A productivity index model for Montana soils
by Stephen Paul Sandor

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

Abstract:
Many agricultural soils of Montana are "vulnerable" to erosion-induced productivity decline because they are shallow and have rates of erosion exceeding 20 Mg ha^{-1} yr^{-1}. As agriculture is vital to Montana, it is important to be able to assess this susceptibility to erosion.

The University of Minnesota's productivity index (PI) model estimates soil productivity by characterization of the soil rooting environment and evaluates a soil's "vulnerabilty" by simulated removal of surface soil and by considering the soil properties: 1) available water-holding capacity, 2) bulk density, and 3) pH. While the PI model has performed well in the Corn Belt (Pierce et al., 1984b) and elsewhere (Rijsberman and Wolman, 1985), continued evaluation was required before its use within Montana.

Evaluation of PI model performance by Montana State University's Earth Sciences Department using the SOILS-5 data base for several Montana counties revealed a weak relationship between PI and crop yield, however, this result may have been due to shortcomings of the SOILS-5 data base. Therefore, soil and crop data collected in August and September, 1987 from four fields in Hill and Jefferson Counties were used to evaluate performance and indicate appropriate changes that are needed in the model's design for its use in Montana.

Results indicate that model performance can be improved through the addition of program statements which consider the content and location of organic matter and $CaCO_3$ in the soil profile. Productivity indexes were generated first using the existing form of the model for each of the four fields sampled. The regression of cereal grain yield against PI accounted for 65, 66, 65, and 1 percent of the. variability (tv) in cereal grain yield within Fields 1 through 4, respectively.

Productivity indexes generated by the modified model were also regressed on cereal grain yield. The resulting R^2 values for the four fields increased an average of 42 percent and accounted for 77, 69, 59, and 75 percent of the variation in cereal grain yield within Fields 1 through 4, respectively. Moreover, R^2 increased slightly (0.69 to 0.75) for. all fields collectively when field cropping history was considered. The modified PI model shows promise and will be further tested using the SOILS-5 data base for several Montana counties.

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Stephen Paul Sandor

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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TABLE OF CONTENTS

TABLE OF CONTENTS-Continued

LIST OF TABLES

LIST OF TABLES-Continued

LIST OF FIGURES

ABSTRACT

Many agricultural soils of Montana are "vulnerable" to erosion-induced productivity decline because they are shallow and have rates of erosion exceeding 20 Mg ha^{-1} yr^{-1}. As agriculture is vital to Montana, it is important to be able to assess this susceptibility to erosion. The University of Minnesota's productivity index (PI) model estimates soil productivity by characterization of the soil rooting environment and evaluates a soil's "vulnerabilty" by simulated removal of surface soil and by considering the soil properties: 1) available water-holding capacity, 2) bulk density, and 3) pH. While the PI model has performed well in the Corn Belt (Pierce et al., 1984b) and elsewhere (Rijsberman and Wolman, 1985), continued evaluation was required before its use within Montana.

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INTRODUCTION

Recent and historical evidence justifies the conclusion that wind and water erosion can reduce potential soil productivity for many crops. Natural erosion has shaped the soils of the earth since the beginning of time. Since the advent of agriculture, erosion accelerated by human activities has often resulted in the loss of precious topsoil and a subsequent decline in the yield of crops. In the older civilizations of India, East Africa, China, and the Middle East, extreme cases of erosion led to poverty, forced migration, and destabilized relations between tribes and countries (Bentley and Leskiw, 1985). Similarly in the United States, the westward migration of the 19th century was partly due to the depletion of eastern soils following nearly 150 years of farming.

Following the drought of the 1930s, which resulted in the abandonment or conversion of thousands of acres of cropland, popular attitudes toward land policy began to shift away from one of moving to new frontiers to a conservation ethic. In the years to follow, worries over declining soil productivity subsided as advances in agricultural technology masked the deleterious effects of erosion.

In the 1970s, shifting world grain markets and investment in larger farm machinery spurred U.S. farmers to cultivate millions of acres considered highly susceptible to soil erosion. As the American public began to see the limits of agricultural growth, researchers renewed their efforts to quantify the relationship between soil erosion and soil productivity, principally on the basis of data from major agricultural regions in the United States (Pierce et al., 1983, 1984a,, 1984b; Williams et al., 1983; Maetzold and Alt, 1986; Timlin et al., 1986). One of the most notable attempts has been the Productivity Index (PI) model developed by Pierce and associates at the University of Minnesota.

The 1982 National Resource Inventory (NRI) reports average erosion rates of 22 Mg ha^{-1} yr^{-1} on cultivated and non-cultivated cropland in Montana (Soil Conservation Staff, 1982). Furthermore, many Montana soils are "vulnerable" to erosion-induced productivity decline due to the prevalence of shallow agricultural soils. The 1982 NRI estimated that erosion control practices such as strip cropping, conservation tillage systems, and better residue management were needed on 61 percent of Montana's cropland (Soil Conservation Staff, 1982). This estimate was based on present erosion rates as derived from the Universal Soil Loss Equation and the concept of soil loss tolerance (T). While this estimate may be reflective of the need to remove some lands from production (e.g., the Conservation Reserve Program), the targeting of the most "vulnerable" soils may best be accomplished using the PI model.

Gerhart (1989) working with John Wilson in the Dept. of Earth Sciences, Montana State University tested the existing form of the PI model using the soils of Cascade County, Montana as reported by the SOILS-5 data base. R^2 values for the regression of PI on winter wheat, spring wheat, and barley yield were 0.29, 0.33, and 0.32, respectively (Gerhart, 1989). These relatively poor results indicated that modification of the model might be necessary to improve PI model performance.

Researchers working in regions outside the Corn Belt have sucessfully used the PI model by altering or adding model statements to account for the response of crops to specific soil characteristics found in their region (Rijsberman and Wolman, 1985). Researchers in Montana have identified several important production factors (Schweitzer, 1980; Burke, 1984) which were not included in the PI model. Inclusion of these factors may improve the PI model's performance within Montana.

The Productivity Index Model

The Productivity Index (PI) model estimates soil productivity by characterization of the soil rooting environment. In addition, the PI model evaluates a soil's "vulnerability". A vulnerable soil being one which quickly becomes less favorable to crop growth as surficial materials are removed. The relationships in the PI model have been derived and tested primarily in the Corn Belt with corn as the target crop. The model uses the USDA-SCS SOILS-5 data base and assumes that the major effect of erosion is to change the soil micro-environment for root growth and, consequently, crop growth. The parameters considered are available water-holding capacity (AWC), soil reaction (pH), and bulk density (BD) with adjustments for family textural class and permeability. In addition, the model makes use of an idealized corn root distribution to weight model parameters for a given horizon depth. Erosion is simulated by the incremental removal of surface soil. This soil removal brings about a new combination of soil properties leading to a potential change in the environment of the root system.

The form of the model used to evaluate soil productivity was:

$$PI = \sum_{i=1}^{n} (Ai * Ci * Di * WFi)$$

where Ai, Ci, Di are the sufficiencies of AWC, BD, and pH, respectively. WF is the weighting factor representing an idealized rooting distribution, and n is the number of horizons in the root zone (Pierce et al., 1983). The sufficiency of a soil property is a value between 0 and 1.0 derived from a response curve for root growth. A sufficiency of 1.0 is indicative of a soil with perfect sufficiency or no limitations with respect to the given soil property.

USDA SOILS-5 Data Base

The PI model was designed to use the SCS SOILS-5 interpretations data file containing soil property and interpretive information for soil series of the United States. SOILS-5 is the only data base available to run the PI model for all Montana soil series.

Data in SOILS-5 are generally reported as ranges or classes of values. Therefore, SOILS-5 data are imprecise. This imprecision influences testing (which also depends on the accuracy of yield estimates contained within SOILS-5) and the ultimate performance of the PI model.

Validating Model Modifications

PI model research at Montana State University has had the goal of obtaining some version of the PI model which can perform adequately using the SOILS-5 data base. This study involves model testing and modification based on a small set of data which does not cover the full range of Montana soil conditions. Therefore, suggested changes to the existing PI model contained in this thesis are subject to revision based on findings of a more comprehensive future evaluation using the SOILS-5 data base.

Thesis Objectives

The objectives of this study were to: 1) evaluate the performance of the existing PI model using data collected within single fields in which crop production and soil properties varied widely, 2) identify soil and site variables important to cereal grain production in Montana, and 3) suggest modifications to improve the performance of the PI model in Montana.

LITERATURE REVIEW

This section reviews research findings in three areas: 1) impacts of soil erosion on soil productivity, 2) soil properties important to dryland cereal grain yield, and 3) properties of calcareous soils.

Impacts of Soil Erosion on Soil Productivity

Beginning in the 1930s, research in the Great Plains has provided considerable evidence that soil erosion has reduced the productivity of many soils. Several approaches to study the impact of erosion on soil productivity have been attempted including: 1) the comparison of crop yield on eroded versus non-eroded lands, 2) soil removal studies, 3) rainfall simulator studies, 4) laboratory studies, and 5) computer modeling.

Burnett et al. (1985) discuss the difficulties researchers have faced in attempting to isolate the effect of erosion on soil productivity from the effects of cropping and technological advance. The variation in erosion, climate, and soils within the Great Plains has further confounded results.

Mathews and Barnes (1940) reported severe declines in sorghum yields at Dalhart, Texas following wind erosion in the 1930s. Fryrear (1981), in studying the declines in sorghum yield at Dalhart and two other sites in Texas, concluded that improvements in crop varieties and cultural practices could not counteract the detrimental effects of erosion on yield.

Finnell (cited by Baver, 1951) attempted to evaluate the separate effects of cropping and erosion on soil productivity in the Southern Great Plains. The study reported wheat yields of 1.75 Mg ha^{-1} on new land, and 1.56 and 1.28 Mg ha^{-1} on land cultivated 6 and 27 years, respectively. Three percent of the declines were attributed to nutrient losses by cropping and only four percent were attributed to erosion effects. The remaining percentage decline in yield was not explained.

Several studies in the Great Plains involve the removal of variable thicknesses of soil to simulate loss by soil erosion. It is questionable whether simulated erosion can be compared to erosion due to the differences in time scale and selectivity of the erosion process for finer particles.

Burnett et al. (1985) summarizes a soil removal study begun in 1955 at Akron, Colorado on a Weld silt loam, a member of the fine, montmorillonitic, mesic, Aridic Paleustolls. Extreme soil removal (up to 38 cm) significantly reduced wheat yields while moderate removal had no effect.

Olson (1977) studied the effect of topsoil removal on corn production of a glacial till soil in the Great Plains. The removal of 30 cm of topsoil decreased yields, but further removal had much less effect. Treatment with Zn increased yields on plots having topsoil removed. Seedbed preparation was difficult on exposed subsoils and resulted in poor seed germination and emergence.

Eck et al. (1965) and Eck (1968; 1969) reported reductions in sorghum yield at all levels of topsoil removal (0, 10, 20, 30, and 41 cm) on a Pullman silty clay loam soil. Furthermore, under limited water conditions, fertilizer did not restore the level of yield lost to topsoil removal.

Massee and Waggoner (1985) report that soil erosion greatly reduced wheat yields on deep, loessial soils in the Intermountain region. Reductions were attributed to reduced soil moisture, infiltration, and nutrient levels, and increases in runoff during fallow. Added fertilizer did not fully replace lost topsoil.

Land leveling experiments in Montana (Reuss and Campbell, 1961; Black, 1968) similarly indicate that, in general, crop yields are reduced following topsoil removal if the physical and chemical characteristics of subsoil horizons are significantly different from topsoil. Although, differences in nutrient levels with depth can be treated, restoration of the productivity of soils with deteriorated physical condition is difficult.

Rainfall simulators offer an alternative to mechanized soil surface removal and permit a degree of selective sorting of soil particles. However, this method does not allow for soil weathering which can occur over time. Furthermore, rainfall simulators are cumbersome and time consuming to operate.

Experiments under controlled conditions in the greenhouse or in the laboratory using soil cores can increase the number of treatments studied. With increased control of production factors, important cause-effect relationships can be defined. However, conclusions made concerning disturbed soils in a greenhouse setting must be field validated.

While losses of topsoil by erosion are widely considered to reduce soil productivity, especially where subsoils are less favorable to plant growth, few studies have quantified the effect over a range of soils. The National Soil Erosion-Soil Productivity Research Planning Committee (Williams, 1981) outlined an approach for assessing the productivity of soils in relation to long term soil erosion. Their suggestions resulted in a series of modeling efforts at several locations. The two approaches that have received the most attention are: 1) the Erosion-Productivity Impact Calculator (EPIC) developed by Williams et al. (1984) and 2) the Productivity Index (PI) model developed by Pierce et al. (1983) at the University of Minnesota based on work done by Kiniry et al. (1983) at the University of Missouri.

EPIC is a process model which operates on a daily time step and consists of components which simulate erosion, plant growth, and related processes, and economic components to estimate the cost of erosion and to determine optimal management strategies. Numerous weather, crop, tillage, and soil parameters are required as input to the model.

Like EPIC, the PI model considers changes in soil profile characteristics with depth. In addition, the model examines a soil's vulnerability or rate of productivity decline when subjected to simulated erosion. The model is simple, easy to understand, uses the SOILS-5 data base as input, and has produced adequate results. Pierce et al. (1984b) evaluated model performance by regressing PI against estimated corn yields from county soil surveys and against Minnesota crop equivalent ratings. R^2 ranged from 0.63 to 0.71 and was increased by 26 percent (0.79 to 0.90) by excluding Histosols, frequently flooded and depressional soils, and soils with slopes exceeding 6 percent. This model has been successfully used and modified in several locations outside the Corn Belt including Nigeria, Hawaii, Mexico, and India (Rijsberman and Wolman, 1985).

Soil Properties Important to Dryland Cereal Grain Yield

While the PI approach has been successfully used outside of the Corn Belt, model statements have often been altered or added to account for the response of crops to specific soil characteristics found in other regions. Similarly, the use of the PI model for Montana soils has required the examination of soil and other related factors which are important to cereal grain yield in Montana. Although numerous measurements can be made to identify a minimum set of soil factors necessary for the adequate performance of the PI model, the following review concentrates on those already recognized as important by researchers in dryland cereal grain production.

Gray (1966) found clay to be positively correlated with wheat yield in Oklahoma suggesting that finer textured soils retain greater amounts of plant available water given the specific pattern of rainfall and temperature during the study years. Allgood and Gray (1978), in designing a model to predict grain yield in Oklahoma, found water to be the most limiting factor. Their model predicted yield by considering slope, clay percent, and organic matter content as they affected soil moisture. Bennett et al. (1980) reported that soil depth was highly correlated with wheat yield in New Zealand. Soil depth is the most important determinant of a soil's available water-holding capacity.

In Montana, Schweitzer (1980) examined differences between Scobey and Kevin soils which occur together on glacial till landscapes. Average calcium carbonate equivalents in the Ap horizon were 0.66 and 4.40% for Scobey (depositional) and Kevin (erosional) soils, respectively. This difference in $CaCO_3$ content was inversely related to wheat yield, P, NO_3-N, K, and organic matter content.

Burke (1984) evaluated selected morphological, classification, climatic, and site variables in relation to small grain yield in Montana. All sites sampled were considered under a high degree of management in terms of fertility, weed, and pest control. Multiple stepwise regression identified available water-holding capacity and depth to $CaCO_3$ as the most important in predicting yield.

Cannon and Nielsen (1984) evaluated soil and site variables of Mollisols under native range at 14 sites in Montana, Wyoming, North Dakota, and Alberta, Canada. Using multiple linear regression they concluded that depth of the mollic epipedon was most indicative of long-term production. Precipitation and depth to $CaCO_3$ were also strongly related to range production.

Larson (1986), in studying the influence of soil series on cereal grain yield in Montana, found depth to $CaCO_3$ and pH inversely related to crop yield. Furthermore, organic matter content was positively related to crop yield. These properties were also highly predictive of P and AWC.

Properties of Calcareous Soils

The calcareous nature of many agricultural soils in Montana is primarily derived from sedimentary parent materials (soft black shales and Tertiary valley-fill) of diverse origin and composition and/or from wind deposited fine sand and silt (Montagne et al., 1982).

Soil Taxonomy (1975) defines a soil to be calcareous when added cold HCl produces effervescence. It does not specify a range in calcium carbonate percentage necessary to be termed calcareous. Smith (1986) reports a lack of agreement between laboratory results and acid bottle tests. Soils which had no effervescence and pH values below 7.0 in KCl in some instances had values of 0.02 to 5.0 percent calcium carbonate equivalent by weight loss. Carbonates located within peds and the presence of dolomite, which exhibits a slow effervescence, may explain this inconsistency.

Secondary accumulation of carbonates ($CaCO_3$ and $MgCO_3$) in soil horizons results from: a) capillary rise and evaporation of water from the surface, b) downward translocation and withdrawal of water leading to precipitation of carbonates, and c) some combination of a and b above (Smith, 1986).

Researchers in Montana (Munn et al., 1982; Larson, 1986) and in other parts of the world (Spratt and McIver, 1972; Karathanasis et al., 1980) have demonstrated that the presence of carbonates in soils has a deleterious effect on crop growth. Several explanations have been proposed but much disagreement remains. The presence of an accumulation of carbonates can have a dominating influence on many physical and chemical soil properties. Among these soil properties are those considered by the PI model: pH, AWC, and bulk density.

Calcareous soils are generally characterized as having pH values near 8.3. This can be explained by referring to a pure system of calcium carbonate and CO_2 in solution which is represented by the following electroneutrality equation:

$$2[Ca^{+2}] + [CaHCO_3^{+1}] + [H^+] = [HCO_3^-] + 2[CO_3^{-2}] + [OH^-]$$

Through a knowledge of the appropriate equilibrium relationships and their formation constants, the above expression dictates a specific pH for a given pCO_2 (partial pressure of CO_2) (Lindsay, 1979). For example, a pure system under standard state conditions and at equilibrium with atmospheric CO_2 gives a pH of 8.34. For a higher pCO_2 of 0.003, a commonly used value for soils in an unflooded condition, the pH decreases to about 8.0.

The range of soil pH for calcareous soil systems is only partially explained by differences in pCO_2. Increasing pCO_2 is only one of many sources of protons in a soil system. Furthermore, protons added to a soil system either from carbonic acid or some other source may not increase the pH of the bulk solution because of high cation exchange capacity. The particular chemistry of a calcareous soil, including the purity of the dominating solid phase, clay mineralogy, amount of organic matter, degree of base saturation, and the cation exchange capacity will determine the specific pH value.

Soil reaction is not a good indicator of the percentage of calcium carbonate in a soil. The soil pH will remain fairly constant so long as some minumum percentage (approximately 1.0 percent) of calcium carbonate is present. While increasing percentages of calcium carbonate theoretically will have no effect on pH, there may be a marked effect on other soil properties important to crop growth. Calcareous soils containing significant amounts of calcium carbonate may affect the fertility of the soil by decreasing the availability of phosphate and various micronutrient anions. Nutrient deficiencies may influence the rooting pattern of crops.

Increases in soil bulk density influence growth of crop roots by increasing mechanical impedance, and altering pore space distribution and patterns of aeration and water transmission (Gill and Miller, 1956). Bulk density values may not predict rooting distributions within horizons of $CaCO_3$ accumulation. Roots penetrate the soil by displacing soil particles or by following existing pores or channels (Aubertin and Kardos, 1965). However, pores and planes of weakness can be rare in horizons where secondary $CaCO_3$ has accumulated. Root penetration by displacement of soil particles occurs when the turgor pressure of the root tip exceeds soil strength (Taylor, 1974). Soil strength decreases as soil moisture content increases, although secondary $CaCO_3$ may act to maintain soil strength and inhibit penetration.

Available water-holding capacity (AWC) is generally considered to be that water held in the soil between 0.033 M Pa and 1.5 M Pa potential. It is not known whether secondary $CaCO_3$ will alter the relationship of measured AWC and crop yield predicted by the PI model.

The depth to carbonates in a soil profile has been correlated with the amount of water moving through the soil (Arkley, 1963). Often calcareous phases of soil mapping units are located on higher, more erosion-prone surfaces than corresponding noncalcareous phases. These soils receive equal amounts of precipitation but the calcareous phases probably retain less. Thus, carbonates may indicate a soil which stores less water than its AWC would suggest.

MATERIALS AND METHODS

Approach

Crop and soil data were collected from four fields in Hill and Jefferson Counties, Montana for input to the PI model. Soil properties recognized by the Minnesota model as well as those recognized as important in Montana varied substantially within the selected fields. Sampling within single fields minimized variability in climate and management. This micro-scale approach complimented PI model research conducted by the Earth Sciences Department at Montana State University on the county level with the SOILS-5 data base. Testing and improving the performance of the PI model in Montana involved comparisons of the predictive ability of the existing model and several altered versions which accounted for additional factors important for cereal grain production in Montana.

Study Site Description

Location

The study of model relationships was carried out using data collected along transects in four fields located within two Montana farms: 1) the Petersen Farm located northwest of Havre, in Hill County and 2) the Woodbury Farm, west of Three Forks in Jefferson County (Figure 1). The two farms differed in terms of parent material, soils, crop, and climate.

Transects were located based on: 1) observed heterogeneity in nearly mature fields of spring grains (wheat and barley) using color infrared aerial photography (an assumption was made that increased heterogeneity indicated increased variability of soil properties), and 2) ground truth which attempted to assure that observed crop variability was due solely to variation in soil properties. It was recognized that many crop areas will be nonuniformly influenced by pests and diseases, weeds, management, and micro-climate (e.g., hail and frost damage, and lodging). Areas chosen for grain harvest were free of these problems. Although the PI model assumes optimum fertility, it is anticipated that nutrient deficiencies were unavoidable, particularly in soils having a calcareous plow layer.

Parent Materials and Soils

The two Havre fields have soils developed from glacial till over the Judith River Formation. This formation is made up of soft interbedded sandstone, sandy shale, mudstone, siltstone, and shale (Veseth and Montagne, 1980). Soils at the two Three Forks fields are developed from variable thicknesses of calcareous loess over the Climbing Arrow Formation. This formation is composed of olive, thick-bedded sandy bentonitic clay and coarse sand with subordinate light-colored siltstone, sandstone, conglomerate, and limestone (Robinson, 1963).