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Productivity Index Model Modified to Estimate Variability of Montana Small Grain Yields

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ABSTRACT

The productivity index (PI) model estimates crop productivity by characterization of the soil rooting environment and evaluates a soil's vulnerability by simulated removal of surface soil and consideration of three soil properties, available water-holding capacity, bulk density, and pH. Although the PI model has performed well in the Corn Belt and elsewhere, further testing is required to demonstrate its applicability in northern Great Plains small-grain environments. Evaluation of PI model performance in Cascade County, Montana, revealed a weak relationship between PI and small-grain yield that may have been due to shortcomings in the SOILS-5 database. Therefore, soils and crop data were collected in August and September 1987 from four fields in Hill and Jefferson Counties to evaluate model performance and indicate appropriate changes in the model's design to allow its use in Montana. Results indicate that model performance can be improved by addition of the content and location of organic matter and $CaCO_3$ in the soil profile. Productivity indices were first generated with the original model. The regression of small-grain yield against PI accounted for 64, 67, 63, and 1% of the variability in yield within Fields 1 through 4, respectively. When the modified PI values were used, R^2 increased an average of 44% and accounted for 77, 69, 60, and 75% of the variation in grain yield within Fields 1 through 4, respectively. Moreover, R^2 increased slightly (0.69 to 0.75) for all fields collectively when cropping history was considered. These results have encouraged further efforts to develop a modified and improved version of the PI model that uses the SOILS-5 database for county-scale assessments in northern Great Plains small-grain environments.

ALTHOUGH LOSSES OF TOPSOIL by erosion are widely considered to reduce crop productivity, this has not been well quantified over a wide range of soils. The National Soil Erosion-Crop Productivity Research Planning Committee recently advocated the need for new approaches to evaluate changes in the productivity of soils in relation to long-term soil erosion (Williams, 1981). Two approaches have emerged: (i) the Erosion-Productivity Impact Calculator (EPIC) developed by Williams et al. (1984); and (ii) the PI model developed by Pierce et al. (1983) at the University of Minnesota based on some earlier work by Kiniry et al. (1983) at the University of Missouri.

The EPIC is a process model that operates on a daily time step and consists of components that simulate erosion, plant growth and related processes, and economic components to estimate the effects and costs of erosion and to determine optimal management strategies. Numerous weather, crop, tillage, and soil parameters are required as input to the model. The difficulty and cost of generating these inputs restrict applications of this model to national assessments.

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The PI model, like EPIC, considers changes in soil profile characteristics with depth. The PI model can be used to examine the vulnerability or rate of productivity decline of a soil when subjected to simulated erosion. A vulnerable soil is one that quickly becomes less favorable to crop growth as surficial materials are removed. Relationships in the PI model have been derived and tested primarily in the Corn Belt with corn (*Zea mays* L.) as the target crop. The model uses the USDA-SCS SOILS-5 database to predict current crop yield and assumes that the major effect of erosion is to change the soil microenvironment for root growth and, consequently, future yields. The model incorporates factors for available water-holding capacity (AWC), soil reaction (pH), and bulk density (D_b) with adjustments for family particle-size class and permeability. In addition, the model makes use of an idealized corn root distribution to weight model parameters for different horizon depths. Erosion is simulated by the incremental removal of surface soil. This soil removal brings a new combination of soil properties leading to a potential change in the root environment.

Pierce et al. (1984b) evaluated model performance in the Corn Belt by regressing PI against estimated corn yields from county soil surveys and Minnesota corn-equivalency ratings. The R^2 ranged from 0.63 to 0.71 and was increased by 26% (0.79 to 0.90) by excluding Histosols, frequently flooded and depressional soils, and soils with slopes exceeding 6%. Modified versions of the PI model (with altered model statements or new statements to account for the response of crops to local soil characteristics) have been successfully applied to several locations outside the Corn Belt, including Nigeria, Hawaii, Mexico, and India (Rijsberman and Wolman, 1985). Gerhart (1989), however, evaluated PI model performance in Cascade County, Montana, using the SOILS-5 database and found a weak relationship ($R^2 < 0.35$) between PI and estimated small-grain yield. This result may have been due to shortcomings in the SOILS-5 database.

Results of prior research on dryland small-grain yields in Montana suggest that several new or modified model statements are required to achieve adequate model performance in northern Great Plains environments. Schweitzer (1980) examined differences between Scobey (fine, montmorillonitic Aridic Argiboroll) and Kevin (fine-loamy, mixed Aridic Argiboroll) soils which occur together in complexes on glacial-till landscapes in Montana. Average $CaCO_3$ 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 morphologic, classification, climatic, and site variables in relation to small-grain yield in Montana. All sites sampled were under a high degree of management in terms of fertility, weed, and pest control. Multiple

stepwise regression identified AWC and depth to $CaCO_3$ as the most important variables in predicting yield. Larson (1986) examined the influence of soil series on small-grain yield in Montana, and found depth of $CaCO_3$ and pH were inversely correlated to grain yield and organic-matter content was positively correlated to yield. These properties were also highly predictive of soil test P and AWC. Depth to $CaCO_3$ and organic-matter content, two variables identified as important determinants of small-grain yield in these Montana studies, are not incorporated in the original (Minnesota) version of the PI model.

The calcareous nature of many agricultural soils in Montana is derived from sedimentary parent materials (soft black shales and Tertiary valley fill) of diverse origin and composition or from wind-deposited fine sand and silt (Montagne et al., 1982). Although 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, there remains much disagreement about the exact cause-effect relationships. The presence of an accumulation of carbonates can have a dominating influence on many physical and chemical soil properties, including pH, AWC, and D_b considered by the PI model. Excessive amounts of $CaCO_3$ may affect the fertility of the soil by decreasing P and micronutrient availability. Nutrient deficiencies may influence crop rooting patterns. Similarly, D_b 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). Pores and planes of weakness, however, may be rare in horizons where secondary $CaCO_3$ has accumulated and it may act to maintain soil strength and inhibit root penetration.

The objectives of this study were to: (i) evaluate the performance of the existing PI model using data collected within single fields in which crop yield and soil properties vary widely, (ii) identify soil and site variables important to small-grain yield in Montana, and (iii) suggest modifications to improve the performance of the PI model in Montana.

MATERIALS AND METHODS

Study Area Description

The study of model relationships was completed using data collected along transects in four fields on two Montana farms: (i) the Petersen Farm northwest of Havre, in Hill County (48°40′N, 110°00′W) and (ii) the Woodbury Farm, west of Three Forks in Jefferson County (45°55′N, 111° 40′W). The two farms differed in terms of parent material, soils, crops, and climate.

Transects were based on observed heterogeneity in nearly mature fields of hard red spring wheat (*Triticum aestivum* L., cv. Bronze Chief and Newana) and two-rowed barley (*Hordeum vulgare* L., cv. Lewis) using color infrared aerial photography. An assumption was made that heterogeneity of the grain crops was largely due to variation in soil properties. This was verified through field observations on the ground. It was recognized that many crop areas will be nonuniformly influenced by pests and diseases, weeds, management, and microclimate (e.g., hail and frost damage, and lodging). Areas chosen for grain harvest were free of these problems.

Table 1. Mapped soil series along four transects in Hill and Jefferson Counties, Montana.

Transect	County	Soil series	Family classification
1	Hill	Joplin	Fine-loamy, mixed Aridic Argiboroll
		Hillon	Fine-loamy, mixed (calcareous), frigid Ustic Torriorthent
		Evanston	Fine-loamy, mixed Aridic Argiboroll
		Phillips	Fine, montmorillonitic Borollic Paleargid
2	Hill	Telstad	Fine-loamy, mixed Aridic Argiboroll
		Joplin	Fine-loamy, mixed Aridic Argiboroll
		Gerdrum	Fine, montmorillonitic Borollic Natrargid
		Creed	Fine, montmorillonitic Borollic Natrargid
		Phillips	Fine, montmorillonitic Borollic Paleargid
		Elloam	Fine, montmorillonitic Borollic Natrargid
3	Jefferson	Yetull	Mixed, frigid Ustic Torripsamments
		Varney	Fine-loamy, mixed Aridic Argiboroll
		Ethridge	Fine, montmorillonitic Aridic Argiboroll
		Brocko	Coarse-silty, mixed Borollic Calciorthid
4	Jefferson	Floweree	Fine-silty, mixed Aridic Haploboroll
		Brocko	Coarse-silty, mixed Borollic Calciorthid

The two Hill County 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 Jefferson County fields 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).

Soil series along each transect were identified from USDA-SCS soil surveys field sheets. Thirteen soil series classified in eight great groups of Mollisols, Aridisols, and Entisols were mapped within the four fields (Table 1). Soils differed primarily in texture, rooting depth, organic-matter content of the surface horizon, and depth to and quantity of $CaCO_3$ (Table 2).

Long-term climatic data for the two farms were estimated with the Montana Agricultural Potentials System (MAPS) database (Nielsen et al., 1990). The range in mean annual precipitation (250-410 mm) and growing degree days (83–100 d) was the same for both farms, but the Hill County farm has a longer frost-free period (110–125 vs. 90–105 d) than the Jefferson County farm.

Grain Harvest and Soil Sampling Procedures

Plants were clipped at the soil surface from 57 1-m^2 plots along transects selected to represent the range of yield variability within the four fields. Clipped plants were oven dried and weighed to estimate aboveground biomass. Grain was obtained by threshing the heads and cleaning with an air-blower separator. Soil horizons directly below the plots were sampled by removal of three cores approximately 122 cm long and 3.2 cm in diam. using a hydraulic probe. Following removal of each soil core, horizons were identified using color and other distinguishing properties (e.g., texture and effervescence). Horizon identification was facilitated by exposing profiles in small pits, dug with a shovel, adjacent to the sample plots. Depth of soil (rooting environment) was recorded for each core based on presence of roots. The thickness of each horizon was measured and recorded. A segment approximately 3.0 cm in length was removed from each horizon and maintained intact for determination of 33-kPa water content. Sample core segments from 10 to 18 cm long from each horizon, excluding the Ap horizon, were measured, dried, and weighed for D_b determination. The sufficiency of D_b in the Ap horizon was assumed to be 1.0 to accommodate the effect of tillage on D_b (Pierce et al., 1983).

Table 2. Means and ranges of soil properties along four transects (Tr) in Hill (Tr 1 and 2) and Jefferson (Tr 3 and 4) Counties, Montana.

A. Soil profiles

Tr	n	Root depth		Depth of $CaCO_3$		AWC†	
		Mean	Range	Mean	Range	Mean	Range
		cm				%	
1	18	104	71–123	28	0–48	15	7–21
2	15	95	72–123	17	0–48	14	9–19
3	13	78	23–123	27	7–48	13	3–22
4	11	115	16–123	6	0–26	21	10–27

B. Within Ap horizons

Tr	n	Horizon	Clay		$CaCO_3$ equivalent		pH		Organic matter	
			Mean	Range	Mean	Range	Mean	Range	Mean	Range
		cm	%						g kg^{-1}	
1	18	0–16	27	14–38	1.7	0.5–9.0	6.8	5.8–7.8	10.4	5.7–20.7
2	15	0–17	30	18–42	2.5	0.6–8.0	6.9	5.5–7.6	10.5	5.7–17.2
3	13	0–16	39	28–44	1.4	0.7–4.0	7.2	6.3–7.6	5.9	1.8– 9.0
4	11	0–14	23	12–29	5.1	1.0–12	7.2	6.2–7.7	14.9	12.0–17.9

C. Within Bw and Bk horizons

Tr	n	Horizon depth	Clay		$CaCO_3$ equivalent		pH		Bulk density	
			Mean	Range	Mean	Range	Mean	Range	Mean	Range
		cm	%						Mg m^{-3}	
1	18	19–79	33	18–43	5.2	0.6–18.6	7.2	6.0–8.2	1.51	1.37–1.78
2	15	26–58	34	18–46	8.7	1.0–16.2	7.6	6.2–8.0	1.49	1.34–1.65
3	13	18–40	36	7–50	3.5	1.3–10.9	7.7	7.2–7.8	1.42	1.25–1.60
4	11	17–93	23	12–30	14.4	2.2–21.3	7.9	7.6–8.1	1.36	1.28–1.52

† Available water-holding capacity.

The following properties were measured for each soil horizon: percent sand, silt, and clay; family particle-size class, $CaCO_3$ equivalent and effervescence class; pH; organic-matter content; AWC; D_b; and water content. Three topographic variables (slope position, gradient, and aspect) were also measured.

Laboratory Procedures

Soil reaction (pH) was determined using a 1:2 ratio of soil and 0.01 *M* $CaCl_2$ (Peech, 1965). Soil D_b was determined by the core method using dry weight and field-state volume of each sample under water conditions at the time of sampling (Blake, 1965). Available water-holding capacity was estimated by measurement of the water-retention difference between 33- and 1 500-kPa tension (Soil Survey Staff, 1967). Intact core segments were placed on a pressure-plate apparatus to determine 33-kPa water content. The segments were allowed to equilibrate and were weighed to obtain their water content. A subsample of the same core segments (92 cores) was ground and placed in retainer rings to estimate the weight of water held at 1 500-kPa tension. Permeability classes (saturated hydraulic conductivity) were taken from official series descriptions. Percent sand, silt, and clay were estimated by hand. The hydrometer method described by Day (1965) was used on a representative subsample (45 samples) and differed from hand estimates by an average of 6%.

Carbonates were determined by two methods: (i) gravimetric method for loss of CO_2 (U.S. Salinity Laboratory Staff, 1954, Method 23b), and (ii) qualitative evaluation of effervescence using 100 g Kg^{-1} HCl. The following four effervescence classes were used for the second method: (i) noneffervescent, (ii) slightly effervescent when bubbles were readily observed, (iii) strongly effervescent when bubbles formed a low foam, and (iv) violently effervescent when a thick foam "jumped" up (Soil Survey Staff, 1974). These classes are the same as those used for official soil series descriptions.

RESULTS AND DISCUSSION

Evaluation of Existing Model

Productivity indices were generated with the original Minnesota PI model for each plot and regressed on the corresponding crop yield using simple linear regression for all four transects individually and collectively (Fig. 1a). In three of four transects, PI was fairly predictive of grain yield (average $R^2 = 0.65$), but PI was unrelated to yield in Transect 4 ($R^2 = 0.01$). Overall, PI was relatively poorly related to yield when all plots were combined ($R^2 = 0.46$).

The outlier points (plots) were then identified and evaluated in terms of existing model criteria as well as quantity and depth of $CaCO_3$ and organic-matter content. An attempt was thus made to evaluate model performance by focusing on deviant plots. Deviant plots are those that are rated too low or too high with respect to plots of similar yield. This occurs when: (i) the PI model inaccurately interprets the relationship between existing model parameters and crop response, or (ii) crop response is partially a function of soil or site parameters not considered by the model. Nine of the 13 deviant points (plots) identified in this study were most easily accounted for with the latter explanation.

Evaluation of New Versions of Productivity Index Model

Percent $CaCO_3$ equivalent for each horizon was used rather than depth of $CaCO_3$ in the revised versions. The PI model calculates a productivity index by obtaining the product of soil-property sufficiencies for each soil horizon and summing the products. Therefore, to use depth to $CaCO_3$ would have been inconsistent with the model's basic structure. The use of percent $CaCO_3$ accounted for both the $CaCO_3$ content and depth to $CaCO_3$ because the PI model's table of weighting factors places more weight on values of $CaCO_3$ that are closer to the soil surface, where root density is greater.

The sufficiency of $CaCO_3$ was considered as another multiplicative factor. The sufficiency relationship for $CaCO_3$ (Fig. 2) was produced with data on weighted profile $CaCO_3$ from the transect in Field 4 that was strongly correlated to small-grain yield ($R^2 = 0.55$). Grain yield was normalized by dividing all yields in Field 4 by the greatest yield sampled (6.68 Mg ha^{-1}). The sufficiency of $CaCO_3$ was not allowed to fall lower than 0.40, based on the assumption that the individual effect of $CaCO_3$ is to reduce average grain yield to a minimum of 40% of its potential, when other soil properties are not limiting. In extreme cases of $CaCO_3$ accumulation and induration, the decrease in potential yields will be much more. The model, however, should respond well to such a case because the sufficiency of D_b would control the generated index. The 40% level was derived by comparing the yields of those profiles rated high by the PI model (i.e., PI > 0.60) and having the shallowest depth to $CaCO_3$ within each field with the average maximum yield in the four fields (5.72 Mg ha^{-1}). The average of these yields was 2.31 Mg ha^{-1}, indicating that the individual effect of $CaCO_3$ in the four fields was to decrease grain yield to 40% of the average maximum.

Figure 1b shows scatterplots of PI vs. small-grain yield following the addition of the model statements for profile $CaCO_3$. The relationship of PI to yield increased an average of 34% and explained 72, 78, 62, and 39% of the variation in yield in Fields 1 through 4, respectively.

Within the four fields under study, surface organic-matter content ranged from 0.31 to 3.58%. Generally, surface organic-matter content of soils within the rolling landscapes of Montana, is expected to increase from upper- to lower-slope positions (i.e, from ridge to toeslope positions). Table 3 summarizes mean organic-matter contents for each of five slope positions for all four study fields. Mean organic-matter contents ranged from 1.2% on ridges to 2.7% on toeslopes.

Interactions of climate and topography may account for much of the variation in organic matter encountered within the study fields. The amount of precipitation entering the soil profile at a given point is influenced by aspect, slope gradient, and slope position. Lower hillslope positions will accumulate upslope runoff, which contributes to the overall productivity and accumulation of organic matter. Conversely, upper-slope positions may not benefit from all of the precipitation that occurs since a part may be lost to overland and subsurface flow, removal of snow by wind, and greater evapotranspiration. Fur-

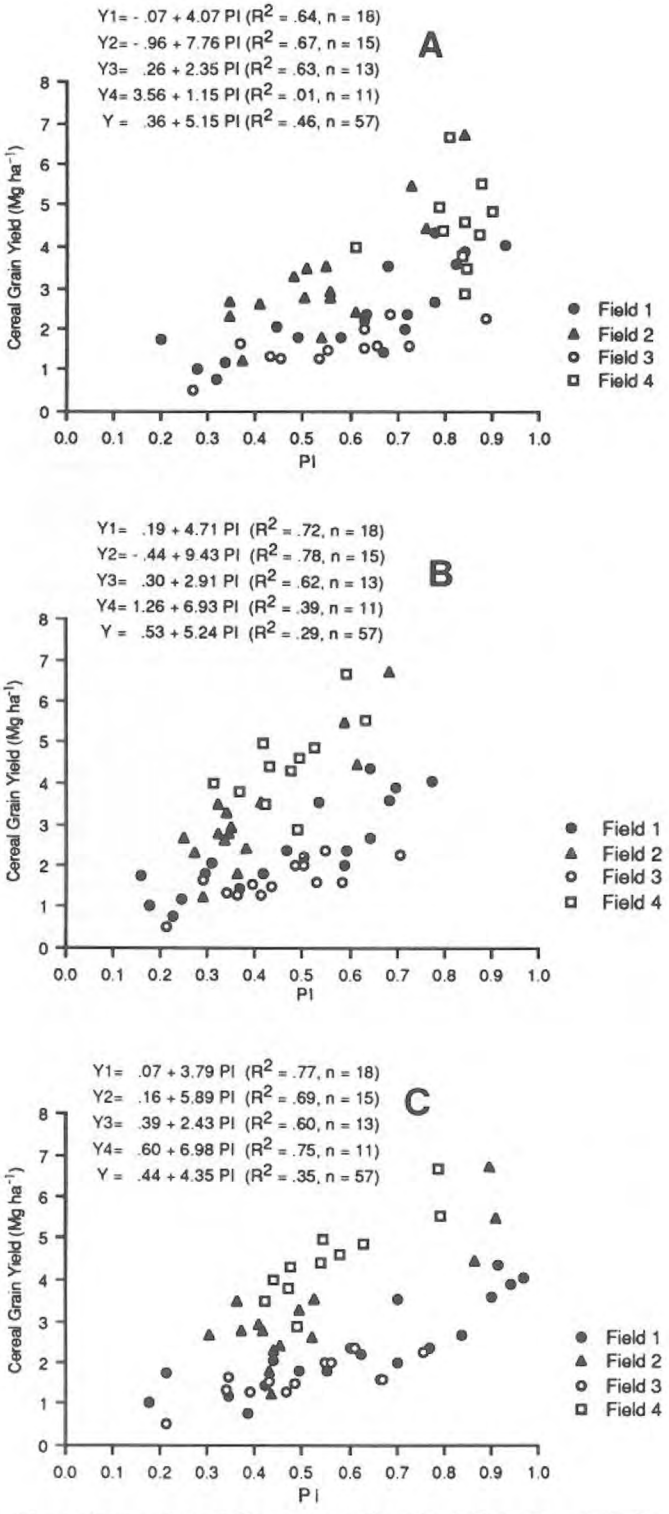

Fig. 1. Scatterplots of PI versus small grain yield for four fields in Hill and Jefferson Counties, Montana; (a) With Minnesota PI model; (b) With revised Montana PI model incorporating $CaCO_3$ factor; (c) With revised Montana PI Model incorporating $CaCO_3$ and organic matter factors.

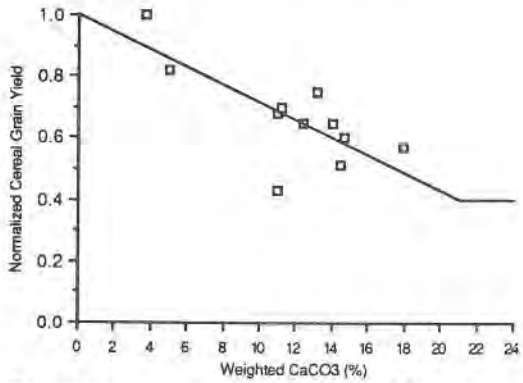

Fig. 2. Proposed sufficiency relationship for $CaCO_3$ based on values of weighted $CaCO_3$ equivalent and normalized small grain yield from plots in Field 4, Jefferson County, Montana. $R^2 = 0.55$ calculated from individual data points ($n = 11$).

thermore, erosion of surface horizons and their organic matter by wind and water is more likely to occur on upper-slope positions. The organic matter that is lost from these upper slopes will tend to accumulate locally at lower-slope positions. Thus, grain yield will generally be lower on upper-slope positions.

Several other soil properties important to crop growth were also related to slope position (Table 3). Soils on lower positions were generally deeper, had greater depth to $CaCO_3$, and greater AWC than upper positions. These data suggest a general movement of water from higher to lower positions, leading to increased yield of small grains in lower positions.

Several statements were added to the PI model to account for organic matter as an indicator of yield. Although this implies that organic matter has a direct effect on crop growth and that every increase in organic-matter content equates to a specified increase in yield, this approach is not supported by the literature. Rather, organic matter is an indicator of climate, topography, and soil properties favorable to crop production. With the addition of the $CaCO_3$ component, the PI model contained four of many possible factors that could be considered in defining a soil's productivity. The PI function relating these four soil properties remained multiplicative, thus any single factor that limits productivity could control the generated index. Unlike these four factors, organic matter was included in the calculation of PI as an additive factor. Pierce et al. (1984a) regarded the presence of organic matter as additive since a lack of organic matter does not equate to low productivity when a high level of management, including adequate nutrient supplies, is assumed.

Numerous attempts were made to arrive at a function that would compute the sufficiency of organic matter for a given level of organic matter within each soil horizon. Following the addition of the $CaCO_3$ component, regression equations for PI on grain yield were considered for the four fields individually and collectively. The relationship between organic-matter content of the Ap horizon and the residuals of these models was poor and of no help in improving the model. The organic-matter content in the Ap horizon was correlated against grain yield for each field and all fields collectively. This was repeated following normalization of the data relative to the greatest yield in each field and the greatest yield in all fields. This last correlation revealed a R^2 of 0.64 (Fig. 3).

Table 3. Small-grain yield and selected soil properties for five slope positions in all four fields.

Position	n	Yield	Soil properties: Organic matter	AWC‡	Rooting depth	Depth to $CaCO_3$
		Mg ha^{-1}	%		cm	
Ridge	9	1.99c†	1.2b	9.9b	62c	10b
Shoulder	10	2.48bc	1.5b	15.3a	92b	11b
Backslope	19	2.44bc	1.7b	15.2a	102ab	17b
Footslope	11	3.66ab	2.0b	18.7a	115a	30a
Toeslope	8	4.06a	2.7a	17.6a	113a	41a

† Data entries followed by different letters indicate statistically significant differences ($P = 0.05$) as determined by one-way analysis of variance and the Student-Newman-Keuls multiple-comparison test.
‡ Available water-holding capacity.

Soil profiles that the PI model (with added $CaCO_3$ component) rated as the least limiting (PI > 0.49) were considered next. The PIs for these profiles explained little of the variation in grain yield ($R^2 = 0.16$), suggesting that the relationships of other important soil properties to crop growth had been overlooked. The organic-matter content of the Ap horizon, however, was strongly correlated ($R^2 = 0.73$) to yield (points designated by circles in Fig. 3). This strong relationship indicates that organic matter serves as a good indicator of the sufficiency of soil properties important to crop growth other than AWC, D_b, pH, and $CaCO_3$. Viewed this way, organic matter within the PI model indicates past productivity and the sufficiency of some unidentified soil properties not included in the model.

The slope of the line representing organic matter in the Ap horizon was 0.25, indicating a 25% increase in PI per percent of organic matter. However, the inclusion of an additive organic-matter factor in the PI model meant that the use of the 0.25 slope caused the level of organic matter to be too influential in the model. Therefore, a slope of 5% was chosen as reasonable and was effective for levels of organic matter between 0.5 and 3.0%. This approach meant that the PI values computed with the first four factors were increased by 0.05 and 0.15 for soils with 1.0 and 3.0% organic matter, respectively. In addition, the organic matter adjustment was only added to the computed horizon sufficiency when the sufficiency of $CaCO_3$ was greater than 0.75 (i.e., the $CaCO_3$ content was less than 9.0%). It was not clear why this last condition was useful, since it applies to those horizons having both high amounts of $CaCO_3$ and organic matter. The improved performance of the model with this last qualification suggests that the effects of high levels of $CaCO_3$ on crop productivity are not offset by increases in organic matter within the range of 0.5 to 3.0%.

The PI model with added $CaCO_3$ and organic-matter components improved the relationship of PI to grain yield an average of 12.4% compared with the version containing only the $CaCo_3$ component. The PI then accounted for 77, 69, 60, and 75% of the variation in yield within Fields 1 through 4, respectively (Fig. 1c; Table 4). This was a 44% improvement, compared with the Minnesota version of the PI model. The inclusion of $CaCO_3$ and organic-matter factors in

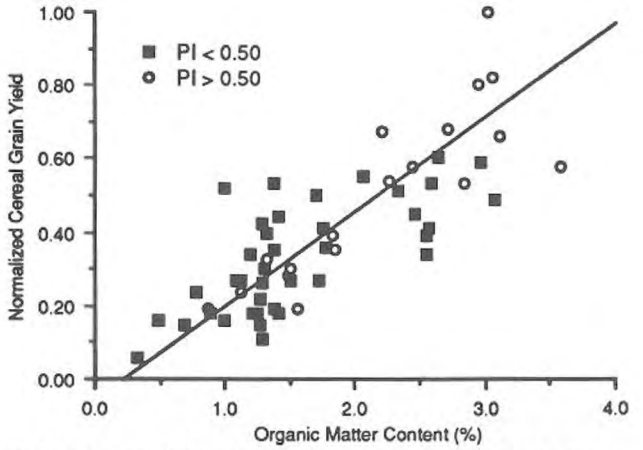

Fig. 3. Relation of the organic matter content of the Ap horizon to normalized small grain yield from plots in four fields, Hill and Jefferson Counties, Montana. $R^2 = 0.73$ calculated from individual data points with PI > 0.49 ($n = 18$).

the revised PI model, however, increased the average R^2 for Fields 1, 2, and 3 from 0.65 to only 0.69 (Table 4). The organic-matter factor actually reduced R^2 from 0.71 to 0.69 for these fields. These results indicate the need to exercise caution when using the revised model until the improvements in the results for Field 4 (R^2 increased from 0.01 to 0.75 with the same modifications) can be explained.

The discovery that R^2 for all four fields combined was only 0.35, compared with R^2 of 0.46 using the original Minnesota model (Fig. 1a and 1c), indicate further shortcomings with the revised model. Figures 1b and 1c reveal two distinct sets of plots associated with field differences, which help to explain the poor overall relationship of PI to small-grain yield. Plots in Fields 1 and 3 form one group and plots in Fields 2 and 4 form another based on their similar regression equation intercepts.

Differences between these two groups of plots cannot be attributed to crop species or climate. Barley plots in Fields 1 and 2 are in different groups, but are located in adjacent fields subjected to the same climate. Similarly, spring wheat plots in Fields 3 and 4 are in different groups, but they too were in adjacent fields subject to the same climate.

Differences in cropping history may explain decreased grain yields, relative to PI for plots in Fields 1 and 3. Both of these fields were planted with spring wheat prior to this study, whereas Fields 2 and 4 were fallowed the previous year. Recropping may have depleted stored water and resulted in less available water during the growing season. Recropping may also have reduced the supply of available N. Carlson (1988), during the same year as this study, measured the relative yield on recropped vs. fallowed fields for 11 varieties of spring grains using a paired-plot design near Fields 1 and 2, and found that yields on recropped plots averaged 65% of fallowed plot yields.

The PI model considers only a few of the many variables that determine crop productivity. The model does not consider production factors that cause annual variations in crop yield, but attempts to assign a relative index of productivity to a soil based on soil properties that are persistent in the long term. The model assumes a high degree of management, including equal availability of stored water, unless limited by soil condition. The addition of model statements concerning organic matter attempted to evaluate, in part, a soil's water history, although the additional organic-matter model statements could not account for short-term depletions of water.

Table 4. Correlation coefficients between modeled and observed yields of grain in four fields.

Productivity models	Field 1	Field 2	Field 3	Field 4	Averages 1–3	Averages 1–4
	R^2					
Minnesota PI	0.64	0.67	0.63	0.01	0.65	0.49
Montana PI, $CaCO_3$	0.72	0.78	0.62	0.39	0.71	0.63
Montana PI, $CaCO_3$, OM	0.77	0.69	0.60	0.75	0.69	0.70

Table 5. Comparison of the simple linear regression equations and summary statistics for the Minnesota and final modified Montana forms of the productivity index (PI) model with consideration of recropping status within four fields in Montana.

Field	n	Recropped	Model	R^2	P
			Minnesota PI model		
1 & 3	31	Yes	Yield = −0.13 + 3.70(PI)	0.55	0.0001
2 & 4	26	No	Yield = 0.18 + 5.46(PI)	0.53	0.0001
All	57	–	Yield = 0.83 + 4.47(PI) −1.41 (Recrop)†	0.69	0.0001
			Montana PI model		
1 & 3	31	Yes	Yield = −0.04 + 3.72(PI)	0.73	0.0001
2 & 4	26	No	Yield = 0.29 + 6.48(PI)	0.63	0.0001
All	57	–	Yield = 1.27 + 4.65(PI) −1.84 (Recrop)†	0.75	0.0001

† Recrop (indicator variable) equals 0 if fallowed previous year and 1 if recropped.

The PI should be a better indicator of long-term crop productivity than the crop yields used in this study to evaluate PI model performance. Unfortunately, crop yield is the only way that PI can be evaluated. Sorting all plots into groups based on their recropping history may give a more precise evaluation of the performance of the PI model. Simple linear regression equations and summary statistics for the Minnesota PI model and the final modified form of the PI model with consideration of recropping status are shown in Table 5. Grouping plots according to their recropping history increased R^2 for both the Minnesota and Montana forms of the model. Furthermore, by considering recropping status as another independent variable the relationship of PI and recropping status to small-grain yield was good: R^2 equaled 0.69 and 0.75 for the Minnesota and Montana forms of the model, respectively.

CONCLUSIONS

Grain yields in Montana are partially a function of soil, topographic, and cropping factors not considered by the Minnesota PI model. Organic matter and $CaCO_3$, variables not considered by the original model are factors that helped explain differences in grain yields studied in Montana. Addition of statements accounting for these variables increased PI model performance for most single fields and for all fields collectively when field cropping history was considered. These results have encouraged further efforts to

develop a version of the PI model that uses the SOILS-5 database for county-scale assessments of soil erosion/crop productivity effects in northern Great Plains environments.

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