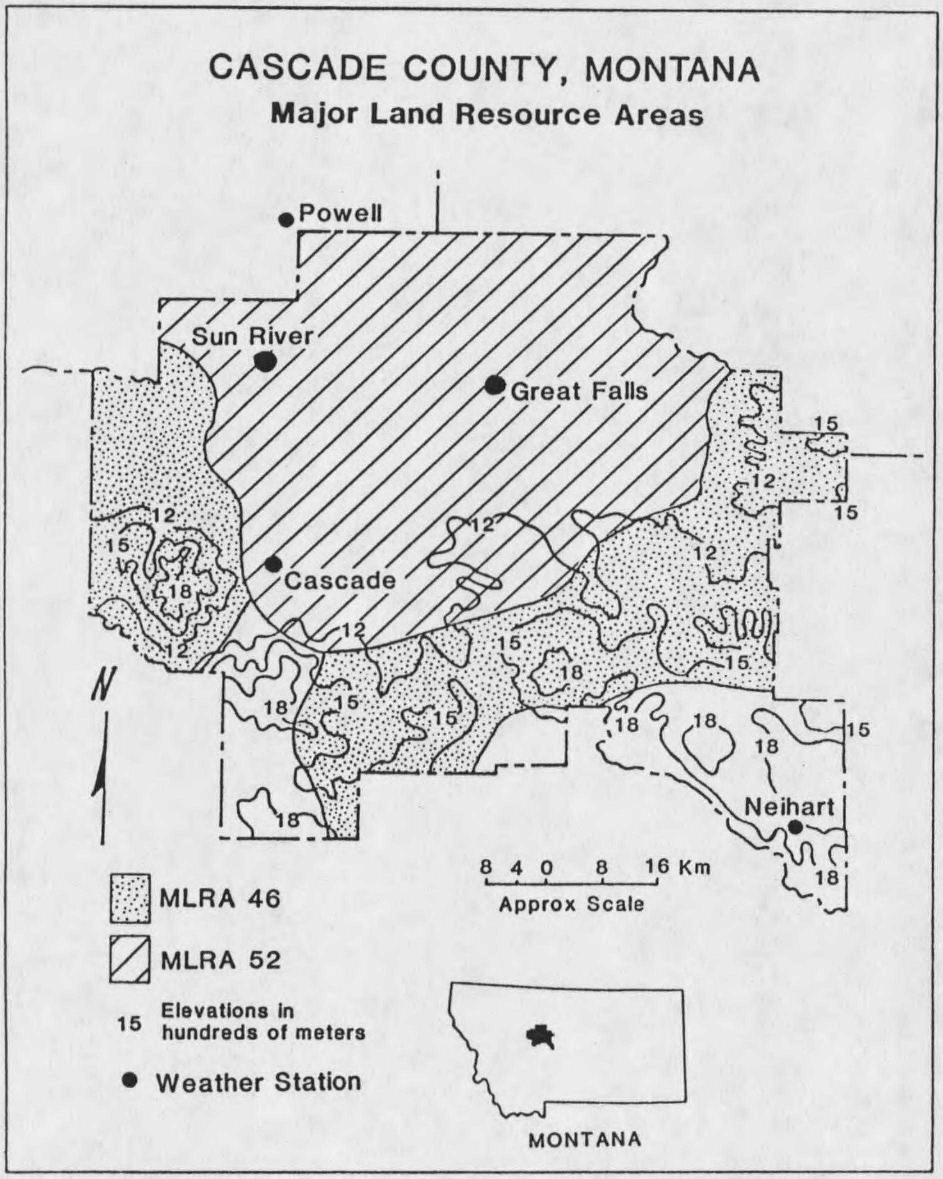

Figure 1. Location of Cascade County, Montana in relation to the Rocky Mountains and Major Land Resource Areas (USDA-SCS, 1982a; 1982b).

higher hills and low mountains are forested. Annual precipitation for both areas ranges from 25 to 43 cm (10 to 17 in), but higher elevations in MLRA 46 receive up to 76 cm (Figure 2). Subsurface glacial till yields ground water in moderate quantities, though in lesser quantities

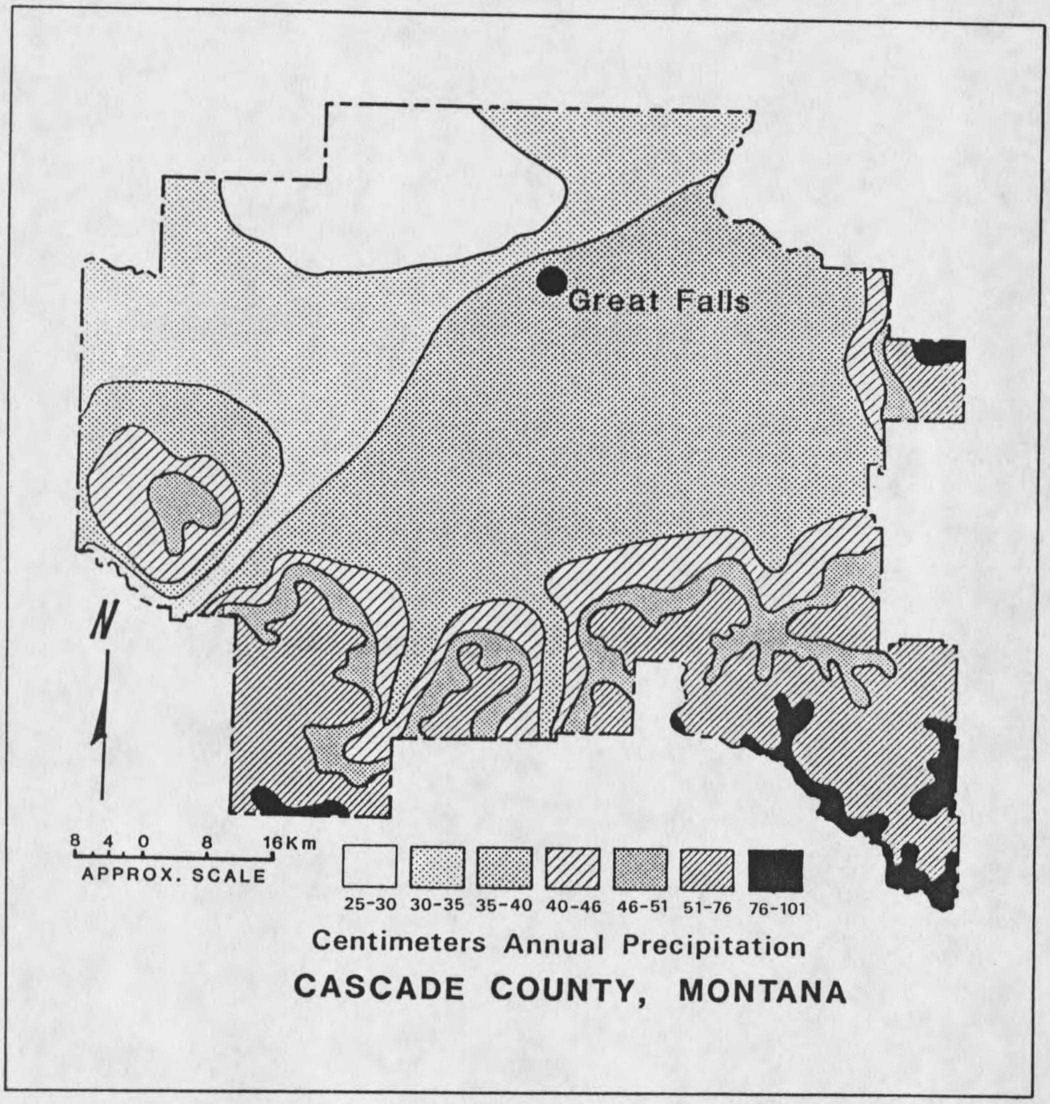

Figure 2. Average annual precipitation over Cascade County (unpublished map prepared by Cascade County Conservation District personnel, January 1987).

in MLRA 46. Soils of both areas are not strongly developed (haploborolls are common) and are often within the ustic soil moisture regime and frigid/cryic temperature ranges (Montagne et al., 1982).

These characteristics indicate cool/cold soils with inadequate plant available water for much of the year (Donahue et al., 1983). MLRA 46 contains mainly Alfisols, while MLRA 52 soils are mostly Mollisols, soils which are preferable for agriculture since they contain higher organic matter contents. Soils in MLRA 52 also commonly exhibit higher amounts of $CaCO_3$ (Calciborolls and Calciorthids) (Montagne et al., 1982; Donahue et al., 1983).

Overall, Cascade County's climate is characterized by low humidity, low winter and hot summer temperatures, and mostly sunny days. In this cool steppe environment precipitation amounts may be highly variable from year to year. By comparing regional topography and relative locations of climate stations (Figure 1) with precipitation data (Table 1, Appendix A, and Figure 2), it is evident that large year to year fluctuations in precipitation are compounded by area to area topographic variations within and adjacent to Cascade County. These data show that locations closer to mountain ranges experience greater precipitation variability than locations removed from the mountain-induced effects. Hence, the weather station at Cascade measured large precipitation fluctuations between 1974 and 1980 when compared to the weather station at Great Falls, located only 40 km to the northeast (Table 1 and Appendix A).

Winter precipitation, which originates in the Pacific mP air mass, falls mainly as snow. Typically snow occurs from November to March, but may fall as early as September or as late as July (Ruffner, 1978). The month of highest precipitation is June, which is then followed by occasional thunderstorms throughout the summer. Most of the summer

Table 1. Mean annual total precipitation (cm) and standard deviation for five weather stations in Cascade County, 1951-1980 (National Oceanic and Atmospheric Administration, 1951 through 1980).

	Climate Station				
	Cascade	Great Falls	Neihart*	Power*	Sun River
Mean Annual Precip.	38.7	37.7	50.7	27.6	31.0
Standard Deviation	10.6	8.5	12.0	6.8	8.6

* Less than thirty years of available data; see Appendix A.

moisture arrives from local thunderstorms and Gulf of Mexico maritime tropical air masses when pressure ridges over the southern Great Plains permit (Warrick, 1975).

Severe droughts lasting two to three years are infrequent. Warrick (1975) states that such dry periods result from development of abnormally persistent mid-continental high pressure ridges which can have the compound effect of both repelling invasion of moist Gulf of Mexico air, and of forcing hot, dry air northward from the southwestern deserts. Less lengthy, but nonetheless critical precipitation fluctuations are common in Cascade County (Table 1 and Appendix A).

The county's position in the lee of the Rocky Mountains imposes a marked rain shadow effect mainly in the northern half of the county (Figures 1 and 2). Here, many farm operations are forced to irrigate in order to obtain profitable crop yields. In the south, the higher elevation benchlands receive more precipitation and are cooler, thus maintaining a higher soil moisture supply. Further, the Little Belt mountain range, located in the southeast part of Cascade County, precludes development of a rainshadow by uplifting and cooling westerly air thus causing higher precipitation in that area of the county.

Cascade County temperatures range from mean monthly lows of -12° C (10° F) to mean monthly highs of 28° C (82° F). Frost-free periods range from 85 to 135 days, the average being 110 days (Montana Agricultural Experiment Station Farm Economics Division and USDA Economics Research Service, 1971). Growing degree days (GDD), another measure of growing season temperature, represent the cumulative number of degrees Fahrenheit over a designated threshold temperature achieved during a year. Based on a 50°F threshold, Cascade County's GDDs range from 1,800 to 2,600 according to the Montana Agricultural Potentials System (MAPS) database developed by the Department of Plant and Soil Science at Montana State University.

Average wind speeds range between 17 and 26 km hr^{-1} and flow predominantly from the southwest (Ruffner, 1978). More importantly, the highest wind velocities occur in the fall and spring months when soil surfaces are exposed to erosive winds (Ruffner, 1978). In winter, strong, warm Chinook winds along the Rocky Mountain front have the detrimental effect of melting protective snow covers, thus leaving the soil open to wind dessication and removal by either wind or water.

Agricultural soils occur on the flat and sloping terrain of plains, fans, benches and terraces. Nearly all of these soils are classified as Mollisols, Aridisols and Entisols. The region's soils are primarily characterized as young soils because the cold, dry climate and relatively short time since the last glaciation contribute to very slow soil formation. Glaciation and glacial materials exert only a partial