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Dryland cereal grain yield relationships with soil, environmental and crop management factors in Montana
by Linda Ann Spencer

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Soils
Montana State University
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Abstract:
Complex relationships among land attributes, management, and climate dictate soil production potential. Identifying factors affecting cereal yield permits establishment of accurate yield goals; aiding fertilizer management and residue estimation for erosion control. Good management decisions will protect land and water resources.

Soil and site, and crop and management data were collected during 1986-1989 from nearly 50 benchmark soils in Montana's dryland cereal-producing areas. Data were acquired to support the national USDA Soil-Crop Yield database; thirteen potential yield-determining factors in Montana were added to over 100 original factors in the national database. Stepwise forward regressions for spring barley (n=52), spring wheat (n=82) , and winter wheat (n=91) identified the following influential yield-determining factors: moist soil depth in April, soil organic matter, pH, electrical conductivity, A-horizon thickness, elevation, soil fertility, depth to lime, USLE-K, -C, and -R factors, seeding rate, and insect-, water-, and drought-damage indexes. It was determined that crop-specific models were necessary to best explain the results.

Spring barley grain yield was negatively affected by drought and insect damage. Spring wheat grain yield was positively related to soil P and moist soil depth in April. Moist soil depth in April explained 26% of winter wheat grain yield variability which was also related to flooding and seeding rate.

Results of this research substantiate the importance given to good cropping management for maintaining soil and water quality. In general, moist soil depth in April and soil organic matter were the most significant yield-determining factors for Montana dryland cereal grain yield. Further study will refine techniques and substantiate or provide insight into significant relationships.

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Linda Ann Spencer

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APPROVAL

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Linda Ann Spencer

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

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ABSTRACT

Complex relationships among land attributes, management, and climate dictate soil production potential. Identifying factors affecting cereal yield permits establishment of accurate yield goals; aiding fertilizer management and residue estimation for erosion control. Good management decisions will protect land and water resources.

Soil and site, and crop and management data were collected during 1986-1989 from nearly 50 benchmark soils in Montana's dryland cereal-producing areas. Data were acquired to support the national USDA Soil-Crop Yield database; thirteen potential yield-determining factors in Montana were added to over 100 original factors in the national database. Stepwise forward regressions for spring barley (n=52), spring wheat (n=82), and winter wheat (n=91) identified the following influential yield-determining factors: moist soil depth in April, soil organic matter, pH, electrical conductivity, A-horizon thickness, elevation, soil fertility, depth to lime, USLE-K, -C, and -R factors, seeding rate, and insect-, water-, and drought-damage indexes. It was determined that crop-specific models were necessary to best explain the results.

Spring barley grain yield was negatively affected by drought and insect damage. Spring wheat grain yield was positively related to soil P and moist soil depth in April. Moist soil depth in April explained 26% of winter wheat grain yield variability which was also related to flooding and seeding rate.

Results of this research substantiate the importance given to good cropping management for maintaining soil and water quality. In general, moist soil depth in April and soil organic matter were the most significant yield-determining factors for Montana dryland cereal grain yield. Further study will refine techniques and substantiate or provide insight into significant relationships.

INTRODUCTION

Soil productivity in dryland cereal grain systems is dependent on complex relationships of land attributes, climate, and management. The combined effect of chemical, physical, and biological soil properties, site characteristics, climate, and land management practices is expressed by grain yield and crop quality. Although many relationships cannot be readily explained, identification of the primary factors affecting yield provides a basis for estimating potential yields which influence management decisions, input efficiency, and the quality of land and water resources.

Montana researchers (Decker, 1972; Burke, 1984; Larson, 1986; Osman, 1988; Sandor, 1989) have previously attempted to model yields as a function of soil properties and climate in Montana. The present study incorporates more factors and more soil series over a larger geographic area and uses site data spanning a longer period of time than the preceding studies.

Objectives

A long-term project was initiated in 1986 (Osman, 1988) to collect Montana data for the USDA Soil-Crop Yield database and to develop corresponding forms and monitoring procedures. A data processing system has been maintained for four crop years (1986-1989). The primary objective of this study was to develop models describing dryland cereal grain yield relationships to a minimum number of soil, climatic, and management attributes and determine the significance of the relationships. The Soil-Crop Yield data subsequently contributes to Montana Soil Conservation Service offices and the National Interagency Soil-Crop Yield database. Potential applications for relationships discovered will be suggested.

LITERATURE REVIEW

Efforts to relate soil productivity to a few prominent factors influencing yield have stimulated many research efforts. Complex interrelationships among hundreds of yield-determining factors are not fully understood, but modeling can identify significant relationships and provide a basis for accurate yield prediction. Baseline data obtained from benchmark soil studies may be extrapolated if similar field conditions are present. Yield potential models are tools which 1) help producers set optimum production goals, 2) guide management decisions, and 3) ultimately affect natural resource quality as well as sustainability of production.

Soil productivity has been evaluated for numerous crops, soil conditions, and climatic regions in the United States. Studies relating productivity to soil type and other characteristics have been performed in many geographic regions (Odell, 1949; Fenton, 1975; Allgood and Gray, 1977; and Pierce et al., 1983, 1984a, 1984b; Ulmer and Patterson, 1988). Huddleston (1984) provides an excellent overview on the use and development of soil productivity ratings in the United States.

Soils and Landscape Relationships to Dryland Cereal Grain Yield

Allgood and Gray (1977) used a multiple linear regression analysis, laboratory soil test data, and published yield information to predict crop yield indices for Oklahoma soils. Their models indicated that water was a major limiting factor for winter wheat, sorghum, and cotton production. Increases in slope resulted in decreased winter wheat grain yield. Increased grain yield resulted from increased soil calcium, deeper A horizon, decreased solum depth, and increased pH.

In an earlier study of two silt loam soils in north-central Illinois, Odell (1949) reported as surface soil (A1 horizon) depth increased by 2.5 cm, corn grain yields increased 69 to 194 kg/ha on the average. Surface soil depth was negatively related to slope gradient. Grain yield could be associated with amount of erosion in the cultivated area, subsequent soil water relationships, and accumulated soil organic matter.

Larson (1986) studied cereal grain yield for 21 Montana soil series. Depth to lime, soil organic matter, and pH were highly and positively correlated with yield. Montana soils have strongly calcareous horizons and limited available soil water. Soils with increased depth to lime apparently retain more plant-available water and decreased nutrient fixation resulting in greater crop yields.

Ulmer and Patterson (1988) reported hard red spring wheat yield increased 40 to 255 kg/ha with a 2.5 cm increase in A-horizon thickness. Thickness of the A horizon explained 35 to 80% of yield variation ($P<0.05$) within soil management units. A soil management unit is a specific combination of soil type, management factors, associated erosion, moisture, and fertility conditions.

Ulmer et al. (1988) developed empirical regression models for predicting long-term yields of hard red spring wheat and sunflower for soil taxonomic units in North Dakota using soil, climate, management, and yield data. The best linear spring wheat model contained eight factors including nitrogen fertility, organic carbon, and A-horizon thickness; all positively related to yield.

Leeper (1974) reported that soil depth as related to soil water storage significantly affected crop growth. Hairston et al. (1988) found that the negative effect of decreasing soil depth on water storage could be positively compensated for by soil organic matter contributions and the amount and distribution of precipitation.

Empirical regression models for predicting long-term yields of hard red spring wheat in North Dakota (Ulmer et al., 1988) indicated plant-available water at seeding was the most important variable affecting spring wheat production. Precipitation was also a significant yield-determining factor and both factors were positively related to grain yield.

Sharpley (1986) investigated the disposition of labeled fertilizer P in winter wheat over a four-year period in south central Oklahoma. Winter wheat dry matter P content accounted for 83% of yield variability. Residual soil P was inversely related to recovery of fertilizer P by winter wheat. As residual P increased, P fertilizer efficiency decreased. Sharpley suggested 30 kg/ha of P fertilizer was adequate for maximum initial responses and succeeding years' maintenance rates could be decreased without yield decline.

In a four-year study of five soils in eastern Montana, Power et al. (1961) concluded dryland spring wheat yield increases due to P fertilization were influenced by soil water, precipitation, and available soil P. The amount of water at seeding was directly proportional to yield increases on soils testing in the medium-P range.

Veeh and Skogley (1986) studied the effect of 47 soil characteristics on small grain response to fertilizer K on Montana soils. Data included results from small grain soil fertility experiments and soil information from SCS soil series descriptions at over 100 sites. Crop yield response to fertilizer K was positively related to elevation and spring stored soil water. Elevation was also positively related to spring stored soil water.

For statistical evaluation of selected soil, site, and climate variables on dryland small grain yields, Burke (1984) collected 14 years of available experimental data in Montana.

Winter wheat yield was positively related to total available water (R^2=0.26) and depth to lime (R^2=0.11). Depth to lime roughly indicates the predominant depth of water penetration in soils. Rainfall, which was positively related to total spring soil water and total available water explained three-fourths of Montana spring wheat yields. Spring barley yields were dependent on structure type and size in the Ck and B horizons (R^2=0.74).

Preliminary study of the 1986 Montana Soil-Crop Yield data (Osman, 1988) identified several relationships for yield-determining factors and dryland cereal grain yield under Montana agricultural conditions. Spring barley grain yield was increased by gains in available water with additional effects from elevation. Moist soil depth in April measured with the Brown Probe (Brown, 1960) had the greatest positive effect on dryland spring and winter wheat grain yield. Spring wheat yields were positively related to soil P in the 0-15 cm depth and elevation. Winter wheat grain yield was positively affected by soil K in the 0-15 cm depth.

Management Factors Impacting Soil Productivity

Available water is a major yield limiting factor in the semi-arid Northern Great Plains. The amount of available water is dependent on the ability to store water and is affected by soil surface conditions, soil texture, organic matter content, and other factors. Summer fallowing and stubble management also influence soil water storage. Summer fallowing is practiced extensively to increase nutrient availability and stored soil water, and to control weeds. Soil water storage additions from fallowing vary. In the Northern Great Plains, during the 21-month fallow period for spring wheat, only 19% (Haas et al., 1974b) to 30% (Massee and Cary, 1987) of precipitation received was stored. For annually cropped spring wheat, 32% of precipitation received during the nine-month period from harvest to seeding was stored. For winter wheat, 18% storage efficiencies were obtained on fallowed soils (Haas et al., 1974b).

Management affects the soil's ability to store water. Soils with high organic matter content, fine texture, and a moderate degree of structural development have greater water retention at field capacity. Fallowing decreases soil organic matter (Janzen, 1987). To maintain soil productivity, organic matter conservation and replenishment are necessary. Manipulation of agronomic practices may decrease the amount and rate of decline. Janzen (1987) found application of nitrogen fertilizer over an 18-year period in Lethbridge, Canada significantly enhanced soil organic C and N in winter wheat-fallow systems. Maintaining mineralizable nitrogen from organic sources may preclude the necessity of future heavy inputs of inorganic fertilizers.

Haas et al. (1974a) reported that a 4.3 cm mean increase in water storage was possible by implementing crop-fallow practices as opposed to annual cropping spring wheat in the Northern Great Plains. Loss of total N and organic C was generally greater in crop-fallow systems. It is postulated these losses are from volatilization, denitrification, and erosion. The presence of crop residues will usually cause NO_3-N to be lower, due to microbial immobilization. Fallowed soils were found to be generally greater in NO_3-N and P at planting compared to continuously cropped soils. Tanaka et al. (1987) found soil water storage during fallow was generally greater on chemical fallow than on stubble-mulch near Sidney, Montana.

In winter wheat rotations in the Northern Great Plains, Black et al. (1974) reported that as available soil water decreased, the contribution of fertilizer phosphorus (P) to percent of total plant P uptake increased. Increased fertilizer use-efficiency resulted. Winter wheat extracts all available water to a depth of 1.5 or 1.8 m and spring wheat, to 0.9 m. Winter wheat produced after fallow usually had higher test weights and grain protein than continuously cropped winter wheat. Recropped soils also required more N to produce similar yields and grain quality compared to fallow soils.

More efficient water storage can be obtained by decreasing evaporation from soils, the primary source of water loss from fields (Caprio et al., 1985; Massee and Cary, 1987). Cereal grain stubble in fallow fields was especially effective during dry winters at trapping snow and thereby increasing stored soil water (Caprio et al., 1989). Additional water stored in the soil may be the key to future cropping successes.

Soil Productivity Indices

Productivity indices assign relative values to soils according to their potential to produce a particular crop under specific management conditions. These index numbers are useful in land use decisions, erosion research, farm insurance applications, and implementation of farm programs.

Pierce et al. (1983, 1984a, 1984b) are credited with the Productivity Index (PI), a model which quantifies soil productivity changes due to erosion. The PI model can be used to produce productivity indices from two existing data sources, the USDA-SCS SOILS-5 and the Natural Resource Inventory (NRI). Data were summarized for Major Land Resource Areas (MLRA) in the Corn Belt. Available water storage capacity and resistance to root penetration (affected by bulk density and pH) are represented in the model. Erosion effects on soil productivity are dependent on rooting characteristics and erosion rates (Pierce et al., 1984a).

Gerhart (1989) studied the performance of the PI Model (Pierce et al., 1984a) in Cascade County, Montana using data from the SOILS-5 database and reported limited success. The researcher postulated that potential additions to the model include water balance, growing degree days, slope, and depth to lime. Simultaneously, Sandor (1989) reported content and location of soil organic matter and lime significantly improved the performance of the PI Model for soils in Hill and Jefferson Counties, Montana.

Allgood and Gray (1977) used two methods for computing soil productivity ratings for mapping units in Oklahoma. Their Soil-Properties Model was the result of a multiple linear regression computer program which used laboratory soil test data and published yield information to predict crop yield indices. Where this type of information is not available, a second model, the Soil-Classification Model, could be helpful. Inputs for the Soil-Classification Model were soil diagnostic horizon data from USDA's Soil Taxonomy.

MATERIALS AND METHODS

In 1983, the USDA documented the means to collect soil-crop yield data in an attempt to characterize soil productivity in the United States (Soil Conservation Service, 1983). Montana State University personnel and Soil Conservation Service staff modified the USDA Soil-Crop Yield database and implemented a five year study in 1986 to monitor productivity of nearly 50 Montana benchmark soils (Table 1). By 1989, 26 counties distributed across major dryland cereal producing areas in the state were involved (Figure 1). Results presented in this section are from the 1986 through 1989 growing seasons. Most sites were in a dryland crop-fallow rotation.

Table 1. Classification of Soils in the Soil-Crop Yield Data Study, 1986-1989.

Soil Series	Classification*
Absarokee	Fine, Montmorillonitic Typic Argiborolls
Amesha	Coarse-Loamy, Mixed Borollic Calciorthids
Bearpaw	Fine, Montmorillonitic Typic Argiborolls
Bonfri	Fine-Loamy, Mixed Borollic Haplargids
Brocko	Coarse-Silty, Mixed Borollic Calciorthids
Cambert	Fine-Silty, Mixed Frigid Typic Ustochrepts
Cherry	Fine-Silty, Mixed Frigid Typic Ustochrepts
Chinook	Coarse-Loamy, Mixed Aridic Haploborolls
Cushman	Fine-Loamy Mixed, Mesic Ustollic Haplargids
Danvers	Fine, Montmorillonitic Typic Argiborolls
Ethridge	Fine, Montmorillonitic Aridic Argiborolls
Fairfield	Fine-Loamy, Mixed Typic Argiborolls
Farland	Fine-Silty, Mixed Typic Argiborolls
Fort Collins	Fine-Loamy, Mixed, Mesic Ustollic Haplargids
Gilt Edge	Fine, Montmorillonitic, Mesic Haplustollic Natrargids

Table 1. cont.

Soil Series	Classification*
Gird	Coarse-Silty, Mixed, Frigid Typic Haploxerolls
Half Moon	Fine-Silty, Mixed Typic Eutroboralfs
Havre	Fine-Loamy, Mixed (Calcareous), Frigid Ustic Torrifluvents
Havrelon	Fine-Loamy, Mixed (Calcareous), Frigid Typic Ustifluvents
Hesper	Fine, Montmorillonitic, Mesic Ustollic Haplargids
Judith	Fine-Loamy, Carbonatic Typic Calciborolls
Keiser	Fine-Silty, Mixed, Mesic Ustollic Haplargids
Kobar	Fine, Montmorillonitic Borollic Camborthids
Kremlin	Fine-Loamy, Mixed Aridic Haploborolls
Lambeth	Fine-Silty, Mixed (Calcareous), Frigid Ustic Torriorthents
Lonna	Fine-Silty, Mixed Borollic Camborthids
Marias	Fine, Montmorillonitic, Frigid Udorthentic Chromusterts
Martinsdale	Fine-Loamy, Mixed Typic Argiborolls
McCollum	Coarse-Loamy, Mixed, Frigid Typic Haploxerolls
McRae	Fine-Loamy, Mixed, Mesic Ustollic Camborthids
Musselshell	Coarse-Loamy, Carbonatic Borollic Calciorthids
Olney	Fine-Loamy, Mixed, Mesic Ustollic Haplargids
Pendroy	Very-Fine, Montmorillonitic, Frigid Udorthentic Chromusterts
Phillips	Fine, Montmorillonitic Borollic Paleargids
Rothiemay	Fine-Loamy, Mixed Aridic Calciborolls
Sappington	Coarse-Loamy, Mixed Aridic Argiborolls
Savage	Fine, Montmorillonitic Typic Argiborolls
Scobey	Fine, Montmorillonitic Aridic Argiborolls
Shaak	Fine, Montmorillonitic Abruptic Argiborolls
Shambo	Fine-Loamy, Mixed Typic Haploborolls
Shane	Very-Fine, Montmorillonitic Abruptic Argiborolls
Tally	Coarse-Loamy, Mixed Typic Haploborolls
Tanna	Fine, Montmorillonitic Aridic Argiborolls
Telstad	Fine-Loamy, Mixed Aridic Argiborolls
Turner	Fine-Loamy over Sandy or Sandy-Skeletal, Mixed Typic Argiborolls
Vanstel	Fine-Silty, Mixed Borollic Haplargids
Varney	Fine-Loamy, Mixed Aridic Argiborolls
Williams	Fine-Loamy, Mixed Typic Argiborolls
Winifred	Fine, Montmorillonitic Typic Haploborolls
Yamac	Fine-Loamy, Mixed Borollic Camborthids

* Soil Classification according to Soil Taxonomy (Soil Survey Staff, 1975).

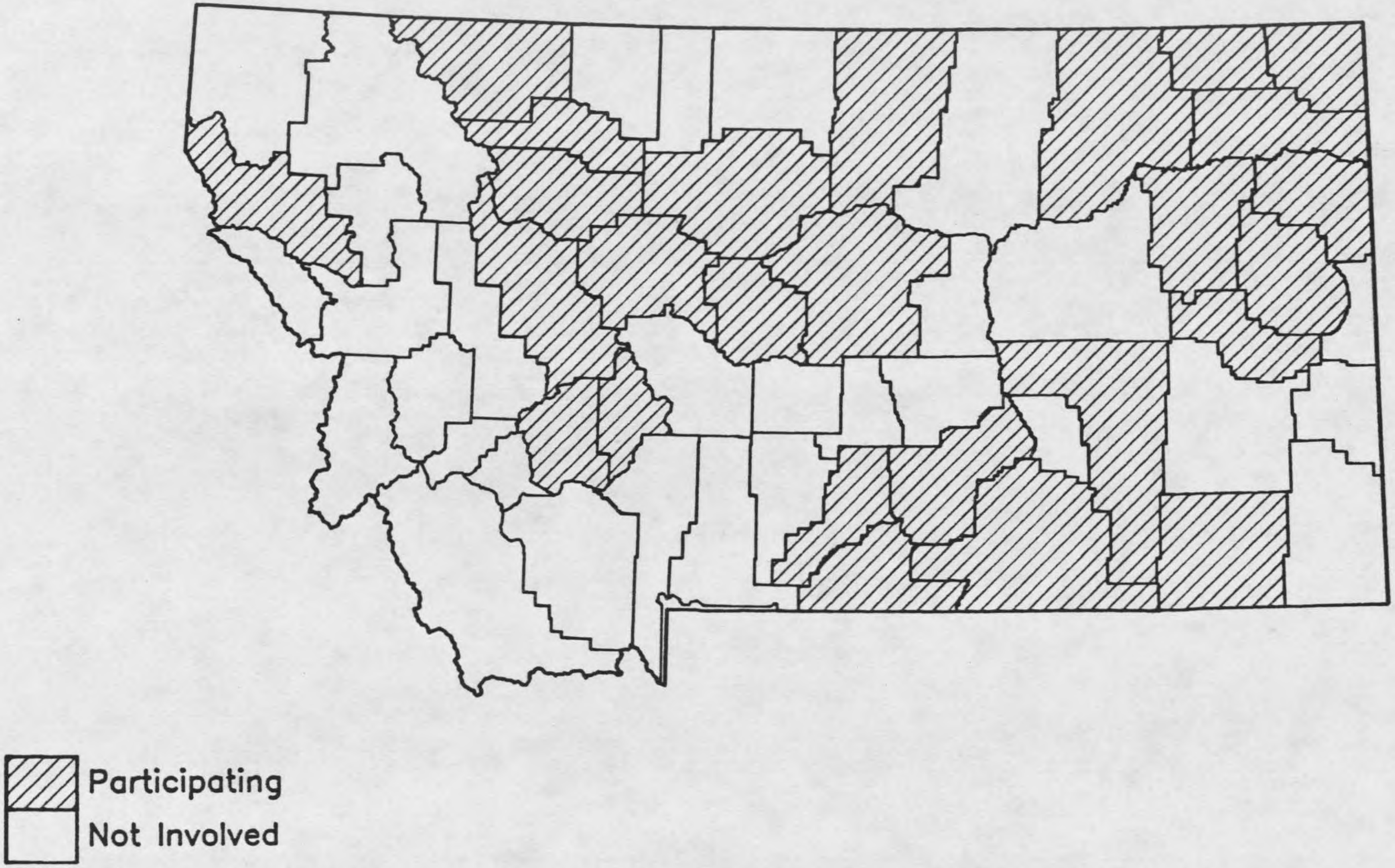

Figure 1. Montana counties in the Soil-Crop Yield Data study, 1986-1989.

Variable Selection

Over 100 variables are monitored at each site every crop year (Osman, 1988). Soil and site characteristics, climate, and management were monitored in three plots in each soil series. At the onset of the study in 1986, eleven potential yield determining factors were added to the USDA Soil-Crop Yield database in an attempt to more precisely predict dryland cereal grain yields for Montana agricultural conditions. These factors were selected by Montana State University Plant and Soil Science faculty and Montana USDA-SCS staff and include seven soil and site, and four crop yield characteristics (Table 2).

Table 2. Potential yield determining factors added to the USDA Soil-Crop Yield Database.

Soil and Site Characteristics
Depth to lime (cm)
Moist soil depth in April (cm)
Plot surface drainage class
Electrical conductivity, 0-15 cm depth (S/m)
Plot fertility (g/kg)
NO_3-N for 0-15 and 15-60 cm depth
Olsen P for 0-15 cm depth
Extractable K for 0-15 cm depth
Extractable S for 0-15 cm depth
Mulch cover at seeding (percent)
Elevation (m)
Crop Yield Characteristics
Grain test weight (kg/ha)
Grain kernel weight (gm/1000 kernels)
Crop head density (heads/0.91 m)
Hail damage index

Site Identification

Four soil series were selected for each county participating in the Montana Soil-Crop Yield Data Study. Series were selected based on their potential for dryland cereal grain production and extent of occurrence. USDA-SCS area soil scientists identified soil series. Soils in plots were within the range of characteristics published in official USDA soil series descriptions.

Three sets of paired 4 m^2 plots (1 in crop, 1 in fallow) represented each soil series. The three plots in a series were located within a 930 m^2 area. More than one series may be present in a field. Plot locations were permanently marked to permit field staff to return to the same plot each time soil and grain samples were obtained.

Soil Sampling and Analysis

Soil Conservation Service field staff collected preplant soil samples in plots to be harvested the following crop year. Samples were taken between rows after removing surface crop residues. Three random samples for a plot were divided into 0-15 cm and 15-60 cm depth increments and mixed by depth. The samples were air-dried immediately and transported to Montana State University for grinding and sieving through a 2 mm screen. The Soil Analytical Lab performed the following analyses on nearly 400 soil samples per year: NO_3-N (0-15 and

15-60 cm depths), Olsen P (0-15 cm), extractable K (0-15 cm), extractable S (0-15 cm), organic matter (0-15 cm), pH (0-15 cm, 2:1 extract), and electrical conductivity (0-15 cm, 2:1 extract). The sulfur analysis was discontinued in 1988.

Grain Sampling and Analysis

Soil Conservation Service staff collected grain samples from each plot, harvesting four representative rows to obtain a sample from 1/1000 acre. Grain heads were clipped from three rows, head density was measured in one 0.91 m row, then grain heads from the fourth row were added to the others. Three bags of grain were collected at each site, one from each plot. Grain samples were sent to the nearest Montana Agricultural Research Center or to Montana State University for sample weight, kernel weight, test weight, and yield determinations.

Development of a Factor List

The primary objective of this study was to develop simple models explaining relationships between dryland cereal grain yield and a minimum of soil, climatic, and management factors in Montana. Prior to model development or selection of the minimum data set, means were calculated from the three plot values describing soil organic matter, pH, electrical conductivity, soil NO_3-N, Olsen P, extractable K, and grain yield from each site. Recrop grain yields were adjusted upward by 30% to reflect the yield decline which is observed in continuous cropping as compared to crop-fallow rotation.

Results from previously published studies including Helwig (1978), Burke (1984), Larson (1986) and Osman (1988), and SAS regression analysis (1982, 1988) were used to reduce the over 100 factors in the Soil-Crop Yield database to six significant variables highly correlated to dryland cereal grain yield. Four regressions were used to assist in variable selection and modeling; 1) an initial selection of 31 independent variables highly correlated to dryland cereal grain yield was made based on preliminary analysis of the database, 2) a secondary regression and correlation analysis indicated the ten most significant of the 31 variables, 3) six variables which were easily measured and highly correlated to grain yield were chosen as a minimum data set, and 4) additional variables highly correlated to yield but difficult to measure or whose relationships were not easily explained were added to the minimum data set (Table 3). Variables entering the stepwise forward linear regressions were restricted by a significance level of $P<0.05$. No cases with missing data were included. Correlations were examined at each step to facilitate variable selection and model interpretation.

Regression analysis for winter wheat, spring wheat, and spring barley were evaluated. Significance of reduced models (individual crops) versus full models (combined crops) was determined from the equation:

$$F\ df_{FM}-df_{RM},\ df\ MSE_{FM} = \frac{(SS_{FM} - SS_{RM})/df_{FM} - df_{RM}}{MSE_{FM}}$$

where df = degrees of freedom for full model (FM) and reduced models (RM), MSE = mean square error for the full model, and SS = sum of squares for full (FM) and reduced (RM) models (Draper and Smith, 1981). Significant F statistics indicated individual crop models were necessary to explain soil-crop yield relationships.

Table 3. Variables selected for stepwise multiple regression analysis.

Independent Variables in Regression

- A-horizon thickness
- Crop damage indexes
    - Insect
    - Water
    - Drought
- Depth to lime*
- Extractable K*
- Electrical conductivity*
- Elevation*
- Moist soil depth in April*
- Olsen P*
- Organic matter
- pH
- Rooting depth
- Seeding rate
- USLE-C factor
- USLE-K factor
- USLE-R factor

* Factor added to USDA Soil-Crop Yield database for use in Montana.

RESULTS AND DISCUSSION

SAS statistical analysis was used to provide simple models from four years (1986-1989) of Soil-Crop Yield data. Three stepwise forward linear multiple regression equations were produced for spring barley, spring wheat, and winter wheat, respectively, which will provide understanding of relationships between soil, management, and climatic features and Montana dryland cereal grain yield.

Grain Yield and Climatic Variability

Long-term records help to establish yield relationships with climate, soils, and management. The range in spring barley, spring wheat, and winter wheat grain yields measured during the four-year (1986-1989) Soil-Crop Yield Data Study are listed in Table 4.

Table 4. Range, mean and number of observations for cereal grain yields.

		Grain Yield (kg/ha)	
Crop	n*	Range	Mean
Spring barley	53	56 - 5964	2570
Spring wheat	83	83 - 5319	2128
Winter wheat	91	458 - 7423	2803

* Number of sites

In Montana dryland agricultural areas, the growing season was characterized by moderate to extreme dryness in late June/early July of 1987, 1988, and 1989, but not in 1986.

Selection of Independent Variables

The ten variables supported by published literature and statistical analysis to be related to dryland cereal grain yields in Montana include rooting depth, A-horizon thickness, soil organic matter, pH, moist soil depth in April, elevation, depth to lime, soil NO_3-N, Olsen P, and extractable K. Six variables were significantly related to grain yield of all three crops (spring barley, spring wheat, and winter wheat) and will be considered the minimum data set for predicting potential dryland cereal grain yields in Montana: A-horizon thickness, soil organic matter, pH, moist soil depth in April, elevation, and depth to lime.

Additional variables ("plus") were selected which correlated to yield, but were not easily quantified, predicted, or explained. These factors were limited to those which contributed more than 0.03 to R^2 in the 31 variable regression ($P<0.05$). The variables were not statistically significant for all three crops based on data collected during the study period (1986-1989). Spring barley grain yield was most affected by two "plus" variables, drought damage and insect damage indexes. Damage indexes represent crop damage from various sources and values range from 0, representing no damage to 3, severe damage. The "plus" variables for spring wheat were Olsen P, seeding rate, and USLE-C (cropping-management) factor, and USLE-K (soil erodibility) factors from the Universal Soil Loss (Wind and Water Erosion) Equation (USLE) (Troeh et al., 1980). The five "plus" variables for winter wheat were water damage index, seeding rate, USLE-C (cropping-management) factor, USLE-R (rainfall and runoff) factor, and electrical conductivity.

To most accurately represent crop yield response to independent variables, three crop-specific models were necessary.

Table 5. Mean and range of soil and site variables for spring barley, spring wheat, and winter wheat.

Variable	Crop*	Range	Mean
A-horizon thickness, cm	SB	9 - 23	14
	SW	7 - 29	14
	WW	11 - 36	15
Depth to lime, cm	SB	0 - 79	20
	SW	0 - 81	25
	WW	0 - 135	22
Electrical conductivity, S/m	SB	0 - 0.10	0.03
	SW	0 - 0.52	0.04
	WW	0 - 0.08	0.03
Elevation, m	SB	717 - 1482	1089
	SW	575 - 1376	933
	WW	632 - 1426	1030
Erosion index	SB	1 - 3	1.4
	SW	1 - 3	1.5
	WW	1 - 2	1.3
Extractable K, mg/kg	SB	121 - 939	366
	SW	112 - 716	352
	WW	99 - 870	357
USLE-K factor	SB	0.17 - 0.43	0.34
	SW	0.20 - 0.43	0.34
	WW	0.20 - 0.45	0.36
Moist soil depth in April, cm	SB	6.8 - 135.0	84.0
	SW	13.5 - 135.0	83.0
	WW	13.5 - 135.0	88.0

Table 5. cont.

Variable	Crop*	Range	Mean
NO_3-N, mg/kg	SB	3.7 - 337.8	41.5
	SW	1.5 - 325.3	62.3
	WW	2.1 - 237.2	40.4
Olsen P, mg/kg	SB	3.2 - 48.4	15.2
	SW	1.6 - 115.7	17.6
	WW	2.8 - 37.6	14.5
Rooting depth, cm	SB	56 - 135	120
	SW	56 - 135	126
	WW	50 - 135	121
Slope, percent	SB	0.5 - 7.0	2.8
	SW	0.5 - 5.0	2.1
	WW	0.1 - 9.0	2.4
Soil organic matter, g/kg	SB	9 - 43	20
	SW	8 - 40	22
	WW	7 - 40	20
Soil pH	SB	5.3 - 8.6	7.7
	SW	5.9 - 8.7	7.7
	WW	5.7 - 8.6	7.7

* SB = spring barley (n=53x3), SW = spring wheat (n=83x3), WW = winter wheat (n=91x3).

Table 6. Mean and range of climatic variables for spring barley, spring wheat, and winter wheat.

Variable	Crop*	Range			Mean
Drought damage index	SB	0	-	3	0.8
	SW	0	-	3	0.8
	WW	0	-	3	0.7
Hail damage index	SB	0	-	2	<0.1
	SW	0	-	1	<0.1
	WW	0	-	3	0.1
USLE-R factor	SB	15	-	45	29
	SW	15	-	50	33
	WW	15	-	45	30
Water damage index	SB	0	-	1	<0.1
	SW	0	-	1	<0.1
	WW	0	-	3	<0.1

* SB = spring barley (n=53x3), SW = spring wheat (n=83x3), WW = winter wheat (n=91x3).

Table 7. Mean and range of cropping and management variables for spring barley, spring wheat, and winter wheat.

Variable	Crop*	Range	Mean
USLE-C factor	SB	0.07 - 0.80	0.35
	SW	0.10 - 0.90	0.36
	WW	0.07 - 0.90	0.35
Insect damage index	SB	0 - 3	0.9
	SW	0 - 3	0.8
	WW	0 - 3	0.8
Other damage index	SB	0 - 2	0.2
	SW	0 - 3	0.3
	WW	0 - 2	0.3
Row spacing, cm	SB	14 - 32	23.0
	SW	14 - 45	21.3
	WW	14 - 45	25.3
Seeding rate, kg/ha	SB	34 - 112	64.4
	SW	45 - 123	69.2
	WW	30 - 101	66.5
Weed chemical use	SB	0 - 1	0.7
	SW	0 - 1	0.6
	WW	0 - 1	0.8
Number of cultivations to control weeds	SB	0 - 6	1
	SW	0 - 5	2
	WW	0 - 6	2
Weed damage index	SB	0 - 2	0.3
	SW	0 - 2	0.3
	WW	0 - 2	0.4

* SB = spring barley (n=53x3), SW = spring wheat (n=83x3), WW = winter wheat (n=91x3).

Identifying Characteristics Influencing Dryland Cereal Grain Yield

Spring Barley

Moist soil depth in April was highly positively related to spring barley grain yield and explained 22% (R^2=0.22) of grain yield variability during this study (Table 8). Moist soil depth in April is related to the amount of plant-available water.

Larson (1988) indicated the importance of soil organic matter and pH in predicting Montana cereal yields. The results in Table 8 indicate soil organic matter and pH in the 0-15 cm depth explained an additional 10% of spring barley grain yield variability. Organic matter improves soil physical and chemical characteristics which in turn provide better growing conditions. Soil pH in the 0-15 cm soil depth was negatively related to spring barley grain yield possibly indicating negative effects of increasing soil pH on availability of soil P. Soil pH ranged from 5.3-8.6 for fields in spring barley production during 1986-1989.

The negative relationship between Olsen P in the 0-15 cm soil depth and grain yield was unexpected. Further study may indicate this relationship is a product of statistical anomaly.

Six of the ten independent variables were significantly related to spring barley grain yield (R^2=0.37).

Table 8. Dryland spring barley model (1986-1989) showing the significant six of ten independent variables.

	Model R^2
$Y^* = 1215.3$	
$+ 18.3\ x1$	0.22
$+ 49.8\ x_2$	0.30
$- 415.8\ x_3$	0.32
$+ 89.3\ x_4$	0.34
$+ 1.1\ x_5$	0.36
$- 25.6\ x_6$	0.37

* Y = Grain yield (kg/ha), x_1 = Moist soil depth in April (cm), x_2 = Soil organic matter (g/kg), x_3 = Soil pH, x_4 = A-horizon thickness (cm), x_5 = Elevation (m), x_6 = Olsen P (mg/kg).

In the regression of six independent variables (minimum data set) against the dependent variable spring barley grain yield (Table 9), the preceding results were not significantly altered. The ordering of variables and contributions to the model were similar.

Positive relationships between A-horizon thickness and spring barley grain yield indicates yields were generally higher on soils with deeper A-horizons. This may have been related to better physical conditions or nutrient availability.

Results from one year (1986) of Soil-Crop Yield data (Osman, 1988) indicated barley grain yield was positively affected by elevation. Increases in elevation are often related to increased precipitation in Montana, as well as changes in growing season onset and length.

Table 9. Dryland spring barley model (1986-1989) showing the significant five of six independent variables.

	Model R^2
$Y^* = -155.0$	
$+ 17.5\ x_1$	0.22
$+ 45.6\ x_2$	0.30
$- 244.0\ x_3$	0.32
$+ 89.3\ x_4$	0.34
$+ 0.9\ x_5$	0.36

* Y = Grain yield (kg/ha), x_1 = Moist soil depth in April (cm), x_2 = Soil organic matter (g/kg), x_3 = Soil pH, x_4 = A-horizon thickness (cm), x_5 = Elevation (m).

Two variables, drought and insect damage indexes were significantly ($P<0.05$) related to spring barley grain yield in addition to the minimum data set (Table 10). In each six "plus" variable regression, significant ($P<0.05$) factors for a single crop were added to the minimum data set of six independent variables. These supplementary factors are not easily measured or understood, or may affect yield "after-the-fact", such as drought damage.

Drought damage and insect damage had large negative effects on grain yields during the 1986 through 1989 crop years. Drought and insect damage indexes explained 32% and 10% of yield variability, respectively. Drought and insect cycles may occur in tandem and cause substantial yield losses. Drought and insect damage indexes were not highly correlated. Grasshoppers were the major cause of insect damage.

Table 10. Dryland spring barley model (1986-1989) showing the significant six of six "plus two" independent variables.

	Model R^2
$Y^* = -\ 316.3$	
$-\ 416.9\ x_1$	0.32
$+\ 16.6\ x_2$	0.41
$-\ 570.1\ x_3$	0.51
$+\ 38.1\ x_4$	0.57
$+\ 1.2\ x_5$	0.60
$+\ 10.4\ x_6$	0.62

* Y = Grain yield (kg/ha), x_1 = Drought damage index, x_2 = Moist soil depth in April (cm), x_3 = Insect damage index, x_4 = Soil organic matter (g/kg), x_5 = Elevation (m), x_6 = Depth to lime (cm).

Spring Wheat

Olsen P in the 0-15 cm soil depth markedly influenced spring wheat yield (R^2 = 0.20) (Table 11). Soil P was positively correlated to moist soil depth in April (r=0.98). Under better spring moisture conditions, adequate soil test P enhances early growth, root formation, and improves yield (Black et al., 1974).

Three water-related factors, moist soil depth in April, elevation, and soil organic matter (0-15 cm depth) were positively related to spring wheat grain yield and contributed an additional 0.22 to R^2. For the test data (1986-1989) a 1 cm increase in moist soil depth in April increased potential grain yield 13 kg/ha. Power (1961), Burke (1984), and Ulmer et al. (1988) indicated similar results for relationships between soil water and spring wheat grain yield. Osman (1988) also reported Olsen P, moist soil depth in April, and elevation were the three most significant grain yield-determining factors for dryland spring wheat using data from the 1986 Montana Soil-Crop Yield data.

Nitrate-N was positively related to dryland spring wheat grain yield. Recalling that soil samples were collected in a preplant condition, soil test results indicated residual nutrient status. Depending on the cooperators' management plans, fertilizer N in addition to the residual amounts indicated by soil test values would be made available to the crops generally increasing potential yield.

The appearance of NO_3-N, depth of lime, extractable K, A-horizon thickness, and rooting depth in the model shown in Table 11 indicates significant relationships to dryland spring wheat grain yield. It is obvious that none of these variables contributed more than 0.02 to R^2. This is not an exception for the type of statistical procedure used to analyze this data.

Table 11. Dryland spring wheat model (1986-1989) showing the significant nine of ten independent variables.

	Model R^2
$Y^* = -\ 2140.8$	
$+\ 10.4\ x_1$	0.20
$+\ 12.7\ x_2$	0.27
$+\ 1.8\ x_3$	0.37
$+\ 31.4\ x_4$	0.42
$+\ 2.7\ x_5$	0.44
$-\ 10.2\ x_6$	0.45
$-\ 0.6\ x_7$	0.46
$+\ 32.2\ x_8$	0.46
$+\ 3.9\ x_9$	0.46

* Y = Grain yield (kg/ha), x_1 = Olsen P (mg/kg), x_2 = Moist soil depth in April (cm), x_3 = Elevation (m), x_4 = Soil organic matter (g/kg), x_5 = NO_3-N (mg/kg), x_6 = Depth to lime (cm), x_7 = Extractable K (mg/kg), x_8 = A-horizon thickness (cm), x_9 = Rooting depth (cm).

In the regression including the six minimum data set variables, five variables were significantly related to dryland spring wheat grain yield and accounted for 38% of grain yield variability: elevation, moist soil depth in April, soil organic matter, depth to free, and A-horizon thickness (Table 12).

Analysis of 1986 through 1989 data show elevation and moist soil depth in April made positive contributions of 18 and 12%, respectively to the model. For every meter elevation gain, potential yield increased by 2 kg/ha for this data set.

Ulmer et al. (1988) reported soil organic carbon was positively related to hard red spring wheat yields in North Dakota. Positive soil organic matter relationships to tilth, fertility, and water-holding capacity enhance yield. When all other factors are constant, this model indicates an increase in soil organic matter of 1 g/kg (0.1%) increases dryland spring wheat yield by 44 kg/ha. Soils ranged from less than 10 to 40 g organic matter per kg of soil (1-4%).

Data indicate that as the depth to lime increased, dryland spring wheat grain yield declined. This negative relationship is not understood.

Table 12. Dryland spring wheat model (1986-1989) showing the significant five of six independent variables.

	Model R^2
$Y^* = -\ 2216.8$	
$+\ 2.2\ x_1$	0.18
$+\ 13.1\ x_2$	0.30
$+\ 43.6\ x_3$	0.37
$-\ 7.5\ x_4$	0.38
$+\ 28.7\ x_5$	0.38

* Y = Grain yield (kg/ha), x_1 = Elevation (m), x_2 = Moist soil depth in April (cm), x_3 = Soil organic matter (g/kg), x_4 = Depth to lime (cm), x_5 = A-horizon thickness (cm).

Nine of ten independent variables significantly affected spring wheat yield when the four "plus" variables (Olsen P, USLE-C factor, seeding rate, and USLE-K factor) were added to the minimum data set (Table 13).

Twenty percent of yield variability was explained by soil P. Osman (1988) reported soil P explained 12% of spring wheat yield variability for one year of Montana Soil-Crop Yield data.

All variables were assigned positive coefficients except the USLE-C (cropping-management) factor. This factor represents soil surface roughness, residue management, and cover conditions. Smaller USLE-C values correspond to less potential erosion under current management conditions compared to fallow. Therefore a negative relationship between this variable and yield is the expected result. Crop residue management is particularly effective during dry winters at storing water and residues protect the soil surface from erosion (Caprio et al., 1989).

The USLE-K factor was positively related to spring wheat grain yield. This factor indicates soil erodibility and is dependent on soil texture, structure, organic matter content, and infiltration. Smaller USLE-K values are favorable, thus the negative relationship between this factor and grain yield is not straightforward. Soil erodibility is dependent on factors too numerous to list here. Further investigation of this relationship is suggested.

Table 13. Dryland spring wheat model (1986-1989) showing the significant nine of six "plus four" independent variables.

	Model R^2
$Y^* = -\ 5984.1$	
$+\ 18.9\ x_1$	0.20
$-\ 1961.3\ x_2$	0.31
$+\ 14.7\ x_3$	0.41
$+\ 25.2\ x_4$	0.49
$+\ 1.3\ x_5$	0.55
$+\ 5061.9\ x_6$	0.59
$+\ 60.8\ x_7$	0.60
$+\ 189.4\ x_8$	0.60
$+\ 12.0\ x_9$	0.60

* Y = Grain yield (kg/ha), x_1 = Olsen P (mg/kg), x_2 = USLE-C (cropping-management) factor, x_3 = Moist soil depth in April (cm), x_4 = Seeding rate (kg/ha), x_5 = Elevation (m), x_6 = USLE-K (soil erodibility) factor, x_7 = A-horizon thickness (cm), x_8 = Soil pH, x_9 = Soil organic matter (g/kg).

Winter Wheat

Moist soil depth in April was positively related to winter wheat yield in the regression model resulting from ten independent variables (Table 14). Moist soil depth in April contributed 0.26 to the model R^2. For the Soil-Crop Yield data from 1986 through 1989, this model illustrates a positive coefficient of 18.8 assigned to moist soil depth in April. This indicates that a 1 cm increase in moist soil depth in April corresponded to a nearly 19 kg/ha winter wheat grain yield increase.

The addition of several other factors (soil organic matter, extractable K, depth to lime, and elevation) improved model performance (R^2=0.39). Extractable soil K was positively related to yield. This relationship can be explained by recalling the important role soil K plays in plant-water relations. Potassium is used by plants to regulate stomatal activity and turgor.

Osman (1988) reported similar relationships for moist soil depth in April and soil K to Montana dryland winter wheat grain yield, and Burke (1984) on the effects of stored soil water on Montana winter wheat grain yields.

Rooting depth appears to have a positive effect on winter wheat grain yield. The ability for roots to explore for deeper stored water positively influences dryland yields.

Table 14. Dryland winter wheat model (1986-1989) showing the significant eight of ten independent variables.

	Model R^2
$Y^* = -\ 4609.3$	
$+ 18.8\ x_1$	0.26
$+ 17.6\ x_2$	0.28
$+ 2.1\ x_3$	0.30
$+ 10.9\ x_4$	0.33
$+ 1.5\ x_5$	0.35
$+ 8.5\ x_6$	0.37
$+ 42.0\ x_7$	0.38
$+ 154.5\ x_8$	0.39

* Y = Grain yield (kg/ha), x_1 = Moist soil depth in April (cm), x_2 = Soil organic matter (g/kg), x_3 = Extractable K (mg/kg), x_4 = Depth to lime (cm), x_5 = Elevation (m), x_6 = Rooting depth (cm), x_7 = A-horizon thickness (cm), x_8 = Soil pH.

Four of six factors entered the six-variable model for winter wheat with moist soil depth in April again contributing 26% (Table 15). Soil organic matter, depth to lime, and elevation contributed an additional 6%. All factors were positively related to yield.

The positive relationship between depth to lime and winter wheat grain yield has been previously reported by Allgood and Gray (1977), Burke (1984), and Larson (1988).

Table 15. Dryland winter wheat model (1986-1989) showing the significant four of six independent variables.

	Model R^2
$Y^* = -126.9$	
$+ 19.4\ x_1$	0.26
$+ 19.0\ x_2$	0.28
$+ 8.0\ x_3$	0.30
$+ 0.7\ x_4$	0.32

* Y = Grain yield (kg/ha), x_1 = Moist soil depth in April (cm), x_2 = Soil organic matter (g/kg), x_3 = Depth to lime (cm), x_4 = Elevation (m).

There were five "plus" variables for winter wheat and they appeared in the second through sixth positions of the six "plus" variable regression (Table 16). These factors explained the majority of winter wheat grain yield variation from the 1986-1989 crop years. Moist soil depth in April was positively related to yield and explained 26% of variability.

The water damage index, a factor indicating the severity of damage to the crop due to water inundation was positively related to winter wheat grain yield. The presence of water available for storage or perhaps contributions to soil fertility or tilth by silt or fertilizer deposition from other areas of the field could explain this positive relationship. In addition, water damage was highly correlated to the kind of slope, in effect the slope position (shoulder, summit, etc.) and highly negatively correlated to drought damage. Winter wheat on foot slope positions had increased water damage compared to summit and shoulder positions. The severity of drought damage was reduced when water inundation occurred during the growing season.

Seeding rate was positively related to yield and contributed 0.06 to R^2. Seeding rates for winter wheat during the study period ranged from 30 to 101 kg/ha and averaged 66 kg/ha. Winter wheat is subject to winter kill and spring flooding which can make higher seeding rates advantageous. The USLE-C (cropping-management) factor and USLE-R (rainfall and runoff) factor were negatively related to winter wheat grain yield which is the expected relationship. Smaller values for these factors correspond to less potential erosion.

This model is the first case were electrical conductivity of the 0-15 cm soil layer was significantly related to dryland cereal grain yield. The positive relationship is unexplained and particularly surprising as soils in this study were entirely non-saline. Electrical conductivity ranged from 0 to 0.08 S/m and averaged 0.03 S/m. This relationship deserves further study.

Table 16. Dryland winter wheat model (1986-1989) showing the significant eight of six "plus five" independent variables.

	Model R^2
$Y^* = 608.9$	
$+ 25.2\ x_1$	0.26
$+ 1231.8\ x_2$	0.34
$+ 17.6\ x_3$	0.40
$- 1212.4\ x_4$	0.44
$+ 14532.4\ x_5$	0.47
$- 26.8\ x_6$	0.49
$+ 10.4\ x_7$	0.50
$- 42.2\ x_8$	0.51

* Y = Grain yield (kg/ha), x_1 = Moist soil depth in April (cm), x_2 = Water damage index, x_3 = Seed rate (kg/ha), x_4 = USLE-C (cropping-management) factor, x_5 = Electrical conductivity (S/m), x_6 = USLE-R (rainfall and runoff) factor, x_7 = Depth to lime (cm), x_8 = A-horizon thickness (cm).

SUMMARY AND CONCLUSIONS

Four years (1986-1989) of Soil-Crop Yield data were collected from nearly 50 benchmark soil series in 26 Montana counties. Approximately 100 quantifiable potential yield-influencing variables included soil, climatic, and management data. Of the nearly 100 independent variables, ten and subsequently only six variables (minimum data set) were chosen for yield models based on their historical significance and statistical analysis. Additional ("plus") variables were also studied.

Stronger relationships between dryland cereal grain yield with measured variables were recognized when the data were separated by crop. Spring barley grain yield variability was most related to moist soil depth in April during the 1986 through 1989 crop years (R^2=0.22). Drought and insect damage had large negative effects on spring barley yields. Because spring barley is often planted later than spring wheat or winter wheat, it is apparently more susceptible to drought damage. All other factors constant, a nearly 1000 kg/ha spring barley grain loss occurred from "slight" damage by both insects and drought. Soil organic matter (0-15 cm depth) significantly affected spring barley grain yield.

Spring wheat yield was related to soil P, and enhanced by increased seeding rates, soil organic matter, moist soil depth in April, and elevation. An apparent interaction between adequate soil water and soil P concentration has a positive effect on spring wheat grain yield.

Winter wheat yield was related to moist soil depth in April ($R^2 = 0.26$) and to lesser extents on water damage, seeding rate, USLE-C (cropping-management) factor, and soil organic matter. Water damage in the spring seemed to increase potential grain yield, possibly through additional water storage.

Moist soil depth in April and soil organic matter explained nearly one-third of winter wheat and spring barley grain yield. Spring wheat was less dependent on moist soil depth in April. Mean moist soil depth in April and organic matter were similar for all three crops.

This research has shown that crop residue management contributes to dryland cereal grain yields. The strong positive relationships of moist soil depth in April and organic matter with grain yields may also indicate crop residue effects. Long-term production sustainability is particularly dependent on soil organic matter content in the 0-15 cm layer.

Seeding rate was positively related to both winter wheat and spring wheat grain yields. Seeding rate has direct management implications, however further research into this relationship is suggested before application.

Many factors affecting dryland spring barley, spring wheat, and winter wheat grain yields present management opportunities. This research has shown when soil fertility is adequate, management decisions can directly and indirectly influence dryland cereal grain yields. Managing for increased stored soil water and organic matter increase potential dryland cereal grain yield.

The USDA Soil-Crop Yield database has provided a systematic method for collecting long-term soil performance data. Statistical analysis indicated primary relationships and produced preliminary models. A logical next step would be to calculate soil productivity indices for Montana benchmark soils using data and yield-determining factors available in the Soil-Crop Yield database.

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