



Relationship between Munsell color value and organic carbon content in Montana soils
by Eva Maria Zelenak

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:

Soil color has been successfully used to estimate soil organic carbon content of cultivated surface horizons in several states and countries. Amount of soil organic carbon can influence soil classification, interpretation of soil properties, and pesticide application rates and effectiveness. Soil forming factors vary tremendously in Montana, and weak correlations between Munsell soil color and organic carbon on a statewide basis indicate that other factors may require consideration when attempting to explain variability in organic carbon. Soil organic carbon and Munsell color data sets were analyzed on a statewide basis and at a landscape scale. The relationship between organic carbon and Munsell color, elevation, mean annual precipitation, mean annual soil temperature, and percent clay was evaluated for grassland and cropland soils across the state using multiple regression analysis. Regression models explain approximately 50% of the variation using Munsell color and easily measured climate variables on a statewide basis. Color value alone was sufficient to estimate organic carbon ($r^2 = 0.90$) when the relationship was calibrated for a soil landscape. The regression models provide a feasible means of predicting soil organic carbon from easily measured soil and climate characteristics for Montana cropland and grassland soils.

**RELATIONSHIP BETWEEN MUNSELL COLOR AND ORGANIC CARBON
CONTENT IN MONTANA SOILS**

by

Eva Maria Zelenak

A thesis submitted in partial fulfillment
of the requirements for the degree

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APPROVAL

of a thesis submitted by

Eva Maria Zelenak

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

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ABSTRACT

Soil color has been successfully used to estimate soil organic carbon content of cultivated surface horizons in several states and countries. Amount of soil organic carbon can influence soil classification, interpretation of soil properties, and pesticide application rates and effectiveness. Soil forming factors vary tremendously in Montana, and weak correlations between Munsell soil color and organic carbon on a statewide basis indicate that other factors may require consideration when attempting to explain variability in organic carbon. Soil organic carbon and Munsell color data sets were analyzed on a statewide basis and at a landscape scale. The relationship between organic carbon and Munsell color, elevation, mean annual precipitation, mean annual soil temperature, and percent clay was evaluated for grassland and cropland soils across the state using multiple regression analysis. Regression models explain approximately 50% of the variation using Munsell color and easily measured climate variables on a statewide basis. Color value alone was sufficient to estimate organic carbon ($r^2 = 0.90$) when the relationship was calibrated for a soil landscape. The regression models provide a feasible means of predicting soil organic carbon from easily measured soil and climate characteristics for Montana cropland and grassland soils.

CHAPTER 1

INTRODUCTION

Organic matter quantity and quality can greatly affect important soil properties. Organic matter is a source of nutrients for plants, it favorably affects soil structure, drainage and aeration, and it can increase water holding capacity and buffering and exchange capacities of soil. Scientists have devoted much thought to the development of more accurate, rapid, and dynamic methods of characterizing this important soil constituent.

Soil organic matter content influences pesticide effectiveness and fertilizer requirements (Upchurch and Mason, 1962; Page, 1974; Krishnan et al., 1981; Pitts et al., 1986). Generally, the higher the organic matter, the higher the recommended pesticide rate. Further, the adoption of minimum tillage techniques has resulted in a shift towards more dependence on pesticides for weed control (Griffis, 1985).

Organic matter content often varies across individual fields, and should be determined at several places so that herbicide application can be adjusted accordingly. Over or under application of pesticides or fertilizers can be costly in terms of crop and environmental damage, poor weed control, and inefficient fertilization. Interest in developing agricultural equipment that can determine soil organic matter levels and

adjust application rates on the fly has been widespread (Krishnan et al., 1981; Griffis, 1985; Pitts et al., 1986). Such improvements will require quantification of the relationship between organic matter and other observable soil properties.

Soil color can be reliably associated with important soil properties and is widely used to approximate organic matter content in the field and to judge the presence of diagnostic soil horizons. Generally, the darker the soil color, the higher the organic matter content and the higher the native fertility (Soil Survey Staff, 1975). With publication of standard procedures for determining soil color in the Soil Survey Manual (Soil Survey Staff, 1951) and the adoption of the Munsell color system (Munsell Color Co., 1941), researchers gained a standardized tool for measuring soil color. Many subsequent studies have involved correlations between soil organic carbon and Munsell color value which indicates the total darkness of color. Several researchers have quantified the relationship between soil color and organic carbon content in other states and countries, and have developed field methods and sensors for estimating soil organic carbon from soil color and reflectance characteristics (Alexander, 1969; Page, 1974; Steinhardt and Franzmeier, 1979; Pitts et al., 1986).

Because adequate visual standards for predicting organic matter are not readily available in every state, few people have developed skill in estimating organic matter content by examining a soil sample. Steinhardt and Franzmeier (1979) reported that a colleague asked 45 agriculturalists to estimate the organic matter content of an Ap horizon in Indiana which contained 6.12% organic matter. Responses ranged from 0.2 to 90%. A prediction equation or color chart could aid in education and enable scientists to have greater accuracy in predicting soil organic matter in field situations.

Thesis Objective

This study aims to quantify the relationship between Munsell color value and soil organic matter for selected soils in Montana. The ultimate goal is to provide a practical field guide and educational method for estimation of organic carbon from soil color and other readily available data for certain Montana soils.

Soil forming factors vary tremendously in Montana, and no strong correlation between Munsell soil color and organic matter has been demonstrated on a statewide basis. In Montana, Decker (1972) reported a coefficient of simple determination (r^2) of 0.45 between Munsell color value determined under moist conditions and soil organic carbon statewide. This correlation indicates that other factors may require consideration when attempting to explain variability in organic matter for Montana soils.

Schulze et al. (1993) and Fernandez et al. (1988) have shown that organic carbon is better correlated with soil color within associated soils in the same landscape rather than soils from a wide geographic region. Because these local relationships are generally not consistent from one climatic region to another (Steinhardt and Franzmeier, 1979), prediction of organic carbon from color alone may not be feasible on a statewide basis.

The hypothesis to be tested is that Munsell soil color, singly or in combination with other soil or climate attributes can be used to predict soil organic carbon in Montana soils. Analyses were conducted to determine at what scale and under what

conditions the best relationships were attained. Examining the relationship in different subsets of data, at different scales, and in conjunction with climate and other soil variables may produce a correlation adequate to provide an appropriate field method for estimating organic carbon content from soil color.

Literature Review

Organic Carbon vs. Organic Matter

Organic matter content is usually estimated by multiplying the organic carbon content by 1.72 (Nelson and Sommers, 1982). This assumes that organic matter contains approximately 58% organic carbon. Organic carbon is determined by laboratory analysis. However, Broadbent (1953) concluded after reviewing the literature, that factors of 1.9 and 2.5 would be appropriate for surface soils and subsoils, respectively, and should ideally be experimentally determined for each soil. Because of this problem associated with determining organic matter content, Nelson and Sommers (1982) suggest that investigators determine and report the organic carbon content as a measure of the organic matter in a soil. In this thesis organic carbon content is reported and was used in the analysis. Where research of others is summarized, consistency will be maintained by reporting organic matter or organic carbon as reported by each author.

Methods of Measuring Soil Color

Soil color can be measured with standard color charts or with a number of commercially available spectrophotometers. Discussion will focus on the determination of colors with the Munsell color system, because it is the most practical and economical method for color measurements performed by the Soil Survey Staff and in most field studies.

Munsell Color System

Soil colors are usually determined by visually comparing a soil sample to colored chips in a standard color chart, usually the Munsell Soil Color Charts (Munsell Color Co., 1975). The Munsell soil color system consists of approximately 250 colored chips arranged on hue cards. Adjacent chips represent equal intervals of visual perception. Three coordinates: hue, value, and chroma, describe all the possible colors. Munsell hue, designed to represent cylindrical coordinates, refers to the dominant spectral or rainbow color, with red (R), yellow (Y), green (G), blue (B) and purple (P) comprising the principal hues. Five additional hues; yellow-red (YR), green-yellow (GY), blue-green (BG), purple-blue (PB), and red-purple (RP), represent midpoints between the principal hues. The Munsell hue circle in the Munsell soil color charts usually has 7 hues including 10R, 2.5R, 5YR, 7.5YR, 10YR, 2.5Y, and 5Y (Figure 1). Value indicates the degree of lightness or darkness of a color on a gray scale ranging from black to white. In the Munsell color charts, value ranges from 0 (pure black) to 10 (pure white). Chroma is the purity or saturation of a

spectral color. Chroma ranges from 0 (neutral colors) to 8 (strongest color) in the Munsell color system.

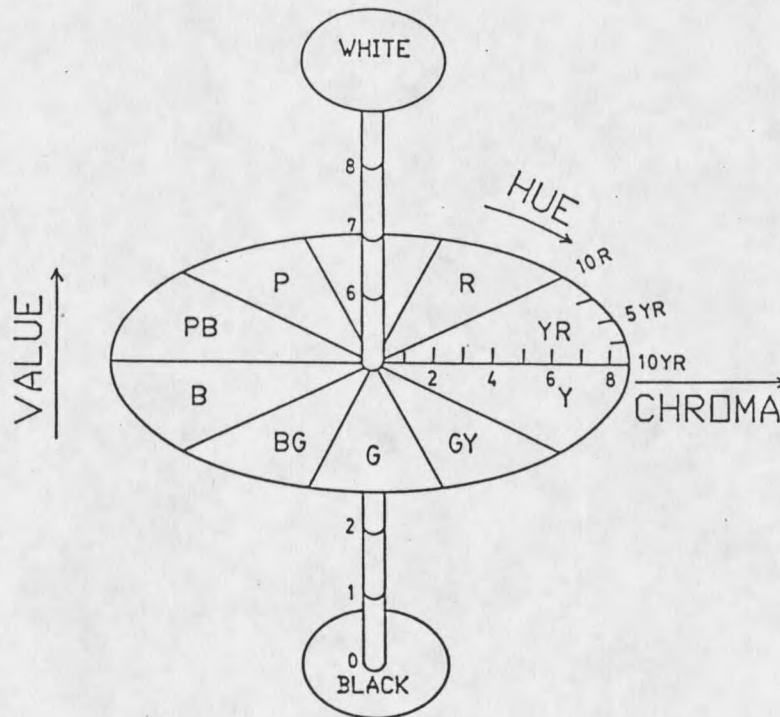


Figure 1. Arrangement of hue, value, and chroma in the Munsell color space (Torrent and Barron, 1993).

In the Munsell color system all chips on a page are of constant hue. Value increases vertically with the darkest colors on the bottom of each page, and chroma increases horizontally with the strongest saturation of colors on the right side of each page. A more detailed description of the Munsell system can be found in the Soil Survey Manual (Soil Survey Staff, 1993).

Many factors can affect the accuracy of a color measurement (Soil Survey Staff, 1993). Quality and intensity of light, roughness of the sample, and moisture content of the sample can affect the amount of reflectance from the soil sample to the eye. Standard conditions of light intensity and quality play an important role in accurately and consistently determining soil color. Incidental light should be as near to a right angle as possible, because roughness of the soil surface can greatly affect the amount of reflectance. Soil color changes with moisture content, (Soil Survey Staff, 1975) therefore it is important that the condition of the sample be recorded. To consistently measure color, two moisture contents can be used: (i) air dry, and (ii) field capacity (Soil Survey Staff, 1975). Field capacity can be sufficiently obtained for color determination by moistening a sample and reading the color as soon as visible moisture films have disappeared (Soil Survey Staff, 1975).

The Soil Survey Staff (1975) report that the probability of perfectly matching any chip in the color chart is less than 100, but that it should be evident which color chip provides the closest match. This, combined with the fact that the ability to sense color differs among people, suggests that there could be uncertainty involved in the reproducibility of consistent colors among different observers. The Soil Survey Staff (1993) suggests that under field conditions, measurements of color are reproducible to within 2.5 units of hue (one page) and 1 unit of value and chroma.

The American Society for Testing and Materials (ASTM, 1993) outlines the procedure for determining Munsell colors for science and industry purposes and describes the limit of precision obtainable using this method. Under controlled

conditions they report a precision of 0.5 hue, 0.1 value, and 0.4 chroma. Kelly and Judd (1976) suggest that an experienced observer can visually interpolate reliably to 0.1 value, to 0.25 chroma, and to one hue step. In both cases this level of precision is only attainable in controlled laboratory conditions with consistent illumination and sample preparation, and a complete set of Munsell color charts (Post et al., 1993).

Other researchers have also tried to quantify the confidence with which soil color measurements can be reproduced. Pomeroy and Knox (1962) suggested, from the results of one observer, that color measurements were reproducible within 1 unit of hue, and 0.5 unit for both value and chroma. Shields et al. (1966) reported that 12 experienced scientists measuring 20 samples determined Munsell values that varied by between 0.5 to 2 units, with an average discrepancy of 1.0 unit of value. Cooper (1990) evaluated the color measuring ability of students who had competed in the 1988 National Soil Judging Contest. Each student had 3 attempts to match colors to the Munsell color chart with the average percent agreement being 62%, 61%, and 67% for hue, value, and chroma respectively.

Post et al. (1993) distributed sets of soil samples to 36 soil scientists to determine dry and moist Munsell colors using the methods outlined in the Soil Survey Manual (Soil Survey Staff, 1988). Their results probably better represent the precision that can reasonably be expected because they take into account the more realistic uncontrolled measuring conditions that prevail when different scientists measure color. The agreement among the soil scientists was 70, 71, and 72 % for chroma, hue, and value respectively.

To evaluate individual color interpretation skill, Post et al. (1993) also calculated an r^2 that measured the relationship between each scientist's Munsell color measurements and the overall mean of multiple observations on each soil sample. The r^2 results ranged from 0.49 for chroma (moist) to 0.79 for value (moist). When the scientists were asked to interpolate estimates between color chips and were given some guidelines to accomplish the measurements, precision was significantly improved. The r^2 results for value reached 0.90 for dry measurements, and 0.95 for moist measurements. Chroma was determined with less precision, with an r^2 of 0.79 for dry measurements, and 0.70 for moist measurements.

It is clear there are limits on the precision of color measurements, especially when conditions are not controlled and consistent, and when different soil scientists collect data. These limitations, combined with the coarse step nature of the data obtained from visually measuring colors, could place a ceiling on the predictive power Munsell color data may have in relationships between soil color and other soil properties. Procedures outlined in the Soil Survey Manual (Soil Survey Staff, 1993) suggest that soil color measurements be made to the nearest whole unit of value and chroma. The range in color produced by differences in organic carbon can be quite small (Schulze et al., 1993). Therefore, color data sets derived from field descriptions of soils will usually have coarse data resolution for Munsell colors, but should provide knowledge of general relationships when compared with other soil properties such as soil organic carbon.

Instrumental Measurements of Soil Color

Commercial tristimulus colorimeters and spectrophotometers have potential as tools for precisely measuring soil colors in the laboratory (Post et al., 1993). Color can be calculated easily from soil reflectance spectral data measured by these instruments (Shields et al., 1968; Fernandez and Schulze, 1987; Escadafal et al., 1988, 1989; Wutscher and McCollum, 1993). The reflected energy measured by colorimeters can be converted into Commission Internationale de l'Eclairage (CIE, 1931) coordinates. Standard tables (Wyszecki and Stiles, 1982) can be used to convert CIE coordinates into Munsell hue, value, and chroma. These measurements are much more accurate than determinations made by scientists by visually matching soil samples to the color standards in the Munsell color book.

Post et al. (1993) reported that the repeatability of measuring soil colors with a chroma meter is very good. The mean standard deviation for hue, value, and chroma color measurements in their study of 10 different soils was only 0.08. Shields et al. (1966) reported a precision of 0.1 unit for Munsell value and chroma when a spectrophotometer was used to measure the spectral reflectance of 20 samples.

Although instrumental measurements of color can be extremely precise and accurate because the potential errors associated with inconsistent lighting conditions and observer differences can be eliminated, accuracy can still be influenced by improper sample preparation. Spectrophotometric color is mostly determined for dry samples because the preparation necessary for moist samples is more complicated. Excess moisture can cause unwanted specular reflection, and evaporation can

influence measurements (Torrent and Barron, 1993). New methods are being developed and tested to overcome these difficulties. Grinding a soil sample can dramatically change its color (Torrent and Barron, 1993). Because the longer a sample is ground, the lighter its color will become, standardized grinding procedures are required if results are to be realistically compared.

Color-Organic Carbon Studies

Alexander (1969) developed a color chart for estimating organic matter content in the surface of cultivated soil in Illinois. The chart was developed by comparing Munsell soil color to organic matter levels determined by lab analysis for over 300 surface soils. Five color chips corresponded to organic matter ranges of 1 to 2%, 1.5 to 2.5%, 2 to 3%, 2.5 to 4%, and 3.5 to 7%. As long as the chart is used with moist soil in cultivated surface soils of medium to fine textures, it claims 95% accuracy in predicting soil organic matter content within these classes in Illinois or other areas of similar climate and geology. Alexander (1969) suggests that the chart can be used to "estimate organic matter well enough to determine application rates of herbicides." Unfortunately, the data used to develop the color chart have not been published and the methods cannot be examined.

Page (1974) measured soil reflectance with a color-difference meter for 96 Ap horizon samples from the Coastal Plain region of South Carolina. The reflectance values were highly correlated with soil organic matter ($r^2 = 0.89$). Page concluded that, for those soils, organic matter could be more quickly and more economically predicted by reflectance methods than by laboratory determinations.

Steinhardt and Franzmeier (1979) reported a semi-quantitative relationship between organic matter content and Munsell color for cultivated silt loam soils of Indiana. Their system divides the samples analyzed ($n = 262$) into 3 categories: (i) samples with Munsell color of 10YR 2/1 contained $> 5\%$ organic matter, (ii) samples with Munsell colors of 10YR 2/2, 3/1, 3/2, and 3/3 contained 3-5% organic matter, and (iii) all other 10YR colors contained $< 3\%$ organic matter. The categories seemed broad, and the data points showed considerable scatter, but they suggest that the system is 90% accurate within these classes and could be used to assist in field problem diagnosis and education.

Franzmeier (1988) grouped 1268 Indiana samples from Ap horizons with hues of 10YR into 5 larger texture classes to quantify the relationship between organic carbon and Munsell color. The 5 regression equations developed for coarse, moderately coarse, medium, moderately fine, and fine texture groups produced r^2 values ranging from 0.31 to 0.47. Both value and chroma were important in predicting organic carbon in these groupings. The authors concluded that soil organic carbon content of the Ap horizons increased with increasing clay content, decreasing color value, and decreasing color chroma. For darker soil colors (10YR 2/2, 3/1, 3/2), poorly drained soils consistently contained more organic carbon than well drained soils with the same colors.

Bingham et al. (1993) studied the relation between Munsell color value and organic carbon content for cultivated surface horizons from two land resource areas in Ohio. They reported a poor correlation for all of the samples combined, but a better relationship for samples within soil landscapes that had similar soil textures.

Several researchers have explored the hypothesis that soil color and organic matter would be more closely related in soil of similar textures within the same soil landscapes. Fernandez et al. (1988) found a strong correlation ($r^2 = 0.94$) between Munsell color value (calculated from reflectance spectra) and organic matter for moist samples in two toposequences of soils in Indiana. They suggest that systems which measure soil color as an estimate of organic matter content might be more successful if they can be "calibrated on a field by field basis" (Fernandez et al. 1988). Schulze et al. (1993) determined that the relationship between soil color and organic matter was poor ($r^2 = 0.31$) for Indiana soils analyzed statewide, but predictable ($r^2 = 0.90$) within soil landscapes with relatively uniform textures. It was also shown that different soil landscapes often had different relationships.

Qian et al. (1993) studied the relationship between Munsell color value and nitrogen in forest mineral soils in British Columbia. Color is used in site classification by foresters to estimate ecological quality and soil nutrient levels. The best regression model ($r^2 = 0.70$) used color value, climate, soil moisture, and soil texture as variables, and climate accounted for the majority of the variation in both mineralizable and total nitrogen.

In Montana, Decker (1972) reported a correlation ($r^2 = 0.45$) between Munsell color value and soil organic carbon on a statewide basis for color determined for crushed peds under moist conditions ($n=164$). Dry color value ($n=132$) explained only 34% of the variability in organic carbon content. Colors determined for crushed peds were more highly correlated to organic carbon than colors measured on the interior or exterior of peds

Several researchers have analyzed soil reflectance data obtained from Landsat Thematic Mapper (TM) images and airborne optical scanners in an attempt to correlate remotely sensed spectral data with organic carbon content (Baumgardner et al., 1970; Escadafal et al., 1989; Bhatti et al., 1991; Wilson et al., 1994). Al-Abbas et al. (1972) quantified the correlation between spectral response bands (obtained with an airborne optical-mechanical scanner) and organic matter for a 25 hectare field in Indiana. Five spectral bands combined to predict 0.57% of the variation in organic matter. Wilcox et al. (1994) analyzed digital TM data from 2 field sites in the Palouse region of eastern Washington state. Regression analysis showed a strong linear relationship for both field sites ($r^2 = 0.88$ and 0.77).

Many agricultural engineers have attempted to correlate spectral properties with soil organic carbon in efforts to develop light reflectance organic carbon sensors for agricultural equipment (Krishnan et al. 1981; Griffis, 1985; Pitts et al, 1986). A practical sensor would be useful for prescription applications of soil-applied chemicals. Recently, Shonk et al. (1991) developed and field tested a prototype real-time soil organic carbon sensor. Preliminary field tests were successful ($r^2 = 0.83$) and the sensor is being further developed and tested.

Relation of Organic Carbon to Soil Properties and Climate

The total amount of soil organic carbon depends on the balance of biomass production and decomposition, and on the soil's capacity to store organic carbon. Therefore, accumulation of organic carbon is sensitive to climatic factors such as

precipitation, and soil temperature (Jenny, 1941; Kononova, 1966; Anderson and Coleman, 1985, Burke et al., 1989). In general, soil organic carbon increases along gradients of increasing precipitation and decreasing temperature. Landscape position, through its influence on microclimate, also affects the accumulation of organic carbon (Schimel et al., 1985; Yonker et al., 1988).

Soil texture, which is related to parent material, exerts some control over the accumulation of soil organic carbon. A higher proportion of plant material is stabilized into soil organic carbon in fine textured soils than in coarse soils (Parton et al., 1987; Schimel et al., 1985). Texture is related to water holding capacity which also influences inputs to organic carbon by affecting plant biomass productivity. In the central and southern Great Plains states, clay content is positively and significantly correlated with soil organic carbon (Nichols, 1984; Burke et al., 1989). Sims and Nielsen (1986) reported that in a study of 130 A horizons from Montana soil pedons, clay percentage was not significantly correlated to soil carbon. In multiple regression analysis elevation and precipitation better predicted carbon content ($R = 0.80$).

CHAPTER 2

MATERIALS AND METHODS

Soil organic carbon and Munsell color data sets were analyzed to quantify the relationships between color and organic carbon for the state of Montana and for a small soil landscape. Two experiments will be described separately in this section and in the results and discussion section: (i) organic carbon relationships on a statewide basis, and (ii) organic carbon relationships in a soil landscape.

Organic Carbon Relationships for Montana Soils

Munsell color and soil organic carbon data from grassland and cropland surface horizons were compared on a statewide basis to examine the possibility that a general relationship may exist. Correlations were expected to be poor in very large areas because of the tremendous variability in Montana soils and climate, and the correlations obtained by Decker (1972) in a statewide analysis. Sample sets were narrowed to smaller subsets to determine at what scale and under what conditions the best relationship existed. Other factors that may account for some of the variation in soil organic carbon were added in multiple regressions or used to further divide and

stratify the data. These include soil texture, status of sample (moist or dry), effervescence (as an indicator of CaCO_3), and climate.

The Montana Soil Pedon Database (MSPD) (Jersey and Nielsen, 1992) comprised the primary source of data for the statewide analysis. The MSPD is composed of site and horizon description data and chemical and physical laboratory data for 1189 horizons of soil pedons sampled throughout Montana. Results from previously published studies were used to select variables that are easily measured and are among soil and climate properties tested by others to be correlates of organic carbon (Table 1).

Table 1. Independent variables selected for stepwise multiple regression analysis on a statewide basis.

| Independent Variables | |
|-----------------------|---|
| Munsell value | Elevation (m) |
| Munsell chroma | Mean annual precipitation (cm) |
| Clay percent | Mean annual soil temperature ($^{\circ}\text{C}$) |

Organic carbon content, Munsell color, particle size analysis, elevation, and mean annual precipitation data for 95 grassland A horizons and 60 cropland Ap horizons were obtained from the MSPD (Figure 2). Colors determined for crushed peds were used whenever possible, but in many cases the ped condition was unspecified. Organic carbon percentages were determined by the acid dichromate digestion method. Mean annual soil temperature data were obtained from MAPS Atlas (Caprio et al., 1994), a Montana Geographical Information System (GIS) that provides estimates of 150 land and climate attributes for Montana.

Montana

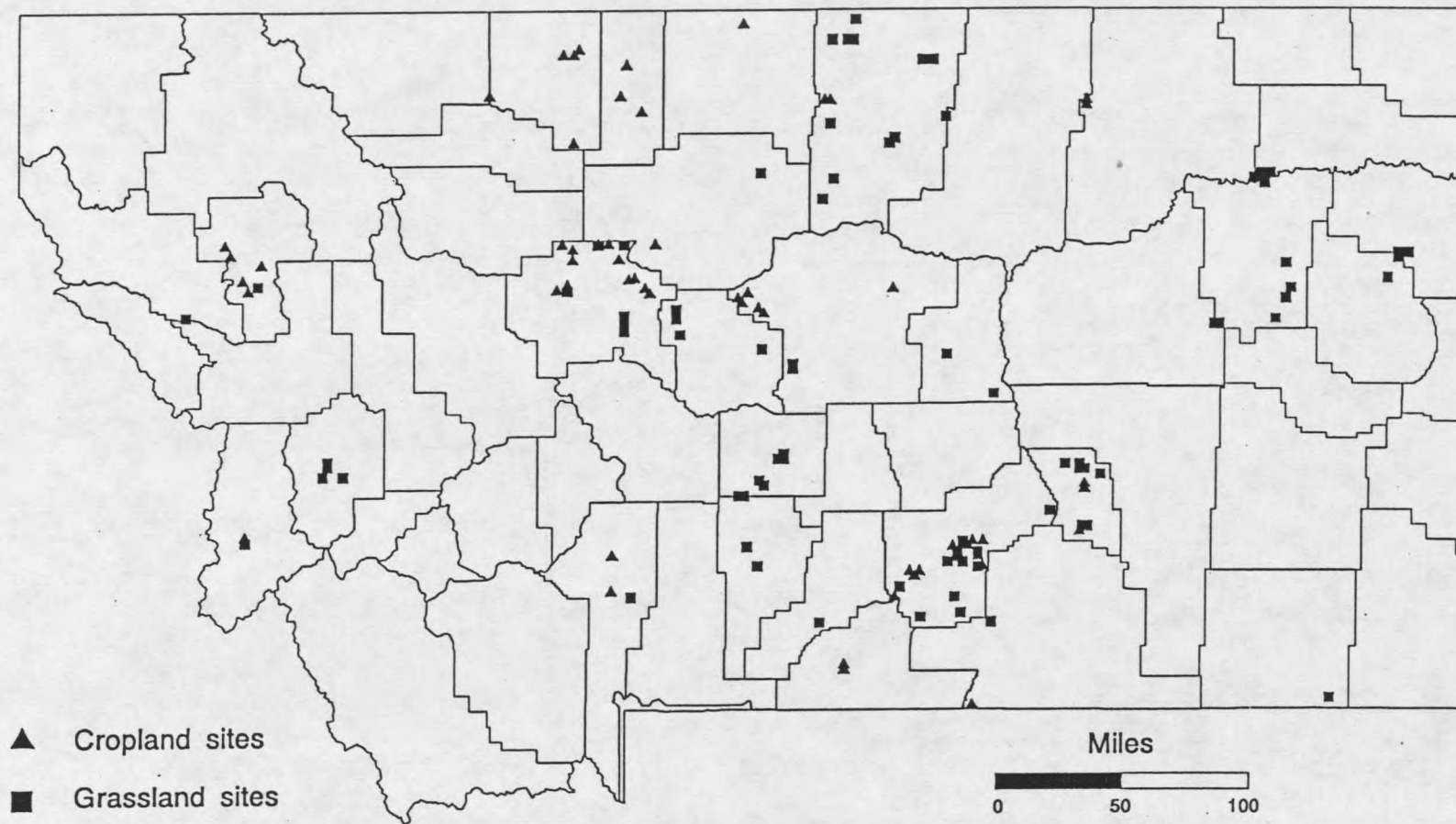


Figure 2. Locations of cropland and grassland sample sites from the Montana Soil Pedon Database that were used in the multiple regression analysis.

The soil and climate attributes that were examined in this study were entered into database files in dBase III+. Files were then exported to SAS (SAS Institute, Inc., 1988), where correlation and regression analyses were performed. A complete list of the data that were analyzed is presented in Appendix A. Stepwise forward regression analysis was used for variable selection and model creation. Dependent variables were considered one-by-one for addition to the regression model. The F-level for entry or deletion of a variable was set to the 0.05 level of significance. The significance of each independent variable was determined by a T-test, and overall significance of the regression model was determined by an F-test. No cases with missing data were included in the analysis.

Residual analysis for the models presented in the results and discussion section were also performed. Residuals of the independent variables were visually examined in scattergrams and probability plots to ensure that the homoscedasticity and normality criteria for multiple linear regression were met. Scatter plots of each independent variable vs. organic carbon were also examined to ensure that the assumption of linearity was met.

Poorly drained soils, Vertisols, soils with vertic subgroups, and salt-affected soils were excluded from the study. In the horizons considered here, it was assumed that all water was supplied through precipitation. Therefore, poorly drained, somewhat poorly drained, and floodplain soils were not evaluated because these soils may have an additional source of moisture. Salt-affected soils and soils with vertic properties were excluded because they can have very dark colors but contain low levels of organic carbon (Soil Survey Staff, 1975).

The data were divided into 2 major subsets, (i) grassland A horizons and (ii) cropland Ap horizons, to account for potential differences in organic carbon levels due to vegetational differences. Further subdivisions for both the grassland and cropland data sets were created to determine relationships that may exist for certain groups of soils (Table 2). Stratifying and analyzing the samples in the groups listed in Table 2 should form subsets of data that are more homogeneous in soil forming factors and should improve the predictive power of regression equations. Separate models were created for each subset of data for dry and moist Munsell colors.

Table 2. Subsets selected for stepwise multiple regression analysis for grassland A horizons and cropland Ap horizons.

All horizons
 Medium textured horizons
 Moderately fine textured horizons
 Horizons with hues of 10YR
 Horizons with hues of 2.5Y
 Horizons that effervesce
 Horizons that do not effervesce
 Second A Horizons

Particle size analysis was used to determine the textural classes of all the A horizons; these textures were grouped for analysis according to the acceptable general terms in Soil Taxonomy (Soil Survey Staff, 1975) listed in Table 3. Sufficient sample size for regression analysis existed only in the medium texture and moderately fine texture groups. The horizons were divided into these 2 texture groups to help decrease variability in organic carbon that may be due to differences in parent material.

Table 3. General groupings for soil textural classes¹.

| Coarse Textured Soils | Moderately Coarse Textured Soils | Medium Textured Soils | Moderately Fine Textured Soils | Fine Textured Soils |
|-----------------------|----------------------------------|-----------------------|--------------------------------|---------------------|
| Sands | Sandy loam | Very fine sandy loam | Clay loam | Sandy clay |
| Loamy sands | Fine sandy loam | Loam | Sandy clay loam | Silty clay |
| | | Silt loam | Silty clay loam | Clay |
| | | Silt | | |

¹From Soil Taxonomy (Soil Survey Staff, 1975).

Horizons with hues of 10YR and 2.5Y were the most numerous and were analyzed separately to determine if relationships improved when colors of a single hue were considered. Because hue is actually designed to geometrically follow cylindrical coordinates, a linear relationship may not exist when colors with different hues are combined.

Horizons that effervesce were separated from horizons with no effervescence. Soils that effervesce could contain amounts of CaCO_3 sufficient to mask or lighten some of the color that may indicate amount of organic carbon. Horizons with an effervescence class of 0 (non-effervescent) were analyzed as non-effervescent soils. Horizons with effervescence classes of 1 (slightly effervescent), 2 (moderately or strongly effervescent) and 3 (violently effervescent) were grouped as effervescent soils.

A2 horizons were analyzed as a separate subset based on research results reported by Sims and Nielsen (1986). In their study of the relationship between

organic carbon, clay content, and climate in Montana soils, better correlations were obtained when data from the second A horizons were evaluated. This is probably related to more erratic biological, climatic, and geomorphical fluctuations at the soil-air interface (Sims and Nielsen, 1986).

Supplemental data were obtained from the Montana Soil Crop Yield database (SCY) which includes data on more than 60 variables representing Montana agricultural soils. Data from the SCY database were used as an independent sample set to test significant models obtained in the statistical analysis of the cropland Ap horizons. Color was measured on 73 soil samples with known organic carbon contents using the procedures outlined by the Soil Survey Staff (1993). Climate attributes were obtained from MAPS Atlas (Caprio et al., 1994). Two models were tested with the SCY data. The predicted organic carbon values obtained from the regression models were compared to the measured organic carbon data using a least squares method to determine the predictive capability of the regression models. The two models were also tested for their predictive capability in subsurface horizons using 26 samples extracted from MSPD.

Organic Carbon Relationships for a Soil Landscape

Samples from a soil terrain, precision farming research field in the Gallatin Valley near Springhill, MT were analyzed to test the hypothesis that the relationship between soil organic carbon and Munsell color will show a higher correlation within

soil landscapes, for example a group of soils occurring in the same field, than for large geographic regions.

Springhill Study Area

The study area at Springhill comprises a topographically diverse field of 20 hectares at the base of the Bridger Mountains near the community of Springhill, MT (T1N, R6E, Section 18). The Wright family has dryland-farmed the field with a grain fallow rotation for the last 50 years.

The study area has moderately strong relief (43m), an average elevation of 1509m, and a general southerly aspect. The mean annual air temperature at the field is 5.4°C, with a mean annual precipitation of 35 cm and mean annual snowfall of 122 cm.

Geologic parent materials are predominantly loess underlain by soft tertiary valley fill sediments derived from Devonian to Cambrian rocks (Veseth and Montagne, 1980). The soils are comprised of Farland silt loams (Fine-silty mixed Typic Argiborolls), Bridger variant clay loams (Fine, mixed Argic Cryoborolls), and Brodyk silt loams (Coarse-silty mixed Typic Ustochrepts).

Multiple Regression Analysis with Terrain Attributes

Soil samples at 70 points in a grid sampling scheme were collected and field Munsell colors measured in May, 1992. Field color measurements were only performed on moist color, and only determined at a subset of 31 locations. To maintain consistency, a regression model was only determined for moist colors

(n=31) at the locations where color data were available. Soil organic carbon (%) was determined by the Walkley-Black method and converted to organic matter by a simplified colorimetric determination (Sims and Haby, 1971). Soil organic carbon was used in the regression analysis and was calculated by dividing percent organic matter by 1.72 (Nelson and Sommers, 1982).

Texture information was not available at the Springhill site, and could not be included in the regression analysis. To attempt to quantify the potential influence of texture or clay content on organic carbon relationships, the samples were grouped according to their taxonomic classification. Unfortunately, there was insufficient color range in these groups to produce meaningful results.

Topographic variables that could be computed by terrain analysis, and that may eventually be available in an on-farm GIS (Geographical Information System) were also added in the multiple regression analysis to determine the effects of these attributes on soil organic carbon (Table 4). Terrain attributes were computed by Damian Spangrud and the following description of the procedures and attributes are paraphrased from his master's thesis (Spangrud, 1995).

Elevation data at 6284 unique locations were collected in the spring of 1992 with an Ashtech P-12 Global Positioning Systems (GPS) receiver as a field station for differential correction, and another Ashtech receiver as the mobile unit. The GPS elevation data were converted to a rectangular 10m digital elevation model (DEM) grid using ANUDEM (Hutchinson, 1989). ANUDEM uses an interactive interpolation algorithm that combines local, kriging, and spline methods.

Table 4. Independent variables selected for stepwise multiple regression analysis at the Springhill soil landscape.

| Independent Variables | |
|---|-------------------------|
| Munsell value (moist) | Plan curvature (°/m) |
| Munsell chroma (moist) | Profile curvature (°/m) |
| Elevation (m) | Aspect (degrees) |
| Specific catchment area (m ² /m) | Slope (%) |
| Wetness index | |

Terrain attributes for the study area were computed from the 10m DEM grid using the Topographical Analysis Programs for the Environmental Sciences program (TAPES) (Moore, 1992). These terrain attributes included slope, aspect, profile (down slope) curvature, plan (across slope) curvature, and specific catchment area (up slope area per unit width of contour). In TAPES a compound topographic index (CTI) or steady state wetness index was calculated from specific catchment area and slope angle (degrees). The CTI has been used to describe the spatial distribution of soil water content (Moore et al., 1993a) and the spatial variability of soil properties (Moore et al., 1993b). The values given by the CTI increase with increasing specific catchment area and decreasing slope. Therefore, the CTI would be higher in areas of water accumulation (flat areas and valleys), and lower where water drains freely (steep side slopes).

Simple Linear Regression Analysis with Munsell Color Value

If predictable relationships within landscapes exist, it would be valuable to determine a method that may be practically used by field scientists to estimate soil

organic carbon using color alone. A method suggested by Schulze et al. (1993) was tested at the Springhill soil landscape to determine its potential usefulness. The procedure recommended by Schulze et al. (1993) is as follows:

1. Sample a series of 5 or 6 Ap horizons that represent the full range of surface colors within the landscape.
2. Obtain laboratory soil organic carbon data for the samples, and measure their color as accurately as possible using a Munsell soil color chart. Interpolate between chips for Munsell value because rounding to the nearest chip will not give sufficient data resolution.
3. Prepare a graph or table of Munsell value vs. organic carbon content to estimate the organic carbon content of unknown samples from the same landscape. Alternatively, one could compare the color of unknown samples directly to the color of soils with known organic carbon contents.

Six Ap horizon samples that represented the entire range of Munsell colors at the site were chosen from a set of samples collected at the Springhill soil landscape in July of 1994. Dry and moist Munsell color values were measured on these samples according to the methods outlined by Kelly and Judd (1976). Sample preparation was consistent and controlled lighting conditions were maintained while the color measurements were performed. Color value measurements were interpolated between chips to 0.5 units. Simple linear regression analysis was used to determine the relationship between organic carbon content and Munsell value for both the dry and moist colors. The model obtained from the regression analysis was tested with an

independent sample set consisting of 17 samples to determine the predictive capability of the 6 sample model. The results from testing the method proposed by Schulze (1993) were used in making a comparison of the strength of relationships obtained from colors measured under controlled vs. uncontrolled environments. The influence of interpolating between chips and the differences between dry and moist color models were also compared.

CHAPTER 3

RESULTS AND DISCUSSION

Organic Carbon Relationships for Montana Soils

Tables 5 and 6 present the correlations between soil organic carbon and the climate and soil variables used in the multiple regression analysis for the cropland Ap and grassland A horizons, respectively. A correlation is presented for both dry and moist Munsell color measurements for each subset.

In the cropland and grassland subsets color value was negatively related to percent soil organic carbon in each case where there was a significant correlation. As color value decreased, or as color got darker, organic carbon was higher. In the cropland data set moist color generally had a higher correlation with organic carbon than dry color. Color chroma also had a negative relation to organic carbon in both the grassland and cropland subsets, indicating that when there was less color saturation, or lower chroma, organic carbon increased.

Table 5. Coefficient of simple correlation (r) between soil organic carbon content and climate and soil properties for cropland Ap horizons.

| Sub-sample | n | Color Value | Color Chroma | Elevation | Soil Temp | Precipitation | Percent Clay |
|----------------------|----|-------------|--------------|-----------|-----------|---------------|--------------|
| Dry Munsell Colors | | | | | | | |
| All Horizons | 60 | -0.46** | -0.40** | 0.29** | -0.42** | 0.51** | -0.23** |
| Medium texture | 21 | -0.40* | NA† | 0.62** | -0.69** | 0.66** | -0.50** |
| Mod fine texture | 29 | -0.31 | -0.67** | 0.03 | -0.33** | 0.47** | -0.12 |
| Hue of 10YR | 30 | -0.29* | -0.53** | 0.03 | -0.58** | 0.48** | -0.42** |
| Hue of 2.5Y | 28 | -0.30 | -0.04 | 0.28** | -0.11 | 0.32** | -0.12 |
| Effervescent | 14 | -0.49* | -0.17 | -0.02 | -0.25 | -0.45** | -0.07 |
| Non-effervescent | 46 | -0.41** | -0.43** | 0.16* | -0.32** | 0.51** | -0.33** |
| Only Ap2 horizons | 13 | -0.15 | -0.46* | 0.34 | -0.47* | 0.63** | -0.28 |
| Moist Munsell Colors | | | | | | | |
| All horizons | 60 | -0.55** | -0.32** | 0.29** | -0.42** | 0.51** | -0.23** |
| Medium texture | 22 | -0.59** | -0.15 | 0.69** | -0.72** | 0.65** | -0.50** |
| Mod fine texture | 29 | -0.46** | -0.57** | 0.09 | -0.34* | 0.47** | -0.12 |
| Hue of 10YR | 37 | -0.60** | -0.44** | 0.20 | -0.56** | 0.51** | -0.40** |
| Hue of 2.5Y | 24 | -0.25 | -0.08 | 0.39* | -0.19 | 0.35 | 0.04 |
| Effervescent | 14 | 0.29 | -0.14 | -0.02 | -0.25 | -0.45* | -0.07 |
| Non-effervescent | 48 | -0.59** | -0.37** | 0.25* | -0.36** | 0.52** | -0.35** |
| Only Ap2 horizons | 13 | -0.20 | -0.38 | 0.34 | -0.47* | 0.63** | -0.28 |

**Statistically significant at the 0.05 α level, *statistically significant at the 0.10 α level.

† Insufficient range of dry chroma in this subset for analysis.

Table 6. Coefficient of simple correlation (r) between soil organic carbon content and climate and soil properties for grassland A horizons.

| Subsample | n | Color Value | Color Chroma | Elevation | Soil Temp | Precipitation | Percent Clay |
|----------------------|----|-------------|--------------|-----------|-----------|---------------|--------------|
| Dry Munsell Colors | | | | | | | |
| All horizons | 95 | -0.61** | -0.55** | 0.50** | -0.38** | 0.57** | 0.11 |
| Medium texture | 50 | -0.52** | -0.52** | 0.46** | 0.33** | 0.51** | 0.33** |
| Mod fine texture | 31 | -0.53** | -0.54** | 0.34** | -0.47** | 0.44** | 0.07 |
| Hue of 10YR | 86 | -0.59** | -0.58** | 0.49** | -0.36** | 0.59** | -0.34** |
| Hue of 2.5Y | 5 | 0.31 | 0.42 | -0.57 | -0.11 | -0.31 | 0.38 |
| Effervescent | 5 | 0.04 | 0.60 | -0.72 | -0.49 | 0.51 | -0.79 |
| Non-effervescent | 90 | -0.60** | -0.55** | 0.48** | -0.36** | 0.56** | 0.21** |
| Only A2 horizons | 29 | -0.55** | -0.63** | 0.61** | -0.26 | 0.74** | 0.22 |
| Moist Munsell Colors | | | | | | | |
| All Horizons | 95 | -0.59** | -0.51** | 0.50** | -0.38** | 0.57** | 0.11 |
| Med texture | 50 | -0.61** | -0.30** | 0.46** | -0.33** | 0.51** | 0.33** |
| Mod fine texture | 31 | -0.47** | -0.62** | 0.34** | -0.47** | 0.44** | 0.07 |
| Hue of 10YR | 84 | -0.59** | -0.56** | 0.46** | -0.37** | 0.52** | 0.44** |
| Hue of 2.5Y | 6 | -0.39 | 0.21 | -0.31 | -0.10 | 0.10 | 0.19 |
| Effervescent | 5 | -0.08 | -0.15 | -0.72 | -0.49 | 0.51 | 0.79 |
| Non-effervescent | 90 | -0.60** | -0.50** | 0.48** | -0.36** | 0.56** | 0.21** |
| Only A2 horizons | 29 | -0.49** | -0.41** | 0.61** | -0.26 | 0.74** | 0.22 |

**Statistically significant at the 0.05 α level, *statistically significant at the 0.10 α level.

Percent clay did not show a consistent relationship with organic carbon, and it was significantly correlated to organic carbon in fewer instances than any other variable. In both the cropland and grassland subsets of moderately fine textures, percent clay was not significantly correlated with organic carbon, but showed significant but opposite correlations (one positive and one negative) for both medium textured horizon subsets.

In the cropland subsets of (1) all horizons, (2) medium textured horizons, (3) horizons with a hue of 10YR, and (4) non-effervescent horizons, there were significant negative correlations between clay content and organic carbon, indicating that as organic carbon content increased, clay content decreased. These findings are contrary to results reported by Nichols (1984) and Burke et al. (1989) from studies in the southern and central Great Plains states. In their research, clay content was positively correlated with soil organic carbon content. This difference may be explained by the fact that Montana has areas of high clay, calcareous soils in dry places (e.g. Eastern Plains). The low levels of precipitation in these areas, generally 30-40 cm per year (Montagne et al., 1982), may account for the lower levels of organic carbon where clay content is high. Therefore, these results may be only a function of the soil samples that were included in those subsets. In the grassland subsets of (1) medium textured horizons, (2) horizons with a hue of 10YR, and (3) horizons that do not effervesce, there was a significant positive relationship between percent clay and organic carbon (Tables 5 and 6).

Independent variables in both grassland and cropland 2.5Y hue subsets showed few significant correlations with organic carbon. In the grassland subsets this is likely due to the extremely small sample size ($n = 6$). In the cropland 2.5Y subset there was a higher sample size ($n = 29$) but no significant correlation existed between color and organic carbon. In both grassland and cropland 10YR hue subsets there were high significant correlations between organic carbon and color value and chroma. This suggests that in the data sets analyzed, color-organic carbon relationships are stronger for soils with color hues of 10YR.

In each case where the correlation between organic carbon and the independent variables elevation and mean annual precipitation was significant, the relationship was positive. Organic carbon was generally higher in soils that received more precipitation and were at higher elevations. Mean annual soil temperature had a negative relationship with organic carbon, and decreased with increasing organic carbon. These general climate relationships are consistent with the findings of Jenny (1941) and other researchers.

Table 7 presents the regression results for the subset containing all the cropland Ap horizons. The first column lists the independent variables that were statistically significant at greater than the 95% probability level and were therefore included in each model. Column 3 shows the coefficient of partial determination (r^2), or the portion of variability that the addition of each term explained. The fourth column indicates that the variability in these attributes combined to explain 57% of the variation in soil organic carbon when dry Munsell colors were used, and 43%

when moist Munsell colors were used. Therefore, the R^2 value, or coefficient of multiple determination is 0.57 for the dry color model and 0.43 for the moist color model.

Table 7. Results of multiple regression analysis for the all horizons cropland subset.

| Variable | Parameter Estimate | Partial r^2 | Model R^2 | F | Prob > F |
|-----------------------------|--------------------|---------------|-------------|-------|----------|
| Dry Munsell Colors (n=60) | | | | | |
| Intercept | 4.92 | | | | |
| Precipitation (cm) | 0.01 | 0.26 | 0.26 | 20.45 | 0.0001 |
| Chroma Value | -0.31 | 0.12 | 0.38 | 11.35 | 0.0014 |
| Soil temperature (°C) | -0.26 | 0.08 | 0.46 | 7.98 | 0.0065 |
| Elevation (m) | -0.15 | 0.06 | 0.52 | 6.89 | 0.0112 |
| | -0.001 | 0.05 | 0.57 | 6.50 | 0.0137 |
| Moist Munsell Colors (n=60) | | | | | |
| Intercept | 2.33 | | | | |
| Chroma Value | -0.21 | 0.30 | 0.30 | 25.43 | 0.0001 |
| Precipitation (cm) | 0.01 | 0.07 | 0.37 | 6.37 | 0.0144 |
| Chroma | -0.30 | 0.06 | 0.43 | 5.79 | 0.0195 |

The basic equation reported in Table 7 for the cropland model that incorporated dry Munsell color is:

$$Y = 4.92 + 0.01x_1 - 0.31x_2 - 0.26x_3 - 0.15x_4 - 0.001x_5 \text{ or}$$

$$Y = 4.92 + 0.01\text{precip} - 0.31\text{chroma} - 0.26\text{value} - 0.15\text{soil temp} - 0.001\text{elev}$$

where Y is percent organic carbon, precip is mean annual precipitation in centimeters, soil temp is mean annual soil temperature in degrees celsius, and elev is elevation in meters. This equation indicates that in this data set of all cropland Ap horizons,

organic carbon increased with increasing mean annual precipitation and with decreasing chroma, value, mean annual soil temperature, and elevation. The terms in the regression model combine to explain 57% of the variation in organic carbon in this cropland Ap horizon data set.

The summary statistics for the cropland Ap all horizons subset are listed in Table 8. Organic carbon varied widely in this subset, ranging from 0.79 % to 3.36%. The range in color value and chroma were quite small, spanning only 3 chips in both dry and moist chroma and in dry value. Moist color value spanned 4 color chips. Because the range of color chips was fairly small, a mean comparison test was also conducted to insure that the mean organic carbon contents for each color value and chroma (ie 2/1, 2/2, 2/3 etc.) were statistically significantly different. In the groups of value and chromas for which sample size was sufficient, a least significant difference test (LSD) for unequal sample sizes statistically supported the hypothesis of unequal means.

Table 8. Summary statistics for the Cropland Ap all horizons subset.

| Variable | n | Mean | Standard Deviation | Minimum | Maximum |
|-----------------------|----|------|--------------------|---------|---------|
| Organic carbon (%) | 60 | 1.44 | 0.46 | 0.79 | 3.36 |
| Dry value | 60 | 4.87 | 0.66 | 4 | 6 |
| Dry chroma | 60 | 2.00 | 0.40 | 1 | 3 |
| Moist value | 60 | 3.05 | 0.77 | 2 | 5 |
| Moist chroma | 60 | 1.99 | 0.36 | 1 | 3 |
| Elevation (m) | 60 | 1057 | 185 | 792 | 1612 |
| Soil temperature (°C) | 60 | 7.7 | 1.1 | 5.6 | 9.5 |
| Precipitation (cm) | 60 | 37.8 | 15.6 | 28 | 102 |
| Percent clay | 60 | 28.7 | 8.3 | 14.7 | 56.3 |

In both the dry color and moist color regression models for the grassland all horizon subset, the variables color value, color chroma, and mean annual precipitation combined to predict almost 50% of the variation in organic carbon (Table 9). Therefore, slightly more than 50% of the variation in organic carbon remains unexplained in this subset of data.

Table 9. Results of multiple regression analysis for the all horizons grassland subset.

| Variable | Parameter Estimate | Partial r^2 | Model R^2 | F | Prob > F |
|-----------------------------|--------------------|---------------|-------------|-------|----------|
| Dry Munsell Colors (n=95) | | | | | |
| Intercept | 5.37 | | | | |
| Value | -0.78 | 0.37 | 0.37 | 54.38 | 0.0001 |
| Precipitation | 0.07 | 0.08 | 0.45 | 14.01 | 0.0003 |
| Chroma | -0.77 | 0.04 | 0.49 | 6.71 | 0.0112 |
| Moist Munsell Colors (n=95) | | | | | |
| Intercept | 3.93 | | | | |
| Value | -0.92 | 0.36 | 0.36 | 51.43 | 0.0001 |
| Precipitation | 0.08 | 0.09 | 0.45 | 16.09 | 0.0001 |
| Chroma | -0.63 | 0.02 | 0.47 | 3.97 | 0.0493 |

The range in organic carbon in the grassland A horizon subset was 0.84% to 9.94%, which is much greater than the range for the cropland Ap subset (Table 10). Dry and moist chroma spanned only 3 color chips, and the range in dry value and moist value was 6 and 4 chips, respectively. A LSD test also revealed statistical differences between organic carbon contents for each color value and chroma.

Table 10. Summary statistics for the all horizons grassland subset.

| Variable | n | Mean | Standard Deviation | Minimum | Maximum |
|-----------------------|----|------|-----------------------|---------|---------|
| Organic carbon (%) | 95 | 3.23 | 2.02 | 0.84 | 9.94 |
| Dry value | 95 | 4.48 | 0.85 | 2 | 7 |
| Dry chroma | 95 | 1.88 | 0.63 | 0 | 3 |
| Moist value | 95 | 2.78 | 0.76 | 2 | 5 |
| Moist chroma | 95 | 1.93 | 0.61 | 0 | 3 |
| Elevation (m) | 95 | 1235 | 340 | 777 | 2133 |
| Soil temperature (°C) | 95 | 6.7 | 1.4 | 3.3 | 9.5 |
| Precipitation (cm) | 95 | 39.0 | 7.9 | 28 | 76 |
| Percent clay | 95 | 24.0 | 8.9 | 10.9 | 59.0 |

In both the cropland and grassland all horizon subsets, the mean moist color value was darker than dry color value by about the same amount (1.82 and 1.72 units, respectively; see Tables 8 and 9). There was relatively little difference in color chroma between moist and dry conditions. These observations are consistent with the range of differences that can be expected. The Soil Survey Staff (1975) indicate that soil colors are commonly darker by 1/2 to 3 units of value, and may change -1/2 to +2 units in chroma in moist vs. dry samples.

An attempt was made to improve performance of models created from the cropland and grassland all horizons subsets by removing potential lithochromic soils that may have formed in black shales. Excluding horizons with parent materials of shale did not improve the predictive power of models created from either subset.

The subset models that showed the best performance were selected for presentation and are discussed below. The remainder of the multiple regression

analysis results and summary statistics for the subsets that were evaluated are presented in Appendix B.

Regression Analysis for the Cropland Ap horizon Subsets

The cropland regression models that showed improvement above the cropland all horizons subset model were in the (1) moderately fine textured horizon subset and in the (2) subset of horizons with a hue of 10YR. The regression model that evaluated medium textured soils also showed slight improvement in predictive power, but did not include any color terms. The models created from the subset for (1) horizons that do not effervesce, and (2) Ap2 horizons, had lower predictive power than the cropland Ap subset model. Analysis of the subset of Ap2 horizons produced a regression equation that included only precipitation ($R^2 = 0.43$), but was probably limited by a very small sample size ($n = 13$). In the subsets of (1) horizons with hues of 2.5Y, and (2) horizons that effervesce, none of the variables met the selection criteria for entry into the model. Therefore, no regression models were created for these subsets. Table 11 reports the results of the regression analysis for moderately fine textured Ap horizons.

Table 11. Results of multiple regression analysis for cropland Ap horizons with moderately fine textures.

| Variable | Parameter Estimate | Partial r^2 | Model R^2 | F | Prob > F |
|-----------------------------|--------------------|---------------|-------------|-------|----------|
| Dry Munsell Colors (n=29) | | | | | |
| Intercept | 6.68 | | | | |
| Chroma | -0.76 | 0.45 | 0.45 | 21.70 | 0.0001 |
| Elevation | -0.002 | 0.08 | 0.53 | 4.43 | 0.0450 |
| Value | -0.41 | 0.20 | 0.73 | 18.05 | 0.0003 |
| Moist Munsell Colors (n=29) | | | | | |
| Intercept | 4.72 | | | | |
| Chroma | -0.34 | 0.32 | 0.32 | 12.74 | 0.0014 |
| Value | -0.62 | 0.10 | 0.42 | 4.34 | 0.0471 |
| Elevation | -0.001 | 0.11 | 0.53 | 5.71 | 0.0247 |

In both the dry color and moist color models created from the moderately fine texture subset, color value, color chroma, and elevation were the variables that entered the predictive equation for organic carbon for that data set (Table 11). The regression models indicate that organic carbon increased with decreasing color chroma, color value, and elevation for this subset. The model that incorporated dry Munsell colors explains 73% of the variation in organic carbon. The use of moist colors did not improve model performance ($R^2 = 0.53$).

The regression results from the horizons in the 10YR color subset show significant improvement in model performance. Table 12 shows that in the dry color model mean annual soil temperature, color chroma and value, mean annual precipitation, and elevation combine in an equation that explains 77% of the variation in organic carbon for this subset. Again the use of moist colors did not significantly improve the ability of the model to predict organic carbon ($R^2 = 0.53$).

Table 12. Results of multiple regression analysis for cropland Ap horizons with a hue of 10YR.

| Variable | Parameter Estimate | Partial r^2 | Model R^2 | F | Prob > F |
|-----------------------------|--------------------|---------------|-------------|-------|----------|
| Dry Munsell Colors (n=30) | | | | | |
| Intercept | 5.79 | | | | |
| Soil temperature | -0.20 | 0.33 | 0.33 | 14.01 | 0.0008 |
| Chroma | -0.60 | 0.17 | 0.50 | 9.28 | 0.0051 |
| Precipitation | 0.01 | 0.17 | 0.67 | 13.22 | 0.0012 |
| Elevation | -0.001 | 0.05 | 0.72 | 4.76 | 0.0388 |
| Value | -0.23 | 0.05 | 0.77 | 4.74 | 0.0395 |
| Moist Munsell Colors (n=37) | | | | | |
| Intercept | 2.81 | | | | |
| Value | -0.28 | 0.36 | 0.36 | 19.53 | 0.0001 |
| Chroma | -0.43 | 0.10 | 0.46 | 6.15 | 0.0183 |
| Precipitation | 0.008 | 0.07 | 0.53 | 4.82 | 0.0353 |

Regression Analysis for the Grassland A Horizon Subsets

The model created from the grassland A2 horizon subset significantly improved model performance above the base level obtained from the grassland all horizon subset analysis (Table 13). Mean annual precipitation and color chroma combined to predict 66% of the variation in organic matter in the dry color model. Mean annual precipitation alone explained 55% of the variation in the moist color data set. Because there was improvement in model performance in the A2 horizon subset, these results suggest that sampling depth should be considered in future studies of organic carbon and its correlates. Perhaps some measure of a weighted average of organic carbon in the top 20 centimeters would provide better correlations with climate and color data.

Table 13. Results of multiple regression analysis for grassland A2 horizons.

| Variable | Parameter Estimate | Partial r^2 | Model R^2 | F | Prob > F |
|-----------------------------|--------------------|---------------|-------------|-------|----------|
| Dry Munsell Colors (n=29) | | | | | |
| Intercept | -0.21 | | | | |
| Precipitation | 0.12 | 0.55 | 0.55 | 33.10 | 0.0001 |
| Chroma | -1.07 | 0.11 | 0.66 | 8.27 | 0.0079 |
| Moist Munsell Colors (n=29) | | | | | |
| Intercept | -3.83 | | | | |
| Precipitation | 0.16 | 0.55 | 0.55 | 33.18 | 0.0001 |

In the moderately fine texture subset there was minimal improvement in model performance (color chroma and mean annual soil temperature combined to account for 52% of the variation in both the dry and moist models). In the other subsets (medium textures, 10YR hues, no effervescence) the predictive power of the regression equations was either the same or slightly lower than the grassland all horizon subset model (Appendix B). In the subsets of (1) horizons with hues of 2.5Y, and (2) horizons that effervesce, none of the independent variables met the selection criteria for entry into the regression model, and no regression equations were created.

Model Validation

Two of the regression models created for the cropland Ap horizons were tested with an independent data set as a validation procedure to test whether models developed from the pedon database were not merely artifacts of the data. Dry color models were used because in most cases they showed a higher predictive power than

models created with moist Munsell colors. For purposes of discussion, the model:

$$\%OC = 4.92 + 0.01\text{precip} - 0.31\text{chroma} - 0.26\text{value} - 0.15\text{soil temp} - 0.001\text{elev} \quad (R^2 = 0.57)$$

will be referred to as the Crop model because it was generated from the cropland Ap

horizon subset. Although this model did not produce as high an R^2 value as the

model generated for soils with colors only of 10YR, it was tested so that performance

could be reported for a model that would be useful when trying to predict organic

carbon for soils with hues including 10YR and 2.5Y. The model:

$$\%OC = 5.79 - 0.20\text{soil temp} - 0.60\text{chroma} + 0.01\text{precip} - 0.001\text{elev} - 0.23\text{value} \quad (R^2 = 0.77)$$

will be referred to as the 10YR model because it was generated only from the subset

of horizons having a color hue of 10YR. Tables 14 and 15 report the summary

statistics for the data used to test the Crop model and the 10YR model respectively.

Table 14. Summary statistics for the Soil Crop Yield independent data set used to test the regression model for cropland Ap horizons (Crop model).

| Variable | n | Mean | Standard Deviation | Minimum | Maximum |
|-----------------------|----|------|-----------------------|---------|---------|
| Organic carbon (%) | 72 | 1.24 | 0.44 | 0.52 | 2.16 |
| Dry value | 72 | 4.97 | 0.67 | 4 | 6 |
| Dry chroma | 72 | 2.24 | 0.51 | 1 | 4 |
| Elevation (m) | 72 | 901 | 181 | 634 | 1332 |
| Soil temperature (°C) | 72 | 6.8 | 0.9 | 5.0 | 8.9 |
| Precipitation (cm) | 72 | 32.6 | 3.9 | 28 | 38 |

Table 15. Summary statistics for the Soil Crop Yield independent data set used to test the regression model for cropland Ap horizons (10YR model).

| Variable | n | Mean | Standard Deviation | Minimum | Maximum |
|-----------------------|----|------|-----------------------|---------|---------|
| Organic carbon (%) | 60 | 1.24 | 0.46 | 0.52 | 2.16 |
| Dry value | 60 | 4.85 | 0.63 | 4 | 6 |
| Dry chroma | 60 | 2.21 | 0.60 | 1 | 4 |
| Elevation (m) | 60 | 896 | 174 | 634 | 1332 |
| Soil temperature (°C) | 60 | 6.8 | 1.0 | 5.0 | 8.9 |
| Precipitation (cm) | 60 | 32.8 | 3.8 | 28 | 38 |

The data for the Ap horizons used to test both models are presented in Table 16. The predicted percent organic carbon and the measured percent organic carbon are also presented. At each sample location data from 3 replicate plots were available, and each replicate is reported in the Table. It is interesting to compare the predicted values with the measured values in Table 16. It is evident that the 10YR model does not do a good job of predicting organic carbon in the 6 samples with coarse textures (Tally fine sandy loam). In each case organic carbon is over-predicted for these horizons. This could be because no coarse textured horizons were included in the original data set used to create the model. It is likely that a different relationship exists between organic carbon and the other independent variables in coarse textured soils, in which a smaller proportion of plant material is stabilized into soil organic carbon than in fine textured soils (Parton et al., 1987).

Table 16. Summary of Soil Crop Yield data used for testing the regression model for cropland Ap horizons.

| County | Series | Sample | Elevation (m) | Precip (cm) | Soil Temp (°C) | Hue | Value | Chroma | Crop model Predicted %OC | 10YR Model Predicted %OC | Measured %OC |
|---------|------------|--------|---------------|-------------|----------------|------|-------|--------|--------------------------|--------------------------|--------------|
| Daniels | Turner sil | 1 | 847 | 38 | 5.0 | 10YR | 4 | 3 | 1.73 | 1.60 | 1.22 |
| | | 2 | 847 | 38 | 5.0 | 10YR | 4 | 3 | 1.73 | 1.60 | 1.05 |
| | | 3 | 847 | 38 | 5.0 | 10YR | 4 | 3 | 1.73 | 1.60 | 1.21 |
| | Williams l | 4 | 751 | 33 | 5.6 | 10YR | 5 | 3 | 1.44 | 1.31 | 1.15 |
| | | 5 | 751 | 33 | 5.6 | 10YR | 5 | 2 | 1.75 | 1.91 | 1.00 |
| | | 6 | 751 | 33 | 5.6 | 10YR | 4 | 3 | 1.70 | 1.53 | 1.08 |
| | Cherry sil | 7 | 777 | 33 | 5.0 | 10YR | 4 | 2 | 2.06 | 2.22 | 1.69 |
| | | 8 | 777 | 33 | 5.0 | 10YR | 4 | 2 | 2.06 | 2.22 | 1.70 |
| | | 9 | 777 | 33 | 5.0 | 10YR | 4 | 2 | 2.06 | 2.22 | 1.77 |
| McCone | Lonna sil | 10 | 719 | 38 | 7.2 | 10YR | 6 | 2 | 1.32 | 1.43 | 1.53 |
| | | 11 | 719 | 38 | 7.2 | 10YR | 6 | 2 | 1.32 | 1.66 | 1.41 |
| | | 12 | 719 | 38 | 7.2 | 10YR | 5 | 2 | 1.58 | 1.63 | 1.74 |
| | Cambert l | 13 | 750 | 38 | 7.2 | 10YR | 5 | 2 | 1.55 | 1.63 | 1.75 |
| | | 14 | 750 | 38 | 7.2 | 10YR | 5 | 2 | 1.55 | 1.63 | 1.66 |
| | | 15 | 750 | 38 | 7.2 | 10YR | 5 | 2 | 1.55 | 1.63 | 1.57 |
| | Cherry sil | 16 | 738 | 38 | 7.2 | 2.5Y | 5 | 2 | 1.56 | NA | 1.78 |
| | | 17 | 738 | 38 | 7.2 | 2.5Y | 5 | 2 | 1.56 | NA | 1.70 |
| 18 | | 738 | 38 | 7.2 | 2.5Y | 6 | 2 | 1.30 | NA | 1.67 | |

Table 16, continued.

| County | Series | Sample | Elevation (m) | Precip (cm) | Soil Temp (°C) | Hue | Value | Chroma | Crop Model Predicted %OC | 10YR Model Predicted %OC | Measured %OC | |
|----------|-----------|----------|------------------|----------------|----------------------|------|-------|--------|--------------------------------|--------------------------------|-----------------|------|
| Rosebud | Lonna sil | 19 | 1030 | 28 | 7.2 | 10YR | 5 | 3 | 0.86 | 0.64 | 1.05 | |
| | | 20 | 1030 | 28 | 7.2 | 10YR | 5 | 3 | 0.86 | 0.64 | 0.85 | |
| | | 21 | 1030 | 28 | 7.2 | 10YR | 5 | 3 | 0.86 | 0.64 | 0.78 | |
| | Vanstel 1 | 22 | 928 | 33 | 8.9 | 10YR | 5 | 3 | 0.76 | 0.46 | 0.58 | |
| | | 23 | 928 | 33 | 8.9 | 10YR | 5 | 3 | 0.76 | 0.46 | 0.62 | |
| | | 24 | 928 | 33 | 8.9 | 10YR | 5 | 3 | 0.76 | 0.46 | 0.55 | |
| | Kremlin 1 | 25 | 823 | 33 | 8.9 | 10YR | 6 | 2 | 0.91 | 0.94 | 0.68 | |
| | | 26 | 823 | 33 | 8.9 | 10YR | 5 | 2 | 1.17 | 1.17 | 0.66 | |
| | | 27 | 823 | 33 | 8.9 | 10YR | 5 | 2 | 1.17 | 1.17 | 0.66 | |
| | | Yamac 1 | 28 | 1049 | 28 | 7.2 | 10YR | 5 | 3 | 0.84 | 0.62 | 0.52 |
| | | | 29 | 1049 | 28 | 7.2 | 10YR | 5 | 3 | 0.84 | 0.62 | 0.55 |
| | | | 30 | 1049 | 28 | 7.2 | 10YR | 5 | 4 | 0.53 | 0.03 | 0.55 |
| | Dawson | Shambo 1 | 31 | 815 | 33 | 6.1 | 10YR | 5 | 2 | 1.60 | 1.73 | 1.66 |
| 32 | | | 815 | 33 | 6.1 | 10YR | 5 | 2 | 1.60 | 1.73 | 1.70 | |
| 33 | | | 815 | 33 | 6.1 | 10YR | 5 | 2 | 1.60 | 1.73 | 1.63 | |
| Shambo 1 | | 34 | 815 | 33 | 6.1 | 10YR | 4 | 2 | 1.86 | 1.96 | 1.92 | |
| | | 35 | 815 | 33 | 6.1 | 10YR | 4 | 3 | 1.55 | 1.36 | 1.97 | |
| | | 36 | 815 | 33 | 6.1 | 10YR | 5 | 2 | 1.60 | 1.73 | 1.81 | |

Table 16, continued.

| County | Series | Sample | Elevation (m) | Precip (cm) | Soil Temp (°C) | Hue | Value | Chroma | Crop Model Predicted %OC | 10YR Model Predicted %OC | Measured %OC |
|---------|-------------|--------|------------------|----------------|----------------------|------|-------|--------|--------------------------------|--------------------------------|-----------------|
| | Cherry sicl | 37 | 817 | 33 | 6.7 | 10YR | 4 | 2 | 1.77 | 1.85 | 1.87 |
| | | 38 | 817 | 33 | 6.7 | 10YR | 4 | 2 | 1.77 | 1.85 | 1.72 |
| | | 39 | 817 | 33 | 6.7 | 10YR | 4 | 2 | 1.77 | 1.85 | 1.98 |
| | Tally fsl | 40 | 893 | 38 | 6.7 | 10YR | 5 | 2 | 1.49 | 1.59 | 0.85 |
| | | 41 | 893 | 38 | 6.7 | 10YR | 5 | 2 | 1.49 | 1.59 | 0.90 |
| | | 42 | 893 | 38 | 6.7 | 10YR | 5 | 2 | 1.49 | 1.59 | 0.94 |
| | Tally fsl | 43 | 893 | 38 | 6.7 | 10YR | 5 | 2 | 1.49 | 1.59 | 0.86 |
| | | 44 | 893 | 38 | 6.7 | 10YR | 5 | 2 | 1.49 | 1.59 | 0.94 |
| | | 45 | 893 | 38 | 6.7 | 10YR | 5 | 2 | 1.49 | 1.59 | 0.85 |
| Pondera | Rothiemay | 46 | 1242 | 33 | 6.1 | 10YR | 4 | 1 | 1.74 | 2.14 | 2.16 |
| | | 47 | 1242 | 33 | 6.1 | 10YR | 4 | 2 | 1.43 | 1.54 | 1.87 |
| | | 48 | 1242 | 33 | 6.1 | 10YR | 4 | 2 | 1.43 | 1.54 | 1.70 |
| | Lonna sil | 49 | 1021 | 28 | 7.8 | 10YR | 5 | 2 | 1.09 | 1.14 | 1.11 |
| | | 50 | 1021 | 28 | 7.8 | 10YR | 5 | 2 | 1.09 | 1.14 | 0.97 |
| | | 51 | 1021 | 28 | 7.8 | 10YR | 5 | 2 | 1.09 | 1.14 | 1.01 |
| | Telstad l | 52 | 1064 | 28 | 7.2 | 10YR | 4 | 3 | 1.08 | 0.84 | 0.93 |
| | | 53 | 1064 | 28 | 7.2 | 10YR | 5 | 2 | 1.13 | 1.21 | 1.15 |
| | | 54 | 1064 | 28 | 7.2 | 10YR | 5 | 2 | 1.13 | 1.21 | 1.00 |

Table 16, continued.

| County | Series | Sample | Elevation (m) | Precip (cm) | Soil Temp (°C) | Hue | Value | Chroma | Crop Model | 10YR Model | Measured %OC |
|-----------|------------------------|------------|------------------|----------------|----------------------|------|-------|--------|------------------|------------------|-----------------|
| | | | | | | | | | Predicted %OC | Predicted %OC | |
| Teton | Rothiemay- Niart cl | 55 | 1332 | 33 | 6.1 | 10YR | 4 | 1 | 1.65 | 2.05 | 1.83 |
| | | 56 | 1332 | 33 | 6.1 | 10YR | 5 | 2 | 1.08 | 1.22 | 1.48 |
| | | 57 | 1332 | 33 | 6.1 | 10YR | 5 | 2 | 1.08 | 1.22 | 1.73 |
| | Marias sicl | 58 | 1146 | 32 | 7.2 | 2.5Y | 6 | 2 | 0.84 | NA | 1.28 |
| | | 59 | 1146 | 32 | 7.2 | 2.5Y | 6 | 3 | 0.53 | NA | 1.16 |
| | | 60 | 1146 | 32 | 7.2 | 2.5Y | 6 | 2 | 0.84 | NA | 1.21 |
| | Kobar sicl | 61 | 1123 | 28 | 7.2 | 2.5Y | 6 | 2 | 0.81 | NA | 1.13 |
| | | 62 | 1123 | 28 | 7.2 | 2.5Y | 6 | 2 | 0.81 | NA | 0.78 |
| | | 63 | 1123 | 28 | 7.2 | 2.5Y | 6 | 3 | 0.50 | NA | 0.95 |
| | Valley | Havre sicl | 64 | 634 | 28 | 6.7 | 10YR | 6 | 2 | 1.39 | 1.52 |
| 65 | | | 634 | 28 | 6.7 | 10YR | 6 | 2 | 1.39 | 1.52 | 1.34 |
| 66 | | | 634 | 28 | 6.7 | 10YR | 6 | 2 | 1.39 | 1.52 | 1.44 |
| Marias c | | 67 | 686 | 28 | 6.7 | 2.5Y | 5 | 2 | 1.59 | NA | 1.43 |
| | | 68 | 686 | 28 | 6.7 | 2.5Y | 5 | 2 | 1.59 | NA | 1.18 |
| | | 69 | 686 | 28 | 6.7 | 2.5Y | 5 | 2 | 1.59 | NA | 1.19 |
| Scobey cl | | 70 | 728 | 28 | 6.7 | 10YR | 5 | 2 | 1.66 | 1.65 | 0.85 |
| | | 71 | 728 | 28 | 6.7 | 10YR | 6 | 2 | 1.43 | 1.43 | 0.73 |
| | 72 | 728 | 28 | 6.7 | 10YR | 6 | 2 | 1.43 | 1.43 | 0.72 | |

A least squares method was employed to quantify the closeness of the model's predicted values of organic carbon to the actual measured values. Table 17 reports the coefficient of simple correlation (r) and coefficient of simple determination (r^2) values that were calculated for the Crop and 10YR models.

Table 17. Model performance results for the Crop and 10YR models when tested for surface horizons.

| Model | Sample size | r | r^2 | % of cases within 0.5% organic carbon |
|-------|-------------|------|-------|---------------------------------------|
| 10YR | 60 | 0.71 | 0.50 | 72 |
| Crop | 72 | 0.61 | 0.37 | 75 |

The r^2 value of 0.50 obtained from testing the 10YR model indicates that predicted values generated by the regression equation explained 50% of the actual variation in organic carbon in the independent sample set. Half of the variation is not accounted for by the regression equation created from the MSPD data. Removing the Tally fine sandy loams (coarse textured soils) from the test data set improved the r^2 value to 0.60.

Figure 3 shows a scatter plot of the measured vs. the predicted values and a regression line which illustrates the 10YR model predicted organic carbon values. Another way to visualize the accuracy of the model predictions is illustrated in Figure 3. An envelope showing $\pm 0.5\%$ organic matter was added to the graph to illustrate how many of the points fall within one-half of one percent of the measured organic carbon. The 10YR model predicted percent organic carbon within 0.5% of the measured values approximately 72% of the time.

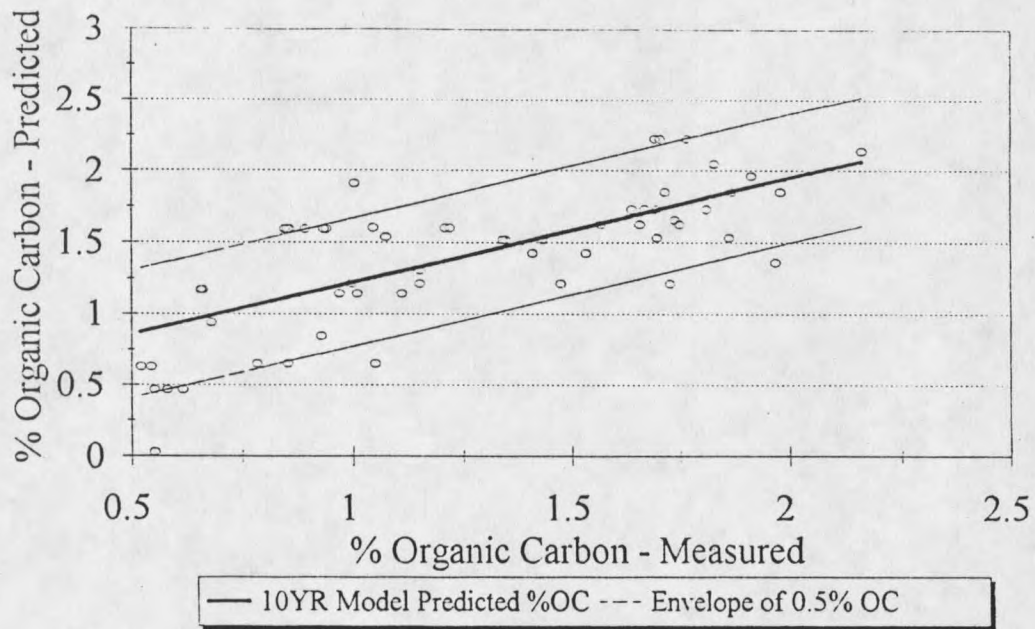


Figure 3. Measured vs. predicted organic carbon (10YR model) for cropland Ap horizons.

Figure 4 shows a scatter plot of the measured vs. the predicted values and a regression line which illustrates the Crop model predicted organic carbon values. The Crop model predicts organic carbon within 0.5% in 75% of the cases tested with the model.

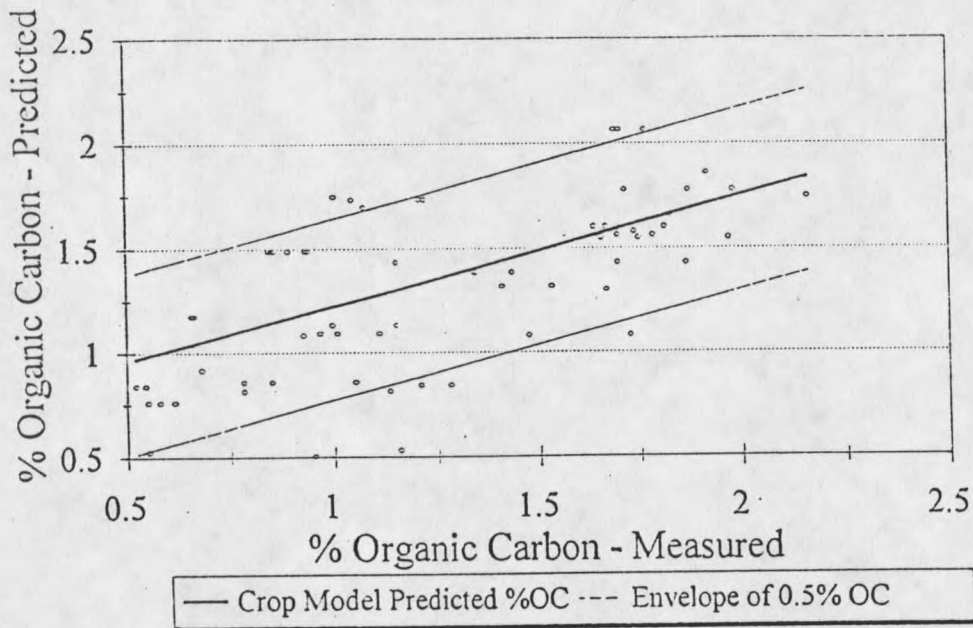


Figure 4. Measured vs. predicted organic carbon (Crop model) for cropland Ap horizons.

In many cases it is also desirable to predict organic carbon for subsurface horizons. Computer models that predict movement and persistence of pesticides and other chemicals through soil generally require input of percent organic carbon for each soil horizon. Models such as CMLS (Nofziger and Hornsby, 1986) and LEACHM (Wagenet and Hutson, 1987) are two examples that researchers are currently using to predict movement of soil applied chemicals. Therefore, both the Crop and 10YR models were tested at depth. Data for 4 soil series were randomly chosen and extracted from the MSPD. Amsterdam, Scobey, Danvers, and Ethridge soil series were used to test the Crop model for each horizon, and the 10YR model for horizons with a hue of 10YR.

The results of testing both the Crop and 10YR models at depth are reported in Table 18. The models, when tested on subsurface horizons, showed a similar trend in performance as when tested on surface horizons. The r^2 values were almost the same as those presented for the model testing in surface horizons. The color and climate data and the measured and predicted organic carbon content values are reported in Table 19. Figures 5 and 6 present the test results for the 10YR and Crop models, respectively.

Table 18. Model performance results for the Crop and 10YR models when tested for subsurface horizons.

| Model | Sample size | r | r^2 | % of cases within 0.5% organic carbon |
|-------|-------------|------|-------|---------------------------------------|
| 10YR | 12 | 0.70 | 0.49 | 67 |
| Crop | 26 | 0.59 | 0.35 | 81 |

Table 19. Summary of Montana Soil Pedon Database data used to test the Crop and 10YR models for subsurface horizons.

| Series | Horizon | Elevation (m) | Precip (cm) | Soil Temp (°C) | Hue | Value | Chroma | Crop Model Predicted %OC | 10YR Model Predicted %OC | Measured %OC |
|-----------|---------|---------------|-------------|----------------|------|-------|--------|--------------------------|--------------------------|--------------|
| Amsterdam | Bw1 | 1463 | 43 | 7.2 | 10YR | 5 | 3 | 0.57 | 0.36 | 0.75 |
| | Bw2 | | | | 10YR | 5 | 2 | 0.88 | 0.96 | 0.62 |
| | Ck1 | | | | 2.5Y | 7 | 2 | 0.36 | NA | 0.48 |
| | Ck2 | | | | 2.5Y | 7 | 2 | 0.36 | NA | 0.32 |
| | Ck3 | | | | 2.5Y | 7 | 2 | 0.36 | NA | 0.32 |
| | C | | | | 2.5Y | 7 | 2 | 0.36 | NA | 0.31 |
| Scobey | Bt1 | 1080 | 30 | 8.3 | 10YR | 5 | 2 | 0.97 | 0.99 | 0.88 |
| | Bt2 | | | | 10YR | 5 | 3 | 0.66 | 0.39 | 0.88 |
| | Bw | | | | 2.5Y | 5 | 2 | 0.97 | NA | 0.91 |
| | Bk | | | | 2.5Y | 6 | 2 | 0.71 | NA | 0.74 |
| | Ck1 | | | | 2.5Y | 6 | 2 | 0.71 | NA | 0.48 |
| | Ck2 | | | | 2.5Y | 6 | 2 | 0.71 | NA | 0.32 |
| | C | | | | 2.5Y | 6 | 2 | 0.71 | NA | 0.36 |
| Danvers | Bt1 | 1127 | 38 | 7.8 | 10YR | 3 | 2 | 1.61 | 1.60 | 2.59 |
| | Bt2 | | | | 10YR | 4 | 2 | 1.34 | 1.37 | 1.44 |
| | Bt3 | | | | 10YR | 7 | 2 | 0.57 | 0.68 | 1.18 |
| | Ck | | | | 10YR | 8 | 2 | 0.31 | 0.45 | 1.18 |
| | C1 | | | | 10YR | 8 | 2 | 0.31 | 0.45 | 0.68 |

Table 19, continued.

| Series | Horizon | Elevation (m) | Precip (cm) | Soil Temp (°C) | Hue | Value | Chroma | Crop Model Predicted %OC | 10YR Model Predicted %OC | Measured %OC |
|----------|---------|------------------|----------------|----------------------|------|-------|--------|--------------------------------|--------------------------------|-----------------|
| | C2 | | | | 10YR | 8 | 2 | 0.30 | 0.45 | 0.15 |
| | Ck | | | | 10YR | 7 | 2 | 0.56 | 0.68 | 0.01 |
| | C3 | | | | 10YR | 7 | 2 | 0.56 | 0.68 | 0.07 |
| Ethridge | Bt1 | 1080 | 28 | 6.7 | 2.5Y | 5 | 3 | 0.89 | NA | 0.88 |
| | Bt2 | | | | 2.5Y | 5 | 4 | 0.58 | NA | 0.91 |
| | Bk1 | | | | 2.5Y | 5 | 3 | 0.89 | NA | 0.79 |
| | Bk2 | | | | 2.5Y | 6 | 2 | 0.94 | NA | 0.59 |
| | Ck | | | | 2.5Y | 6 | 2 | 0.94 | NA | 0.34 |

NA = data from horizons with hues other than 10YR were not used to test the 10YR model.

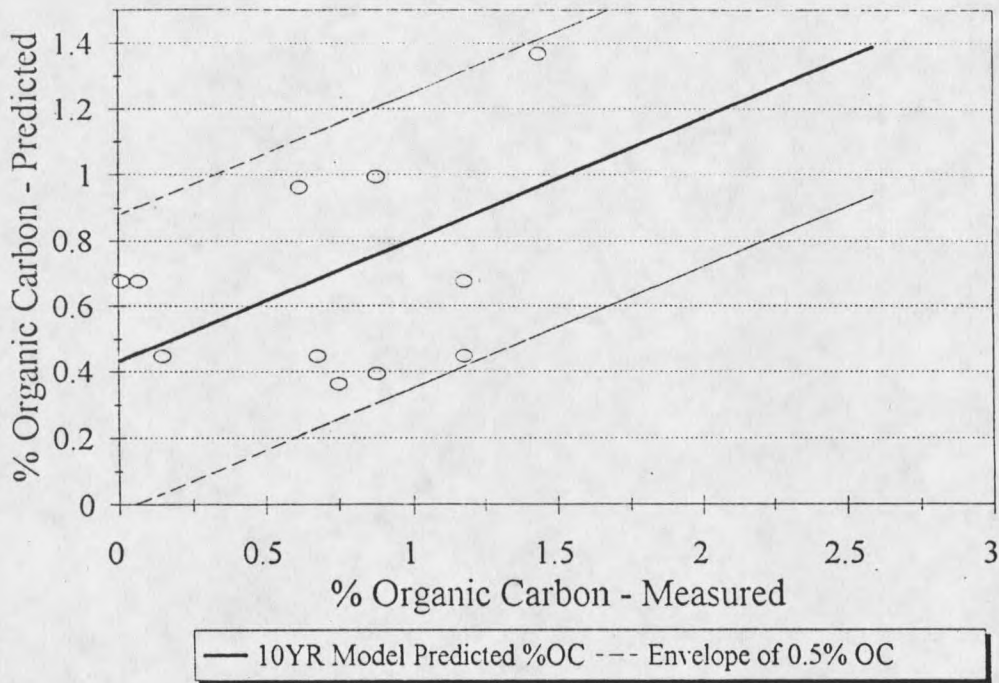


Figure 5. Measured vs. predicted organic carbon (10YR model) for subsurface horizons.

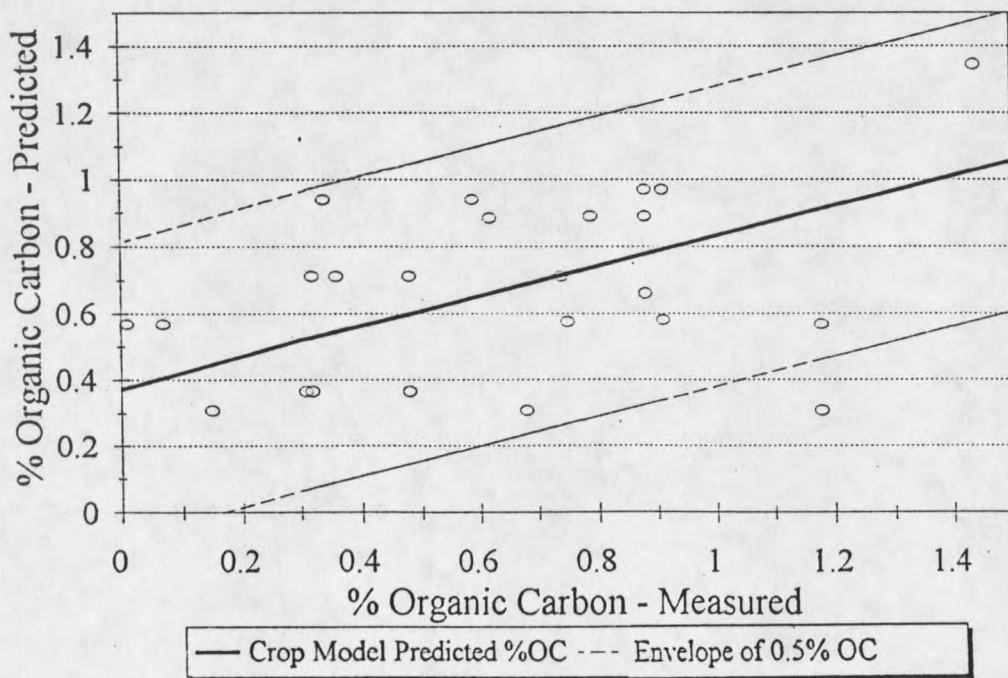


Figure 6. Measured vs. predicted organic carbon (Crop model) for subsurface horizons.

In testing model performance in surface horizons, the Crop and 10YR models predicted values that came within 0.5% of the measured organic carbon contents in $\geq 72\%$ of the cases. For subsurface organic carbon prediction, the Crop model's predicted values were not as highly correlated with the measured values according to the least squares regression analysis, but it predicted organic carbon within 0.5% of the measured values in 81% of the test cases. In each horizon tested, the predicted organic carbon values were always within 1% of the measured values. Although the r^2 values obtained from testing the models were lower than those originally quantified for the analysis of the data from the MSPD, for many uses this accuracy should be sufficient. The potential users of these predictive models can decide, based on these tests, whether the accuracy of the models is within an acceptable range.

There are many potential sources of error in the data from the MSPD that were used to create the regression models. The major source of error comes from what McKenzie and MacLeod (1989) have termed "operator bias." They suggest that in the measurement of morphological properties, including Munsell color, experienced soil scientists can describe the same profile and obtain contrasting results. For instance, color perception can vary from person to person. Decisions on where horizon boundaries are placed or where soil samples are taken will also vary.

The color data in the Pedon database were not measured under controlled conditions. It is probable that sample preparation, moisture status, and light conditions varied when color determinations were made. Further, usefulness of the

data may be limited by their coarse step nature. The method outlined in the Soil Survey Manual (Soil Survey Staff, 1993) suggests that color value and chroma be matched only to the nearest whole unit. Reproducibility of color measurements is also an issue that deserves attention. Research from many scientists suggest that color measurements are only reliably reproducible to within 0.5 to 1 unit of value (Pomeroy and Knox, 1962; Shields et al, 1966; Soil Survey Staff, 1993). If a color measurement is only reproducible by different scientists to within 1 unit of value, and the total range of color only spans 3 or 4 units of value, there is an inherent limit to the predictive capability of field color measurements. Standardizing methods for measuring color and interpolating between chips could improve the accuracy and prediction power of models created with color data. "Operator bias" could be reduced, and precision and potential reproducibility of color measurements increased, in future studies of soil organic carbon-color relationships with the use of colorimeters or spectrophotometers.

Organic Carbon Relationships for a Soil Landscape

Multiple Regression Analysis with Terrain Attributes

The regression results for the Springhill soil landscape are very encouraging (Table 20). In the multiple regression analysis that included Munsell color value and the terrain attributes, the only variable from the data set that met the selection criteria for entry into the model ($F > 0.05$) was color value. Alone it explained 68% of the

variation in organic carbon. A list of the data used to create the regression model can be found in Appendix A.

Table 20. Results of stepwise multiple regression analysis for the Springhill soil landscape.

| Variable | Parameter Estimate | Partial r^2 | Model R^2 | F | Prob > F |
|------------------------------|--------------------|---------------|-------------|-------|----------|
| Moist Munsell Colors (n=31). | | | | | |
| Intercept | 3.57 | | | | |
| Value | -0.59 | 0.68 | 0.68 | 61.79 | 0.0001 |

This relationship is exceptional when considering that the conditions under which the soil colors were measured were not tightly controlled. Despite the fact that determinations of colors were made in the field with no attempt to standardize light conditions and sample preparation, or to interpolate between color chips, soil color alone explained a large amount of the variation in organic carbon.

Table 21 presents the summary statistics for the data set used in the multiple regression analysis at the Springhill soil landscape. Organic carbon ranged from 0.99 to 2.85 %, with a range in color value and chroma of 3 chips. Figure 7 shows a graphical presentation of the regression model.

Table 21. Summary statistics for the Springhill soil landscape color and terrain attribute data.

| Variable | Mean | Standard Deviation | Minimum | Maximum |
|--|---------|--------------------|---------|---------|
| Organic carbon (%) | 2.05 | 0.48 | 0.99 | 2.85 |
| Moist value | 2.58 | 0.67 | 2 | 4 |
| Moist chroma | 1.48 | 0.77 | 1 | 3 |
| Elevation (m) | 1506.58 | 10.83 | 1491.86 | 1531.08 |
| Slope (%) | 9.35 | 3.57 | 2.55 | 16.02 |
| Aspect (degrees) | 191.40 | 51.93 | 102.26 | 332.32 |
| Specific catchment (m ² /m) | 310.77 | 1146.65 | 10.80 | 6417.3 |
| Wetness index (CTI) | 6.73 | 1.34 | 4.53 | 11.74 |
| Plan curvature (°/m) | 0.69 | 8.54 | -17.70 | 28.84 |
| Profile curvature (°/m) | 0.27 | 0.52 | -0.44 | 1.84 |

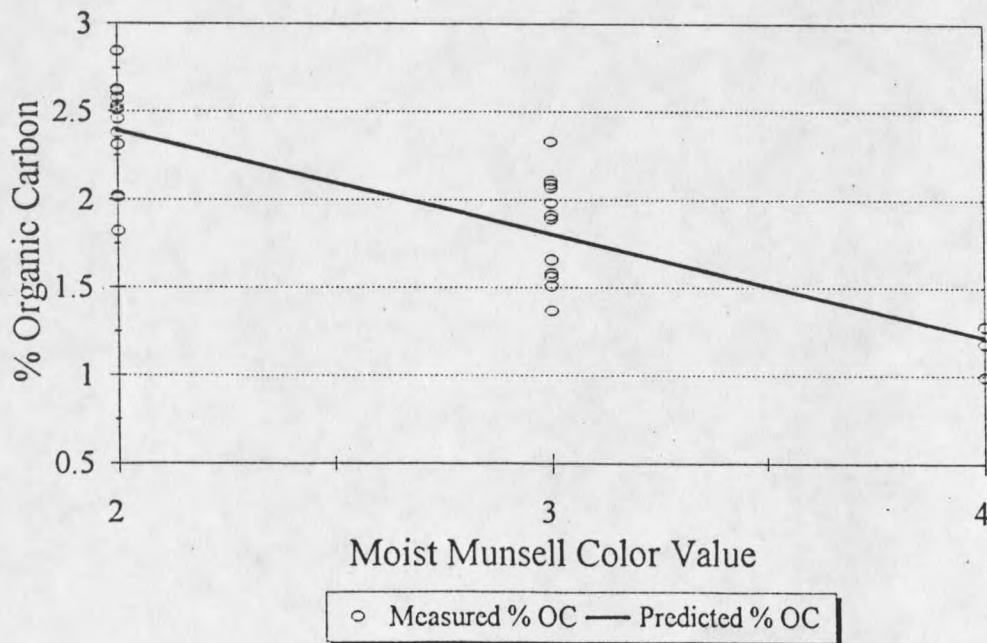


Figure 7. Relationship between moist Munsell color value and percent organic carbon at the Springhill soil landscape.

At the Springhill site, Wilson et al. (1994) quantified the spatial variability of organic matter content using the same terrain attributes in combination with remotely sensed spectral data. Using multiple regression analysis, they created a model in which two spectral band ratios, specific catchment area, and wetness index combined to explain 70% of the variation in organic matter (n=66). The spectral bands alone explained 48% of the total variability in organic matter.

Direct comparisons are difficult to make because a different subset of data was used, but the research presented here supports evidence reported by Wilson et al. (1994) that some measure of color or spectral reflectance can explain a large part of the variation in organic carbon content. The model created here using Munsell color alone, explained only slightly less of the variation in organic carbon than the model reported by Wilson et al. (1994).

Simple Linear Regression Results

The data from the 6 samples used to create organic carbon-color value models using the method outlined by Schulze et al. (1993) are listed in Table 22. In this data set moist color was darker than dry color by about 1 unit of value. Soil organic carbon content ranged from 0.63% to 3.23%.

Table 22. Summary of the data used to create the 6-sample regression models for the Springhill soil landscape

| Sample | % Organic Carbon | Dry Value | Dry Chroma | Moist Value | Moist Chroma |
|--------|------------------|-----------|------------|-------------|--------------|
| 1 | 0.63 | 5 | 3 | 4 | 3 |
| 2 | 1.05 | 5 | 3 | 3.5 | 3 |
| 3 | 1.80 | 4 | 3 | 3 | 1 |
| 4 | 1.91 | 3.5 | 3 | 3 | 2 |
| 5 | 3.23 | 3 | 1 | 2 | 1 |
| 6 | 3.23 | 3 | 1 | 2 | 1 |

Two color models, one for dry value, and one for moist value, were developed from these 6 samples using simple linear regression analysis. The models are as follows:

$$\% \text{ organic carbon} = 5.56 - 1.19 * \text{moist value} \quad (r^2 = 0.98)$$

$$\% \text{ organic carbon} = 6.39 - 1.13 * \text{dry value} \quad (r^2 = 0.92)$$

These models explained almost all of the variation in organic carbon for the 6 samples.

The regression models for the 6-sample moist and dry color models are displayed in Figures 8 and 9 respectively. These equations, developed with more precise and carefully measured color values (color interpolated between chips and determined with controlled lighting and sample preparation), explained significantly more variation in organic carbon than the relationship developed with field measured colors.

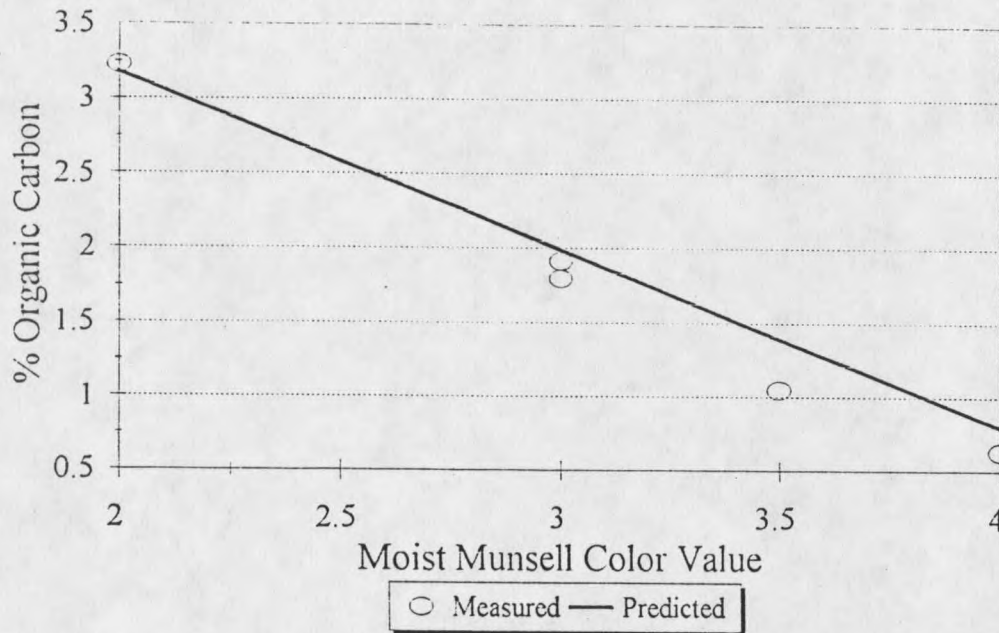


Figure 8. Simple linear regression results for moist color value vs. organic carbon at the Springhill soil landscape.

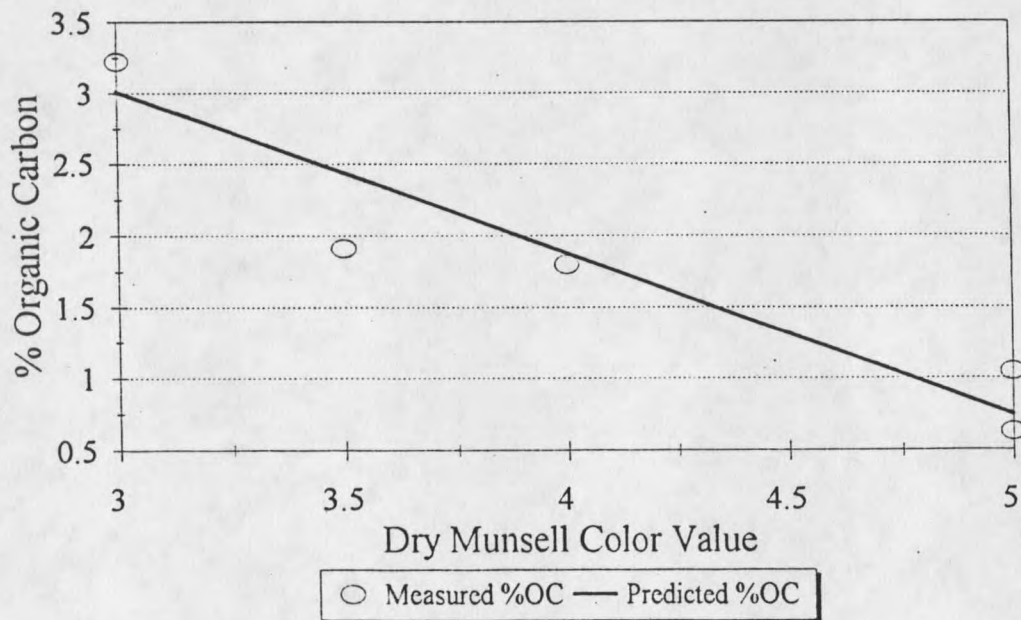


Figure 9. Simple linear regression results for dry color value vs. organic carbon at the Springhill soil landscape.

An independent data set consisting of 17 samples was used to test the validity of using only 6 samples to quantify the relationship between soil organic carbon and color value at the Springhill site. Table 23 summarizes the color data and model predictions. Both the dry and moist color models were tested.

Table 23. Summary of Munsell color values and model predictions from the independent data set at the Springhill soil landscape for the 6 sample dry and moist color models.

| Sample | Dry Value | Moist Value | Dry Model Predicted % Organic Carbon | Moist Model Predicted % Organic Carbon | Measured % Organic Carbon |
|--------|-----------|-------------|--------------------------------------|--|---------------------------|
| 1 | 3.5 | 3 | 2.45 | 1.98 | 1.82 |
| 2 | 3.5 | 2.5 | 2.45 | 2.58 | 2.32 |
| 3 | 4 | 3 | 1.88 | 1.98 | 2.02 |
| 4 | 4.5 | 3.5 | 1.32 | 1.34 | 1.22 |
| 5 | 3.5 | 3 | 2.45 | 1.98 | 1.87 |
| 6 | 4 | 3.5 | 1.88 | 1.39 | 1.34 |
| 7 | 4 | 3 | 1.88 | 1.98 | 1.61 |
| 8 | 4 | 3.5 | 1.88 | 1.39 | 1.41 |
| 9 | 5 | 3.5 | 0.75 | 1.39 | 1.16 |
| 10 | 3 | 2 | 3.01 | 3.17 | 2.81 |
| 11 | 4 | 3 | 1.88 | 1.98 | 1.52 |
| 12 | 4.5 | 3 | 1.32 | 1.98 | 1.69 |
| 13 | 3 | 2.5 | 3.01 | 2.58 | 2.31 |
| 14 | 3.5 | 3 | 2.45 | 1.98 | 1.80 |
| 15 | 3.5 | 2.5 | 2.45 | 2.58 | 2.26 |
| 16 | 4.5 | 3.5 | 1.32 | 1.39 | 1.64 |
| 17 | 3.5 | 2.5 | 2.45 | 2.58 | 2.33 |

The model predictions are in excellent agreement with the measured values. In most cases both models tended to predict slightly higher organic carbon contents than measured values. Least squares regression analysis showed that the model created for moist color value actually explained 90% of the variation in measured organic carbon content in the test data set. The dry model explained slightly less of the variation in measured organic carbon ($r^2 = 0.80$) (Table 24). Figures 10 and 11 show scatter plots of the measured vs. the predicted values for the moist and dry models respectively.

Table 24. Model performance results for the dry and moist color models developed for the surface horizons at the Springhill soil landscape.

| Model | Sample size | r | r ² | % of cases within 0.5% organic carbon |
|-------------|-------------|------|----------------|---------------------------------------|
| Dry color | 17 | 0.89 | 0.80 | 71 |
| Moist color | 17 | 0.97 | 0.90 | 100 |

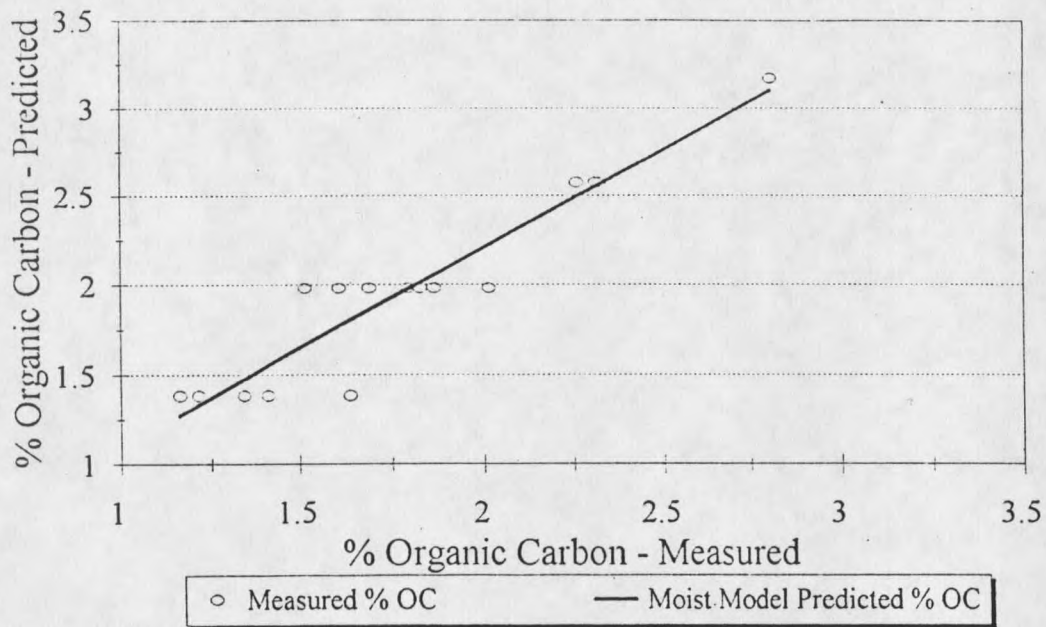


Figure 10. Measured vs. predicted organic carbon (moist color model) for the Springhill soil landscape.

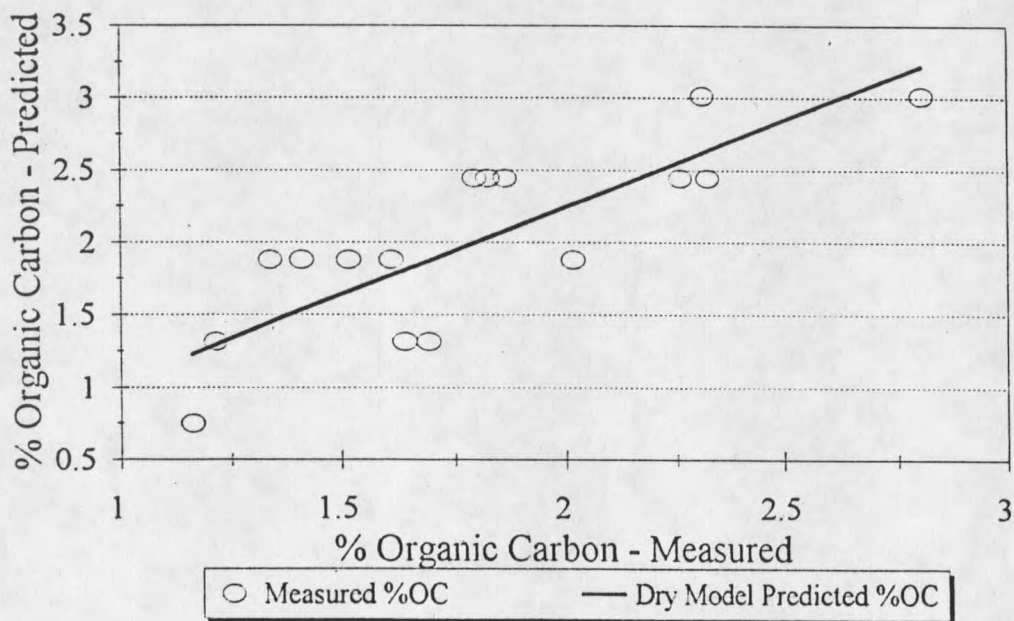


Figure 11. Measured vs. predicted organic carbon (dry color model) for the Springhill soil landscape.

These results suggest that the moist color model generated from the 6 samples was sufficient to characterize soil organic carbon at the site. In all the test samples, the moist model predicted organic carbon within 0.5% of the measured values. Interpolating between color chips to 0.5 units of value, and measuring color under controlled conditions were factors that seemed to contribute to increasing the strength of the relationships between color value and organic carbon. Therefore, this approach has merit for the analysis of Munsell color in future studies of soil organic carbon variability across other Montana landscapes. A tool that could enable field scientists to predict organic carbon based on Munsell color value alone could potentially have useful applications.

No feasible, operational method of spatially determining organic carbon by remote sensing methods currently exists. The research results presented here suggest that on a landscape by landscape basis it may be possible to develop a low tech, economical method to determine organic carbon at many locations. It is conceivable that the method tested at the Springhill site could be incorporated into a practical procedure for generating soil organic matter maps for farmers interested in using precision farming, and for other purposes. A soil scientist could use the method outlined by Schulze et al. (1993) to collect a set of 6 soil samples that characterize the entire range of colors in a field. Aerial photos could aid in ensuring that the samples are representative of the range of color values found in an individual field.

Colors should be measured under controlled conditions with consistent sample preparation. Dry colors should be measured on air-dry samples at the point when

color does not change with additional drying. Moist colors should be measured at the point when the color does not change with additional moistening and there are no visible moisture films (Soil Survey Staff, 1993). Standard conditions of light, artificial light as near the white light of midday as possible, or natural light from a light or moderately overcast sky (or north facing window so there is no direct sunlight) are essential for consistent visual impression (Pendleton and Nickerson, 1951; Soil Survey Staff, 1993). Interpolation between chips (Kelly and Judd, 1976; Pendleton and Nickerson, 1951) would be useful to add precision to color value measurements. Standard Munsell charts with apertures between color chips should be placed above the sample with a mask covering all the chips except those two that most closely match the sample. Unit intervals of color value can then be interpolated between chips.

The relationship between organic carbon results (obtained from laboratory analysis) and the Munsell color values for the 6 samples could be determined by regression analysis. The model created in the analysis could then be used to predict organic carbon for other samples collected at the same field. To obtain detailed information about soil organic matter in a field, a color sampling grid could be established and colors could be measured at grid intersections. Perhaps the colors could then be used to predict organic carbon at each sampling location, and a map created by drawing isotherms, by kriging, by color coding spots at intersections to represent soil organic carbon classes, or by other methods.

Although an excellent relationship between soil organic carbon and Munsell value was quantified at the Springhill site, it is realistic to assume that there are locations where color value will not be sufficient to estimate organic carbon. Lithochromic soils, salt-affected soils, and soils with vertic properties may show weaker relationships between color and organic carbon (Soil Survey Staff, 1975). In landscapes where soil texture or parent material varies widely it may be necessary to develop relationships for groups of textures or for different parent materials (Fernandez et al., 1988; Schulze et al., 1993). In instances where the soil color value range is very small, a spectrophotometer or colorimeter may be useful for adding precision to color measurements.

CHAPTER 4

SUMMARY AND CONCLUSIONS

Soil color has long been associated with important soil properties such as organic carbon. The major focus of this research was to quantify relationships of climate, soil color, and texture to organic carbon in Montana soils. Although limitations caused by coarse data resolution and problems with reproducibility of color measurements made by different scientists were potential sources of error, the data were sufficient to provide general knowledge of color-organic carbon relationships on a statewide basis.

Multiple regression analysis on a statewide basis showed that dry color, in combination with climate variables, better predicted organic carbon than similar moist color models. In general, horizons with lower Munsell values (darker colors) contained more organic carbon than horizons with higher values. Percent clay had little predictive power and did not show a consistent relationship with organic carbon among the different subsets. Regression models for grassland and cropland soils including Munsell color and other easily measured climate variables explained about one-half of the variation in organic carbon. The best statewide relationships were obtained when soil samples were sorted by Munsell color hue and texture groups for

the cropland Ap horizons, and by A2 horizons for the Grassland A horizons. Salt-affected soils, Vertisols, and soils with vertic properties were excluded from the analysis.

The test of the two regression models with an independent data set showed that these relationships may prove to be useful tools for estimating organic carbon from easily measured climate and soil attributes. The models predicted percent organic carbon within 0.5% of measured values in at least 72% of the cases in surface horizons. In subsurface horizons the Crop model predicted organic carbon within 0.5% of measured values in 81% of the cases tested. Predicted values were within 1.0% of measured organic carbon in all tested cases. Depending on the accuracy required for predicting soil organic carbon these equations may be sufficient to estimate organic carbon for many applications. In future studies of the relationship between organic carbon and color, predictive power of models may be improved by standardizing methods for measuring soil color. The use of colorimeters or spectrophotometers should decrease "operator bias" and increase precision and reproducibility of measurements. The error introduced into regression models from measurement error thus would be greatly reduced.

The relationship between color and organic carbon was stronger in the Springhill soil landscape than on a statewide basis, probably because soil forming factors differ less at this scale than they do across the state. Measuring color under controlled conditions and interpolating between color chips seemed to improve the relationships. A model for the Springhill soil landscape created with moist soil color

value ($n=6$) alone was sufficient to provide estimates of organic carbon in an independent data set ($r^2 = 0.90$). These results hold promise for the development of a low-tech method of estimating soil organic carbon at many locations in a single field.

Because the measurement of color value alone was sufficient to estimate soil organic carbon at the Springhill site, the next logical step for predicting organic carbon would be the development of remote sensing methods. Munsell color value measures only the lightness or darkness of a soil sample. Therefore, remote sensing technologies, whether they be Landsat TM images, scanned aerial photos, or real time sensors for agricultural equipment, hold promise for use in rapid estimation of organic carbon across landscapes.

The research presented here suggests that although there is not a strong predictable relationship between organic carbon and color on a statewide basis, estimation of organic carbon by color value for a soil landscape in Montana was possible when the relationship was calibrated for that landscape. In the future, remote sensing methods could also be easily calibrated on a field by field basis using an analogous method to the one applied here and outlined by Schulze et al. (1993). With appropriate testing, the reflectance-organic carbon relationship obtained from 5 or 6 samples that cover the range of colors in a field may also be adequate for calibration of a sensor for an individual landscape.

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APPENDICES

APPENDIX A
DATA TABLES

Table 25. Cropland Ap horizon data from the Montana Soil Pedon Database used for the statewide multiple regression analysis.

| Soil Series | Horizon Number | % Organic Carbon | Moist Color | Dry Color | Elevation (m) | Soil Temp (°C) | Precip (cm) | % Clay | Texture Class | Eff Class |
|-------------|----------------|------------------|-------------|-----------|---------------|----------------|-------------|--------|---------------|-----------|
| Acushnet | 1 | 1.93 | 10YR 2/2 | 10YR 5/2 | 1142 | 6.1 | 36 | 31.9 | CL | 0 |
| Bass | 1 | 2.12 | 10YR 2/2 | 10YR 4/2 | 1280 | 6.1 | 102 | 15.7 | SiL | 0 |
| Chalos | 1 | 2.37 | 10YR 2/2 | NA | 1612 | 5.6 | 56 | 20.5 | L | 0 |
| Charlos | 1 | 1.94 | 10YR 2/2 | 10YR 4/2 | 1612 | 5.6 | 58 | 16.8 | L | 0 |
| Danvers | 1 | 1.50 | 10YR 2/2 | 10YR 4/2 | 1127 | 6.1 | 38 | 30.9 | CL | 0 |
| Danvers | 1 | 1.26 | 10YR 2/2 | 10YR 4/2 | 1127 | 6.1 | 38 | 25.6 | L | 0 |
| Haverson | 1 | 0.82 | 2.5Y 4/3 | 5Y 6/3 | 908 | 6.7 | 33 | 48.6 | SiC | 2 |
| Hopley | 1 | 1.44 | 10YR 3/2 | NA | 937 | 6.7 | 33 | 22.2 | SCL | 0 |
| Joplin | 1 | 1.53 | 10YR4/2 | 10YR 5/2 | 1038 | 5.6 | 28 | 18.9 | L | 1 |
| Joplin | 1 | 1.31 | 10YR3/2 | 10YR 5/2 | 1039 | 5.6 | 28 | 22.4 | SCL | 1 |
| Keiser | 1 | 0.88 | 10YR 4/2 | 10YR 5/3 | 896 | 6.7 | 33 | 30.0 | CL | 0 |
| Kim | 1 | 1.00 | 10YR 4/2 | 2.5Y 5/2 | 975 | 6.7 | 36 | 20.8 | L | 1 |
| McRae | 1 | 0.99 | 10YR 4/2 | 2.5Y 6/2 | 960 | 6.7 | 36 | 16.2 | SL | 1 |
| McRae | 1 | 1.01 | 10YR 4/2 | 2.5Y 5/2 | 975 | 6.7 | 36 | 17.9 | SL | 1 |
| Suffolk | 1 | 1.68 | 10YR 2/2 | 10YR 5/1 | 1142 | 6.1 | 41 | 33.3 | CL | 0 |
| Sula | 1 | 2.43 | 10YR 2/2 | 10YR 4/2 | 1298 | 6.1 | 102 | 18.1 | SiL | 0 |
| Sula | 1 | 1.98 | 10YR 2/2 | 10YR 5/2 | 1298 | 6.1 | 102 | 14.7 | SiL | 0 |
| Thurlow | 1 | 1.23 | 10YR 3/2 | 10YR 5/2 | 1049 | 6.7 | 33 | 32.6 | CL | 0 |

| | | | | | | | | | | |
|----------|---|------|----------|----------|------|-----|----|------|------|---|
| Thurlow | 1 | 1.45 | 2.5Y 3/2 | 2.5Y 4/2 | 905 | NA | 33 | 39.2 | SiCL | 0 |
| Thurlow | 2 | 0.79 | 2.5Y 3/2 | 2.5Y 4/2 | 905 | NA | 33 | 36.0 | SiCL | 0 |
| Nunn | 1 | 1.02 | 2.5Y 4/2 | 2.5Y 5/2 | 792 | 7.2 | 28 | 26.2 | L | 1 |
| Nunn | 2 | 0.97 | 2.5Y 3/2 | 2.5Y 5/2 | 792 | 7.2 | 28 | 28.6 | CL | 2 |
| Nunn | 1 | 1.07 | 2.5Y 4/2 | 2.5Y 5/2 | 792 | 7.2 | 28 | 24.9 | L | 1 |
| Nunn | 2 | 0.85 | 2.5Y 3/2 | 2.5Y 5/2 | 792 | 6.1 | 28 | 21.0 | L | 2 |
| Nunn | 1 | 1.48 | 10YR 3/2 | 2.5Y 5/2 | 792 | 7.2 | 28 | 24.9 | L | 0 |
| Nunn | 2 | 1.48 | 2.5Y 5/2 | 2.5Y 4/2 | 792 | 7.2 | 28 | 25.2 | L | 1 |
| Nunn | 1 | 1.75 | 2.5Y 4/2 | 2.5Y 5/3 | 792 | 7.2 | 28 | 36.9 | SiCL | 1 |
| Nunn | 2 | 1.19 | 2.5Y 3/2 | 2.5Y 5/3 | 792 | 7.2 | 28 | 39.0 | SiCL | 1 |
| Williams | 1 | 1.51 | 10YR 2/2 | 10YR 4/2 | 870 | 5.6 | 38 | 19.8 | L | 0 |
| Williams | 1 | 2.19 | 10YR 2/2 | 10YR 4/2 | 902 | 5.6 | 38 | 20.0 | L | 0 |
| McDonald | 1 | 3.36 | 10YR 2/1 | 10YR 4/1 | 975 | 5.0 | 43 | 28.3 | SiCL | 0 |
| McDonald | 2 | 1.69 | 10YR 2/2 | 10YR 5/2 | 975 | 5.0 | 43 | 28.3 | SiCL | 0 |
| Terrad | 1 | 1.57 | 5YR 3/3 | 5YR 5/3 | 1164 | 6.1 | 40 | 43.2 | C | 0 |
| Acel | 1 | 1.58 | 2.5Y 3/2 | 2.5Y 5/2 | 1080 | 6.1 | 30 | 25.9 | SiL | 0 |
| Acel | 2 | 1.04 | 10YR 3/2 | 2.5Y 5/2 | 1080 | 6.1 | 30 | 35.5 | SiCL | 0 |
| Creedman | 1 | 1.38 | 2.5Y 4/2 | 2.5Y 6/2 | 810 | 5.6 | 28 | 28.9 | SiCL | 0 |
| Ethridge | 1 | 1.36 | 2.5Y 3/2 | 2.5Y 5/2 | 1080 | 5.6 | 28 | 31.4 | CL | 0 |
| Ethridge | 1 | 1.07 | 2.5Y 3/2 | 2.5Y 5/2 | 960 | 5.6 | 28 | 30.6 | CL | 0 |
| Ferdig | 1 | 0.99 | 2.5Y 4/2 | 2.5Y 6/2 | 1020 | 6.1 | 28 | 22.0 | L | 0 |

| | | | | | | | | | | |
|-----------|---|------|----------|----------|------|-----|----|------|------|---|
| Fibea | 1 | 1.11 | 2.5Y 3/2 | 2.5Y 5/2 | 1080 | 6.1 | 30 | 30.9 | SiCL | 0 |
| Inverness | 1 | 1.95 | 2.5Y 3/2 | 2.5Y 5/2 | 1095 | 6.1 | 31 | 47.6 | C | 0 |
| Kerwin | 1 | 1.18 | 2.5Y 4/2 | 2.5Y 6/2 | 1020 | 6.1 | 28 | 29.5 | SiCL | 0 |
| Kinread | 1 | 1.03 | 2.5Y 4/2 | 2.5Y 6/2 | 960 | 5.6 | 28 | 26.7 | SiL | 0 |
| Kinread | 1 | 1.15 | 2.5Y 4/2 | 2.5Y 6/2 | 1005 | 5.6 | 28 | 29.2 | CL | 0 |
| Pylon | 2 | 1.08 | 10YR 4/2 | 2.5Y 6/2 | 1040 | 6.1 | 32 | 37.4 | CL | 0 |
| Pylon | 1 | 1.38 | 2.5Y 4/2 | 2.5Y 6/2 | 1040 | 6.1 | 32 | 33.1 | CL | 0 |
| Scobey | 1 | 1.30 | 10YR 3/2 | 10YR 5/2 | 1080 | 6.7 | 30 | 27.9 | CL | 0 |
| Coffeek | 1 | 1.54 | 10YR 3/2 | 10YR 4/2 | 1112 | 6.1 | 38 | 26.5 | L | 0 |
| Ekah | 1 | 1.73 | 10YR 3/2 | 10YR 4/2 | 1143 | 6.1 | 38 | 22.3 | L | 0 |
| Ekah | 2 | 1.62 | 10YR 2/2 | 10YR 4/2 | 1143 | 6.1 | 38 | 24.3 | L | 0 |
| Komad | 1 | 1.96 | 2.5Y 3/2 | 2.5Y 5/2 | 1113 | 6.1 | 41 | 25.4 | SiL | 0 |
| Komad | 2 | 1.78 | 10YR 3/1 | 10YR 5/1 | 1113 | 6.1 | 41 | 30.5 | SiCL | 0 |
| Komad | 1 | 2.02 | 2.5Y 3/2 | 2.5Y 5/2 | 1097 | 6.1 | 38 | 21.2 | SiL | 0 |
| Matson | 1 | 1.49 | 10YR 3/2 | 2.5Y 5/2 | 1112 | 6.1 | 38 | 22.2 | L | 0 |
| Matson | 2 | 1.25 | 10YR 3/2 | 10YR 5/2 | 1112 | 6.1 | 38 | 28.3 | CL | 0 |
| Amsterdam | 1 | 1.47 | 10YR 1/2 | 10YR 4/2 | 1463 | 6.1 | 43 | 27.3 | SiCL | 0 |
| Amsterdam | 2 | 1.35 | 10YR 2/2 | 10YR 4/2 | 1463 | 6.1 | 43 | 27.5 | SiCL | 0 |
| Shaak | 1 | 1.18 | 10YR 3/2 | 10YR 5/2 | 1103 | 6.7 | 36 | 35.5 | CL | 0 |
| Shaak | 2 | 1.12 | 10YR 3/2 | 10YR 5/2 | 1103 | 6.7 | 36 | 35.6 | CL | 0 |
| Shaak | 1 | 1.34 | 10YR 3/2 | 10YR 5/2 | 1077 | 6.7 | 38 | 34.1 | CL | 0 |

| | | | | | | | | | | |
|----------|---|------|----------|----------|------|-----|----|------|------|---|
| Shaak | 2 | 1.18 | 10YR 3/3 | 10YR 4/2 | 1077 | 6.7 | 38 | 43.4 | C | 0 |
| Shane | 1 | 1.62 | 10YR 3/2 | 10YR 5/2 | 1195 | 5.6 | 36 | 31.8 | SiC | 0 |
| Gallatin | 1 | 0.89 | 10YR 3/2 | 10YR 4/2 | 1372 | 6.1 | 38 | 28.0 | SiCL | 0 |
| Vanda | 1 | 1.02 | 2.5Y 4/1 | 2.5Y 6/1 | 1033 | 6.1 | 36 | 56.3 | C | 0 |

NA = data not available.

Table 26. Grassland A horizon Data from the Montana Soil Pedon Database used for the statewide multiple regression analysis.

| Soil Series | Horizon Number | % Organic Carbon | Moist Color | Dry Color | Elevation (m) | Soil Temp (°C) | Precip (cm) | % Clay | Texture Class | Eff Class |
|-------------|----------------|------------------|-------------|-----------|---------------|----------------|-------------|--------|---------------|-----------|
| Absarokee | 1 | 3.91 | 10YR 2/2 | 10YR 4/2 | 1219 | 7.2 | 41 | 23.4 | L | 0 |
| Absarokee | 1 | 4.83 | 10YR 2/2 | 10YR 4/2 | 1219 | 7.8 | 41 | 22.8 | L | 0 |
| Acushnet | 1 | 5.44 | 10YR 2/2 | 10YR 4/1 | 1310 | 7.2 | 36 | 34.0 | CL | 0 |
| Acushnet | 2 | 3.28 | 10YR 2/2 | 10YR 4/1 | 1310 | 7.2 | 36 | 34.3 | CL | 0 |
| Alder | 1 | 6.36 | 10YR 2/1 | 10YR 4/1 | 1447 | 5.6 | 48 | 29.5 | SiCL | 0 |
| Bearpaw | 1 | 2.66 | 10YR 3/2 | 10YR 5/2 | 945 | 7.2 | 38 | 17.4 | SL | 0 |
| Bearpaw | 1 | 2.06 | 10YR 3/2 | 10YR 5/2 | 933 | 7.2 | 38 | 22.1 | L | 0 |
| Bearpaw | 1 | 5.85 | 10YR 2/2 | 10YR 4/2 | 1094 | 7.2 | 38 | 28.8 | CL | 0 |
| Colby | 1 | 1.00 | 10YR 4/2 | 10YR 5/3 | 1073 | 6.7 | 33 | 14.8 | L | 0 |
| Danvers | 1 | 4.02 | 10YR 2/2 | 10YR 4/1 | 1280 | 7.2 | 38 | 22.9 | L | 0 |
| Danvers | 2 | 2.59 | 10YR 2/2 | 10YR 3/1 | 1280 | 7.2 | 38 | 28.2 | CL | 0 |
| Doughty | 1 | 4.42 | 10YR 2/1 | 10YR 4/1 | 1676 | 7.2 | 46 | 36.3 | SiCL | 0 |
| Doughty | 2 | 4.94 | 10YR 2/2 | 10YR 4/1 | 1676 | 7.2 | 46 | 34.8 | SiCL | 0 |
| Farland | 1 | 3.59 | 10YR 3/2 | 10YR 4/2 | 838 | 6.1 | 34 | 19.8 | SiL | 0 |
| Farland | 2 | 1.45 | 10YR 3/2 | 10YR 4/2 | 838 | 6.1 | 34 | 25.0 | L | 0 |
| Glikon | 1 | 6.09 | 10YR 2/1 | 10YR 4/1 | 1371 | 7.2 | 41 | 29.2 | CL | 0 |
| Glikon | 2 | 3.63 | 10YR 4/2 | 10YR 4/2 | 1371 | 7.2 | 41 | 29.5 | CL | 0 |
| Glikon | 1 | 6.28 | 10YR 2/1 | 10YR 4/2 | 1371 | 6.1 | 46 | 27.2 | CL | 0 |

| | | | | | | | | | | |
|-------------|---|------|----------|----------|------|-----|----|------|-----|---|
| Glikon | 2 | 3.34 | 10YR 1/2 | 10YR 4/2 | 1371 | 6.1 | 46 | 28.4 | CL | 0 |
| Hesper | 1 | 1.39 | 10YR 3/2 | 10YR 5/2 | 971 | 8.9 | 33 | 13.3 | L | 0 |
| Hesper | 1 | 1.63 | 10YR 4/2 | 10YR 6/2 | 1177 | 8.9 | 38 | 14.9 | L | 0 |
| Hesper | 1 | 1.48 | 10YR 4/2 | 10YR 6/2 | 1066 | 7.8 | 33 | 16.9 | L | 0 |
| Hopley | 1 | 1.66 | 10YR 3/2 | 10YR 5/2 | 988 | 8.9 | 33 | 15.7 | SL | 0 |
| Hopley | 2 | 1.06 | 10YR 3/2 | 10YR 5/3 | 988 | 8.9 | 33 | 19.0 | SL | 0 |
| Hopley | 1 | 2.13 | 10YR 2/2 | 10YR 5/2 | 1188 | 7.8 | 36 | 13.4 | L | 0 |
| Hopley | 2 | 1.16 | 10YR 2/2 | 10YR 5/2 | 1188 | 7.8 | 36 | 15.6 | SL | 0 |
| Keiser | 1 | 1.60 | 10YR 4/2 | 10YR 5/2 | 1036 | 7.8 | 36 | 18.9 | L | 0 |
| Maddux | 1 | 1.85 | 10YR 3/2 | 10YR 4/2 | 1347 | 8.3 | 41 | 34.4 | CL | 0 |
| Maddux | 1 | 2.62 | 10YR 3/2 | 10YR 4/2 | 1523 | 6.1 | 38 | 18.7 | SL | 0 |
| Maddux | 2 | 1.96 | 10YR 3/3 | 10YR 4/2 | 1523 | 6.1 | 38 | 27.0 | SCL | 0 |
| Maddux | 1 | 2.38 | 10YR 3/2 | 10YR 4/1 | 1371 | 8.3 | 38 | 14.3 | SL | 0 |
| Manning | 1 | 4.04 | 10YR 3/2 | 10YR 4/2 | 838 | 6.7 | 34 | 14.3 | L | 0 |
| Manning | 1 | 3.02 | 10YR 2/2 | 10YR 4/2 | 838 | 6.7 | 34 | 14.3 | L | 0 |
| Manning | 2 | 1.59 | 10YR 2/2 | 10YR 4/2 | 838 | 6.7 | 34 | 14.5 | L | 0 |
| Martinsdale | 1 | 2.41 | 10YR 3/2 | 10YR 4/2 | 1523 | 6.1 | 38 | 19.6 | SL | 0 |
| Martinsdale | 2 | 2.13 | 10YR 3/3 | 10YR 4/3 | 1523 | 6.1 | 38 | 25.0 | SCL | 0 |
| McRae | 1 | 1.17 | 10YR 4/2 | 10YR 6/3 | 875 | 8.9 | 33 | 14.4 | L | 0 |
| Melville | 1 | 6.10 | 10YR 3/2 | 10YR 4/2 | 1676 | 5.6 | 43 | 28.2 | SCL | 0 |
| Melville | 2 | 3.76 | 10YR 3/2 | 10YR 4/2 | 1676 | 5.6 | 43 | 33.4 | CL | 0 |

| | | | | | | | | | | |
|-------------|---|------|-----------|-----------|------|-----|----|------|-----|---|
| Michelson | 1 | 9.16 | 10YR 2/2 | 10YR 4/2 | 1676 | 5.0 | 43 | 26.3 | L | 0 |
| Michelson | 2 | 4.17 | 10YR 2/2 | 10YR 4/2 | 1676 | 5.0 | 43 | 25.3 | SCL | 0 |
| Monad | 1 | 5.35 | 10YR 2/1 | 10YR 3/1 | 1432 | 6.1 | 43 | 23.3 | L | 0 |
| Monad | 1 | 9.25 | 10YR 2/1 | 10YR 3/1 | 1432 | 5.6 | 48 | 28.0 | CL | 0 |
| Monad | 2 | 5.80 | 10YR 2/1 | 10YR 3/1 | 1463 | 5.6 | 48 | 27.0 | CL | 0 |
| Monad | 3 | 2.73 | 10YR 1/2 | 10YR 4/2 | 1463 | 5.6 | 48 | 27.4 | CL | 0 |
| Philipsburg | 1 | 2.78 | 10YR 2/1 | 10YR 4/1 | 1645 | 4.4 | 38 | 21.8 | L | 0 |
| Philipsburg | 1 | 2.74 | 10YR 2/1 | 10YR 4/1 | 1676 | 4.4 | 38 | 20.1 | L | 0 |
| Phillips | 1 | 2.68 | 10YR 3/2 | 10YR 5/3 | 823 | 6.1 | 30 | 12.7 | L | 0 |
| Phillips | 2 | 0.89 | 10YR 4/3 | 10YR 6/3 | 823 | 6.1 | 30 | 14.1 | L | 0 |
| Phillips | 1 | 5.44 | 10YR 3/2 | 10YR 5/2 | 823 | 5.6 | 30 | 14.0 | L | 0 |
| Phillips | 2 | 1.32 | 10YR 4/2 | 10YR 6/3 | 823 | 5.6 | 30 | 15.6 | L | 0 |
| Pintlar | 1 | 4.09 | 10YR 2/1 | 10YR 3/1 | 1779 | 3.9 | 51 | 18.2 | L | 0 |
| Pintlar | 2 | 1.66 | 7.5YR 3/2 | 7.5YR 5/2 | 1779 | 3.9 | 51 | 16.2 | L | 0 |
| Pintlar | 1 | 4.38 | 10YR 2/2 | 10YR 4/1 | 1786 | 3.3 | 51 | 22.3 | L | 0 |
| Pintlar | 2 | 1.91 | 7.5YR 3/2 | 10YR 4/2 | 1786 | 3.3 | 51 | 19.2 | L | 0 |
| Reedpoint | 1 | 2.64 | 10YR 3/2 | 10YR 5/2 | 1371 | 7.2 | 30 | 30.6 | CL | 0 |
| Reedpoint | 1 | 2.04 | 10YR 3/2 | 10YR 5/2 | 1371 | 7.2 | 30 | 23.9 | L | 0 |
| Scobey | 1 | 3.93 | 10YR 3/2 | 10YR 5/2 | 949 | 5.6 | 28 | 20.5 | L | 0 |
| Scobey | 1 | 3.50 | 10YR 3/3 | 10YR 5/3 | 960 | 5.6 | 28 | 18.6 | L | 0 |
| Shambo | 1 | 4.19 | 10YR 2/2 | 10YR 4/2 | 853 | 6.1 | 34 | 14.5 | L | 0 |

| | | | | | | | | | | |
|------------|---|------|-----------|----------|------|-----|----|------|------|---|
| Shambo | 2 | 1.43 | 10YR 3/2 | 10YR 4/2 | 853 | 6.1 | 34 | 16.2 | L | 0 |
| Shawmut | 1 | 2.44 | 10YR 3/2 | 10YR 5/2 | 1371 | 7.2 | 30 | 21.6 | L | 0 |
| Shawmut | 1 | 2.64 | 10YR 3/2 | 10YR 5/2 | 1371 | 7.2 | 30 | 19.4 | L | 0 |
| Sipple | 1 | 5.24 | 10YR 2/1 | 10YR 4/1 | 1523 | 7.2 | 43 | 25.4 | L | 0 |
| Sweetgrass | 1 | 2.89 | 10YR 3/2 | 10YR 4/2 | 1314 | 8.3 | 46 | 29.0 | CL | 0 |
| Terrad | 1 | 5.46 | 5YR 3/2 | 5YR 4/1 | 1295 | 6.7 | 38 | 38.5 | CL | 0 |
| Teton | 2 | 4.93 | 10YR 2/1 | 10YR 2/2 | 1645 | 5.6 | 48 | 30.5 | CL | 0 |
| Thurlow | 1 | 1.57 | 10YR 4/2 | 10YR 6/3 | 925 | 8.9 | 33 | 25.5 | L | 0 |
| Magnus | 1 | 1.52 | 2.5Y 2/2 | 2.5Y 5/2 | 853 | 7.2 | 36 | 41.2 | SiC | 2 |
| Vananda | 1 | 1.75 | 2.5Y 4/3 | 2.5Y 6/2 | 807 | 8.9 | 30 | 52.1 | SiC | 1 |
| Vananda | 1 | 1.13 | 2.5Y 4/2 | 2.5Y 6/1 | 807 | 8.9 | 30 | 59.0 | C | 0 |
| Vananda | 1 | 1.88 | 5Y 4/2 | 5Y 6/2 | 815 | 8.9 | 30 | 47.3 | SiC | 0 |
| Wishard | 2 | 9.94 | 7.5YR 4/2 | 10YR 4/1 | 2133 | 5.0 | 76 | 10.9 | L | 0 |
| McDonald | 1 | 6.62 | 10YR 2/1 | 10YR 4/1 | 1862 | 5.6 | 51 | 23.5 | L | 0 |
| McDonald | 2 | 2.75 | 10YR 2/1 | 10YR 4/1 | 1862 | 5.6 | 51 | 23.2 | L | 0 |
| McDonald | 3 | 1.07 | 10YR 3/2 | 10YR 5/3 | 1862 | 5.6 | 51 | 21.8 | L | 0 |
| McDonald | 1 | 4.34 | 10YR 2/1 | 10YR 4/1 | 940 | 9.4 | 51 | 33.7 | SiCL | 0 |
| Mc Donald | 2 | 2.20 | 10YR 2/2 | 10YR 5/2 | 940 | 9.4 | 51 | 32.7 | SiCL | 0 |
| Vananda | 1 | 0.98 | 2.5Y 4/3 | 5Y 5/2 | 823 | 8.3 | 28 | 48.9 | SiC | 1 |
| Belain | 1 | 3.96 | 10YR 2/3 | 10YR 4/2 | 1341 | 6.1 | 45 | 20.1 | SCL | 0 |
| Maddux | 1 | 2.29 | 10YR 2/3 | 10YR 4/2 | 1158 | 6.7 | 42 | 19.4 | L | 1 |

| | | | | | | | | | | |
|----------|---|------|----------|----------|------|-----|----|------|------|---|
| Shaak | 1 | 2.59 | 10YR 3/2 | 10YR 5/2 | 1067 | 6.7 | 38 | 15.3 | L | 0 |
| Shaak | 2 | 1.51 | 10YR 3/3 | 10YR 5/3 | 1067 | 6.7 | 38 | 20.0 | L | 0 |
| Warrick | 1 | 3.05 | 10YR 3/3 | 10YR 5/2 | 1064 | 6.7 | 38 | 16.8 | L | 0 |
| Warrick | 2 | 1.33 | 10YR 5/3 | 10YR 7/2 | 1064 | 6.7 | 38 | 18.5 | SiL | 0 |
| Bridger | 1 | 9.88 | 10YR 2/0 | 10YR 3/1 | 1585 | 5.6 | 50 | 28.1 | CL | 0 |
| Bridger | 2 | 5.27 | 10YR 2/1 | 10YR 3/1 | 1585 | 5.6 | 50 | 28.6 | CL | 0 |
| Lambert | 1 | 1.25 | 2.5Y 4/2 | 2.5Y 5/2 | 1067 | 8.3 | 36 | 17.8 | SL | 0 |
| Lambert | 2 | 1.07 | 2.5Y 4/2 | 2.5Y 5/2 | 1067 | 8.3 | 36 | 22.9 | SCL | 0 |
| Woodhawk | 1 | 2.27 | 10YR 3/2 | 10YR 5/2 | 1055 | 7.8 | 31 | 25.7 | L | 0 |
| Alona | 1 | 2.17 | 10YR 3/2 | 10YR 5/2 | 792 | 7.8 | 30 | 27.4 | SiCL | 0 |
| Cambert | 1 | 2.26 | 10YR 3/3 | 10YR 5/3 | 777 | 7.2 | 32 | 19.6 | SiL | 1 |
| Cambert | 1 | 2.03 | 10YR 3/3 | 10YR 5/3 | 777 | 7.2 | 32 | 17.8 | L | 0 |
| Chinook | 1 | 0.84 | 10YR 3/3 | 10YR 5/3 | 840 | 5.6 | 30 | 18.5 | SL | 0 |
| Lonna | 1 | 2.08 | 10YR 4/2 | 10YR 5/2 | 792 | 7.2 | 42 | 26.1 | SiL | 1 |

Table 27. Terrain and soil attributes from the Springhill site used for the multiple regression analysis.

| Sample Number | % Organic Carbon | Moist Color | Elevation (m) | Slope (%) | Aspect (degrees) | Specific Catchment (m ² /m) | Wetness Index | Plan Curvature (degree/m) | Profile Curvature (degree/m) |
|---------------|------------------|-------------|---------------|-----------|------------------|--|---------------|---------------------------|------------------------------|
| 1 | 2.07 | 10YR 3/1 | 1529.03 | 11.340 | 254.922 | 63.20 | 6.323 | 1.893 | -0.191 |
| 2 | 1.37 | 10YR 3/2 | 1531.08 | 10.378 | 129.134 | 22.00 | 5.357 | 1.786 | -0.025 |
| 3 | 2.02 | 10YR 2/1 | 1528.81 | 2.549 | 244.440 | 14.60 | 6.350 | -17.695 | 0.071 |
| 4 | 1.56 | 10YR 3/1 | 1519.17 | 11.710 | 187.853 | 73.50 | 6.442 | 3.113 | 0.446 |
| 5 | 1.89 | 10YR 3/1 | 1519.32 | 6.757 | 177.455 | 128.20 | 7.548 | 5.343 | 0.982 |
| 6 | 2.09 | 10YR 3/1 | 1519.29 | 13.425 | 162.442 | 73.80 | 6.309 | -2.749 | -0.332 |
| 7 | 1.91 | 10YR 3/1 | 1519.12 | 10.842 | 194.421 | 86.40 | 6.681 | 2.220 | 0.255 |
| 8 | 0.99 | 10YR 4/3 | 1499.96 | 11.611 | 257.819 | 10.80 | 4.530 | -7.047 | 1.844 |
| 9 | 2.85 | 10YR 2/1 | 1509.61 | 4.314 | 225.939 | 175.40 | 8.310 | 1.490 | 0.155 |
| 10 | 1.18 | 10YR 4/1 | 1510.07 | 6.642 | 154.592 | 54.90 | 6.717 | 3.061 | -0.113 |
| 11 | 2.11 | 10YR 3/3 | 1503.58 | 11.312 | 163.568 | 997.50 | 9.085 | 21.572 | 1.187 |
| 12 | 2.54 | 10YR 2/1 | 1503.82 | 9.774 | 187.052 | 143.70 | 7.293 | 3.710 | 0.589 |
| 13 | 1.98 | 10YR 3/2 | 1505.52 | 5.450 | 213.398 | 174.10 | 8.069 | -0.831 | -0.084 |
| 14 | 2.46 | 10YR 2/1 | 1499.91 | 8.840 | 135.917 | 236.50 | 7.892 | 5.741 | 0.427 |
| 15 | 1.51 | 10YR 3/3 | 1499.55 | 11.577 | 109.687 | 87.90 | 6.632 | -6.451 | -0.268 |
| 16 | 2.31 | 10YR 2/1 | 1498.05 | 7.338 | 192.995 | 46.30 | 6.447 | -1.521 | -0.187 |
| 17 | 2.38 | 10YR 2/1 | 1505.92 | 10.333 | 332.319 | 22.50 | 5.383 | 0.526 | -0.437 |
| 18 | 2.52 | 10YR 2/1 | 1496.48 | 16.015 | 102.257 | 35.50 | 5.401 | 1.517 | 0.180 |

| | | | | | | | | | |
|----|------|----------|---------|--------|---------|---------|--------|---------|--------|
| 19 | 2.63 | 10YR 2/1 | 1496.95 | 15.076 | 286.572 | 51.20 | 5.828 | -0.990 | 0.231 |
| 20 | 1.66 | 10YR 3/2 | 1504.34 | 6.323 | 247.694 | 18.70 | 5.689 | -6.720 | -0.005 |
| 21 | 2.38 | 10YR 2/1 | 1505.57 | 4.851 | 171.703 | 13.40 | 5.621 | -15.593 | -0.009 |
| 22 | 1.58 | 10YR 3/3 | 1491.86 | 13.844 | 184.557 | 31.40 | 5.424 | -3.292 | 0.968 |
| 23 | 2.01 | 10YR 2/1 | 1497.96 | 9.237 | 258.447 | 43.40 | 6.152 | 0.267 | -0.084 |
| 24 | 2.02 | 10YR 2/1 | 1500.69 | 7.301 | 179.215 | 53.80 | 6.602 | 4.121 | 0.416 |
| 25 | 2.51 | 10YR 2/1 | 1499.68 | 10.159 | 155.579 | 105.60 | 6.946 | -0.139 | 0.154 |
| 26 | 2.33 | 10YR 3/2 | 1497.29 | 3.970 | 196.837 | 22.00 | 6.317 | -5.900 | 0.004 |
| 27 | 2.58 | 10YR 2/1 | 1497.44 | 5.582 | 149.300 | 74.70 | 7.199 | -1.121 | -0.027 |
| 28 | 2.62 | 10YR 2/1 | 1495.69 | 10.958 | 157.179 | 132.80 | 7.100 | 1.270 | 0.207 |
| 29 | 1.82 | 10YR 2/1 | 1509.99 | 12.806 | 193.548 | 132.10 | 6.939 | -0.334 | 0.012 |
| 30 | 1.28 | 10YR 4/3 | 1512.59 | 14.378 | 153.790 | 90.70 | 6.447 | 4.940 | 1.086 |
| 31 | 2.46 | 10YR 2/1 | 1495.53 | 5.092 | 172.666 | 6417.30 | 11.744 | 28.838 | 0.908 |

APPENDIX B
MULTIPLE REGRESSION ANALYSIS
AND
SUMMARY STATISTICS

Table 28. Results of multiple regression analysis for cropland Ap horizons with medium textures.

| Variable | Parameter Estimate | Partial r^2 | Model R^2 | F | Prob > F |
|-----------------------------|--------------------|---------------|-------------|-------|----------|
| Dry Munsell Colors (n=21) | | | | | |
| Intercept | 6.29 | | | | |
| Soil temperature | -0.11 | 0.47 | 0.47 | 16.81 | 0.0006 |
| Precipitation | 0.008 | 0.17 | 0.64 | 8.47 | 0.0093 |
| Moist Munsell Colors (n=22) | | | | | |
| Intercept | 6.91 | | | | |
| Soil temperature | -0.12 | 0.52 | 0.52 | 22.06 | 0.0001 |
| Precipitation | 0.008 | 0.14 | 0.67 | 8.01 | 0.0107 |

Table 29. Summary statistics for cropland Ap horizons with medium textures.

| Variable | n | Mean | Standard Deviation | Minimum | Maximum |
|-----------------------|----|------|--------------------|---------|---------|
| Organic carbon (%) | 22 | 1.64 | 0.44 | 0.85 | 2.43 |
| Dry value | 21 | 4.52 | 0.51 | 4 | 5 |
| Dry chroma | 22 | 2.00 | 0 | 2 | 2 |
| Moist value | 22 | 2.89 | 0.90 | 2 | 5 |
| Moist chroma | 22 | 1.98 | 0.11 | 1.5 | 2 |
| Elevation (m) | 22 | 1081 | 241 | 792 | 1612 |
| Soil temperature (°C) | 22 | 7.8 | 1.1 | 6.1 | 9.5 |
| Precipitation (cm) | 22 | 45.4 | 24.4 | 28 | 102 |
| Percent clay | 22 | 21.9 | 3.6 | 14.7 | 26.5 |

Table 30. Results of multiple regression analysis for grassland A horizons with medium textures.

| Variable | Parameter Estimate | Partial r^2 | Model R^2 | F | Prob > F |
|-----------------------------|--------------------|---------------|-------------|-------|----------|
| Dry Munsell Colors (n=50) | | | | | |
| Intercept | 4.06 | | | | |
| Value | -0.87 | 0.27 | 0.27 | 17.88 | 0.0001 |
| Precipitation | 0.08 | 0.11 | 0.38 | 8.15 | 0.0064 |
| Moist Munsell Colors (n=50) | | | | | |
| Intercept | 3.83 | | | | |
| Value | -1.22 | 0.38 | 0.38 | 29.16 | 0.0001 |
| Precipitation | 0.07 | 0.09 | 0.46 | 7.48 | 0.0088 |

Table 31. Summary statistics for grassland A horizons with medium textures.

| Variable | n | Mean | Standard Deviation | Minimum | Maximum |
|-----------------------|----|------|--------------------|---------|---------|
| Organic carbon (%) | 50 | 2.95 | 1.91 | 0.89 | 9.94 |
| Dry value | 50 | 4.70 | 0.82 | 3 | 7 |
| Dry chroma | 50 | 2.02 | 0.65 | 1 | 3 |
| Moist value | 50 | 2.89 | 0.76 | 2 | 5 |
| Moist chroma | 50 | 2.00 | 0.54 | 1 | 3 |
| Elevation (m) | 50 | 1156 | 378 | 777 | 2133 |
| Soil temperature (°C) | 50 | 6.5 | 1.4 | 3.3 | 8.9 |
| Precipitation (cm) | 50 | 38.1 | 8.8 | 28 | 76 |
| Percent clay | 50 | 19.1 | 4.2 | 10.9 | 26.4 |

Table 32. Summary statistics for cropland Ap horizons with moderately fine textures.

| Variable | n | Mean | Standard Deviation | Minimum | Maximum |
|-----------------------|----|------|-----------------------|---------|---------|
| Organic carbon (%) | 32 | 1.36 | 0.45 | 0.79 | 3.36 |
| Dry value | 31 | 4.94 | 0.63 | 4 | 6 |
| Dry chroma | 31 | 1.97 | 0.48 | 1 | 3 |
| Moist value | 32 | 3.00 | 0.67 | 2 | 4 |
| Moist chroma | 32 | 1.94 | 0.35 | 1 | 3 |
| Elevation (m) | 32 | 1046 | 165 | 792 | 1463 |
| Soil temperature (°C) | 30 | 7.6 | 1.1 | 5.6 | 9.5 |
| Precipitation (cm) | 32 | 33.9 | 5.3 | 28 | 43 |
| Percent clay | 32 | 31.3 | 4.2 | 22.2 | 39.2 |

Table 33. Results of multiple regression analysis for grassland A horizons with moderately fine textures.

| Variable | Parameter Estimate | Partial r ² | Model R ² | F | Prob > F |
|-----------------------------|-----------------------|------------------------|----------------------|-------|----------|
| Dry Munsell Colors (n=31) | | | | | |
| Intercept | 13.13 | | | | |
| Chroma | -2.03 | 0.30 | 0.30 | 12.21 | 0.0015 |
| Soil temperature | -0.82 | 0.22 | 0.52 | 13.14 | 0.0011 |
| Moist Munsell Colors (n=31) | | | | | |
| Intercept | 11.18 | | | | |
| Chroma | -1.62 | 0.39 | 0.39 | 18.35 | 0.0002 |
| Soil temperature | -0.61 | 0.12 | 0.52 | 6.86 | 0.0141 |

Table 34. Summary statistics for grassland A horizons with moderately fine textures.

| Variable | n | Mean | Standard Deviation | Minimum | Maximum |
|-----------------------|----|------|--------------------|---------|---------|
| Organic carbon (%) | 31 | 4.35 | 2.06 | 1.07 | 9.88 |
| Dry value | 31 | 3.90 | 0.65 | 2 | 5 |
| Dry chroma | 31 | 1.61 | 0.56 | 1 | 3 |
| Moist value | 31 | 2.42 | 0.62 | 2 | 4 |
| Moist chroma | 31 | 1.68 | 0.70 | 0 | 3 |
| Elevation (m) | 31 | 1386 | 231 | 792 | 1676 |
| Soil temperature (°C) | 31 | 6.7 | 1.2 | 5.0 | 9.5 |
| Precipitation (cm) | 31 | 42.8 | 5.8 | 30 | 51 |
| Percent clay | 31 | 29.6 | 3.9 | 20.1 | 38.5 |

Table 35. Summary statistics for cropland Ap horizons with a hue of 10YR.

| Variable | n | Mean | Standard Deviation | Minimum | Maximum |
|-----------------------|----|--------|--------------------|---------|---------|
| Dry Munsell Hues | | | | | |
| Organic carbon (%) | 32 | 1.62 | 0.50 | 0.88 | 3.36 |
| Value | 30 | 4.5 | 0.51 | 4 | 5 |
| Chroma | 30 | 1.9 | 0.40 | 1 | 3 |
| Elevation (m) | 32 | 1152 | 189 | 870 | 1612 |
| Soil temperature (°C) | 32 | 7.5 | 0.9 | 5.6 | 8.9 |
| Precipitation (cm) | 32 | 44.4 | 19.8 | 28 | 102 |
| Percent clay | 32 | 26.7 | 6.7 | 14.7 | 43.4 |
| Moist Munsell Hues | | | | | |
| Organic carbon (%) | 37 | 1.56 | 0.49 | 0.88 | 3.36 |
| Value | 37 | 2.69 | 0.68 | 2 | 4 |
| Chroma | 37 | 1.96 | 0.38 | 1 | 3 |
| Elevation (m) | 37 | 1131.3 | 188.3 | 792 | 1612 |
| Soil temperature (°C) | 37 | 7.5 | 1.0 | 5.6 | 9.5 |
| Precipitation (cm) | 37 | 42.8 | 18.9 | 28 | 102 |
| Percent clay | 37 | 26.7 | 6.9 | 14.7 | 43.4 |

Table 36. Results of multiple regression analysis for grassland A horizons with a hue of 10YR.

| Variable | Parameter Estimate | Partial r^2 | Model R^2 | F | Prob > F |
|-----------------------------|--------------------|---------------|-------------|-------|----------|
| Dry Munsell Colors (n=86) | | | | | |
| Intercept | 4.79 | | | | |
| Value | -0.67 | 0.34 | 0.34 | 43.14 | 0.0001 |
| Precipitation | 0.08 | 0.10 | 0.44 | 15.06 | 0.0010 |
| Chroma | -0.79 | 0.04 | 0.48 | 5.92 | 0.0181 |
| Moist Munsell Colors (n=84) | | | | | |
| Intercept | 7.82 | | | | |
| Value | -0.76 | 0.35 | 0.35 | 43.56 | 0.0001 |
| Chroma | -0.85 | 0.08 | 0.43 | 11.74 | 0.0010 |
| Soil temperature(o | -0.37 | 0.04 | 0.47 | 5.58 | 0.0206 |
| Percent clay | -0.07 | 0.04 | 0.51 | 7.00 | 0.0098 |

Table 37. Summary statistics for grassland A horizons with a hue of 10YR.

| Variable | n | Mean | Standard Deviation | Minimum | Maximum |
|-----------------------|----|------|--------------------|---------|---------|
| Dry Munsell Hues | | | | | |
| Organic carbon (%) | 86 | 3.37 | 2.04 | 0.84 | 9.94 |
| Value | 86 | 4.41 | 0.83 | 2 | 7 |
| Chroma | 86 | 1.90 | 0.66 | 1 | 3 |
| Elevation (m) | 86 | 1256 | 336 | 777 | 2133 |
| Soil temperature (°C) | 86 | 6.6 | 1.3 | 3.3 | 9.5 |
| Precipitation (cm) | 86 | 39.4 | 7.9 | 28 | 76 |
| Percent clay | 86 | 22.5 | 6.4 | 10.9 | 36.3 |
| Moist Munsell Hues | | | | | |
| Organic carbon (%) | 84 | 3.31 | 1.93 | 0.84 | 9.88 |
| Value | 84 | 2.71 | 0.72 | 2 | 5 |
| Chroma | 84 | 1.89 | 0.62 | 0 | 3 |
| Elevation (m) | 84 | 1239 | 320 | 777 | 1862 |
| Soil temperature (°C) | 84 | 6.7 | 1.2 | 3.3 | 9.5 |
| Precipitation (cm) | 84 | 38.9 | 6.7 | 28 | 51 |
| Percent clay | 84 | 22.7 | 6.3 | 12.7 | 36.3 |

Table 38. Results of Multiple Regression for Cropland Ap Horizons that do not effervesce.

| Variable | Parameter Estimate | Partial r^2 | Model R^2 | F | Prob > F |
|-----------------------------|--------------------|---------------|-------------|-------|----------|
| Dry Munsell Colors (n=46) | | | | | |
| Intercept | 2.04 | | | | |
| Precipitation | -0.53 | 0.26 | 0.26 | 15.36 | 0.0003 |
| Chroma | 0.013 | 0.18 | 0.43 | 13.40 | 0.0007 |
| Moist Munsell Colors (n=48) | | | | | |
| Intercept | 2.60 | | | | |
| Value | -0.25 | 0.35 | 0. | 24.43 | 0.0001 |
| Chroma | -0.35 | 0.06 | 0.41 | 4.91 | 0.0318 |
| Precipitation | 0.008 | 0.07 | 0.48 | 5.49 | 0.0238 |

Table 39. Summary statistics for cropland Ap horizons that do not effervesce.

| Variable | n | Mean | Standard Deviation | Minimum | Maximum |
|-----------------------|----|------|--------------------|---------|---------|
| Organic carbon (%) | 50 | 1.52 | 0.47 | 0.79 | 3.36 |
| Dry value | 48 | 4.79 | 0.68 | 4 | 6 |
| Dry chroma | 48 | 1.9 | 0.35 | 1 | 3 |
| Moist value | 50 | 1.52 | 0.69 | 2 | 4 |
| Moist chroma | 50 | 1.99 | 0.36 | 1 | 3 |
| Elevation (m) | 50 | 1103 | 176 | 792 | 1612 |
| Soil temperature (°C) | 48 | 7.4 | 0.9 | 5.6 | 9.5 |
| Precipitation (cm) | 50 | 40.0 | 17.1 | 28 | 102 |
| Percent clay | 50 | 28.7 | 7.1 | 14.7 | 47.6 |

Table 40. Results of multiple regression analysis for grassland A horizons that do not effervesce.

| Variable | Parameter Estimate | Partial r^2 | Model R^2 | F | Prob > F |
|-----------------------------|--------------------|---------------|-------------|-------|----------|
| Dry Munsell Colors (n=90) | | | | | |
| Intercept | 5.39 | | | | |
| Value | -0.77 | 0.36 | 0.36 | 48.99 | 0.0001 |
| Precipitation | 0.07 | 0.08 | 0.44 | 13.03 | 0.0005 |
| Chroma | -0.80 | 0.04 | 0.48 | 6.71 | 0.0113 |
| Moist Munsell Colors (n=90) | | | | | |
| Intercept | 4.26 | | | | |
| Value | -0.99 | 0.36 | 0.36 | 49.82 | 0.0001 |
| Precipitation | 0.07 | 0.09 | 0.45 | 13.81 | 0.0004 |
| Chroma | -0.65 | 0.02 | 0.47 | 4.01 | 0.0484 |

Table 41. Summary statistics for grassland A horizons that do not effervesce.

| Variable | n | Mean | Standard Deviation | Minimum | Maximum |
|-----------------------|----|------|--------------------|---------|---------|
| Organic carbon (%) | 90 | 3.31 | 2.05 | 0.84 | 9.94 |
| Dry value | 90 | 4.44 | 0.85 | 2 | 7 |
| Dry chroma | 90 | 1.87 | 0.64 | 1 | 3 |
| Moist value | 90 | 2.75 | 0.73 | 2 | 5 |
| Moist chroma | 90 | 1.89 | 0.60 | 0 | 3 |
| Elevation (m) | 90 | 1258 | 333 | 777 | 2133 |
| Soil temperature (°C) | 90 | 6.7 | 1.4 | 3.3 | 9.5 |
| Precipitation (cm) | 90 | 39.3 | 7.9 | 28 | 76 |
| Percent clay | 90 | 23.3 | 7.9 | 10.9 | 59.0 |

Table 42. Results of multiple regression analysis for cropland Ap2 horizons.

| Variable | Parameter Estimate | Partial r^2 | Model R^2 | F | Prob > F |
|-----------------------------|--------------------|---------------|-------------|------|----------|
| Dry Munsell Colors (n=13) | | | | | |
| Intercept | 0.16 | | | | |
| Precipitation | 0.03 | 0.43 | 0.43 | 8.40 | 0.0145 |
| Moist Munsell Colors (n=13) | | | | | |
| Intercept | 0.16 | | | | |
| Precipitation | 0.03 | 0.43 | 0.43 | 8.40 | 0.0145 |

Table 43. Summary statistics for cropland Ap2 horizons.

| Variable | n | Mean | Standard Deviation | Minimum | Maximum |
|-----------------------|----|------|--------------------|---------|---------|
| Organic carbon (%) | 14 | 1.24 | 0.31 | 0.79 | 1.79 |
| Dry value | 14 | 4.71 | 0.61 | 4 | 6 |
| Dry chroma | 14 | 2.07 | 0.04 | 1 | 3 |
| Moist value | 14 | 3.00 | 0.78 | 2 | 5 |
| Moist chroma | 14 | 2.07 | 0.48 | 1 | 3 |
| Elevation (m) | 14 | 1013 | 189 | 792 | 1463 |
| Soil temperature (°C) | 13 | 8.1 | 1.2 | 5.6 | 9.5 |
| Precipitation (cm) | 14 | 34.6 | 5.7 | 28 | 43 |
| Percent clay | 14 | 31.5 | 6.4 | 21 | 43.4 |

Table 44. Summary statistics for grassland Ap2 horizons.

| Variable | n | Mean | Standard Deviation | Minimum | Maximum |
|-----------------------|----|------|-----------------------|---------|---------|
| Organic carbon (%) | 29 | 2.79 | 1.97 | 0.89 | 9.94 |
| Dry value | 29 | 4.31 | 1.00 | 2 | 7 |
| Dry chroma | 29 | 1.97 | 0.68 | 1 | 3 |
| Moist value | 29 | 2.72 | 0.84 | 2 | 5 |
| Moist chroma | 29 | 1.97 | 0.63 | 1 | 3 |
| Elevation (m) | 29 | 1361 | 376 | 823 | 2133 |
| Soil temperature (°C) | 29 | 6.3 | 1.3 | 3.3 | 9.5 |
| Precipitation (cm) | 29 | 42.7 | 9.5 | 30 | 76 |
| Percent clay | 29 | 23.6 | 6.7 | 10.9 | 34.8 |

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