Predicting soil water distribution using topographic models within four Montana farm fields
by Brian John Kozar

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Land Resources and Environmental Sciences
Montana State University

Abstract:
Soil water content is a major factor controlling plant growth and crop yields in the semi-arid Northern Great Plains, and can vary substantially across a field. Farmers and land managers interested in identifying and delineating this variability need efficient methods to estimate soil water status. I hypothesized that topography influences soil water spatial distribution and could be used to delineate this distribution. The objectives of this study were to identify relationships between topography and soil water content, and determine if relationships discerned were similar across space. I used four farm fields across Northern Montana having moderate relief (15-30 m) with soils predominately formed over glacial till Soil water content was measured throughout one growing season at each site using a neutron moisture meter. Digital elevation models were used to portray the terrain. Relationships at multiple depths were examined for the beginning and end of the growing season through two, methods. Topographic region partitioning delineated the field into areas of presumed similar soil water content. Significant differences in soil water content between regions were tested using ANOVA. Secondly, the compound topographic index (CTI) was correlated with soil water content in a regression model. Study sites and topographic regions were included as covariates. Results identified differences in soil water content between regions, with the Row topographic regionpartitioning method identifying differences at all sites. However, no consistent patterns in differences between regions occurred across sites at any given depth. Reduction of across field soil water variance was also low (maximum = 21%). The strongest correlation between CTI and soil water content occurred at the end of the growing season at 20 cm (R2 = 0.40, p = 0.0001). Relationships between CTI and soil, water content varied from . .field to field. Relationships also differed between Row topographic regions at all four sites, but no differences were identified between Soil-Landscape regions. Inconsistency in model performance across sites suggests that terrain - soil water relationships differ from location to location. Difference in results may be related to differences across sites in climate, soils, and other factors. This indicates a need to integrate site-specific information regarding soils and other factors with terrain models.

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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.

Jon M. Wraith — (Signature) — 7-11-02 Date

Approved for the Department of Land Resources and Environmental Sciences

Jeffrey S. Jacobsen — (Signature) — 7/11/02 Date

Approved for the College of Graduate Studies

Bruce R. McLeod — (Signature) — 7-11-02 Date

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ABSTRACT

Soil water content is a major factor controlling plant growth and crop yields in the semi-arid Northern Great Plains, and can vary substantially across a field. Farmers and land managers interested in identifying and delineating this variability need efficient methods to estimate soil water status. I hypothesized that topography influences soil water spatial distribution and could be used to delineate this distribution. The objectives of this study were to identify relationships between topography and soil water content, and determine if relationships discerned were similar across space. I used four farm fields across Northern Montana having moderate relief (15-30 m) with soils predominately formed over glacial till. Soil water content was measured throughout one growing season at each site using a neutron moisture meter. Digital elevation models were used to portray the terrain. Relationships at multiple depths were examined for the beginning and end of the growing season through two methods. Topographic region partitioning delineated the field into areas of presumed similar soil water content. Significant differences in soil water content between regions were tested using ANOVA. Secondly, the compound topographic index (CTI) was correlated with soil water content in a regression model. Study sites and topographic regions were included as covariates. Results identified differences in soil water content between regions, with the Flow topographic region-partitioning method identifying differences at all sites. However, no consistent patterns in differences between regions occurred across sites at any given depth. Reduction of across field soil water variance was also low (maximum = 21%). The strongest correlation between CTI and soil water content occurred at the end of the growing season at 20 cm ($R^2 = 0.40$, $p = 0.0001$). Relationships between CTI and soil water content varied from field to field. Relationships also differed between Flow topographic regions at all four sites, but no differences were identified between Soil-Landscape regions. Inconsistency in model performance across sites suggests that terrain – soil water relationships differ from location to location. Difference in results may be related to differences across sites in climate, soils, and other factors. This indicates a need to integrate site-specific information regarding soils and other factors with terrain models.

CHAPTER 1

GENERAL INTRODUCTION

Background

Soil water is a major factor limiting plant growth, including crop yields in the semi-arid agricultural systems of the Northern Great Plains. Vegetation depends more on the quantity and timing of plant available soil water than on any other single environmental factor (Kramer and Boyer, 1995). Dryland agricultural management strategies are therefore strongly based on the amount of soil water in a farm field or area to be managed. Many crop yield models rely upon input of plant available soil water evaluated at the beginning of the growing season. However, environmental factors such as soil water can vary substantially in space and time (Bell et al., 1994). Managers of environmental and agricultural systems therefore find that soil water conditions are difficult to assess in an accurate or rapid manner.

To characterize the status and spatial variability of soil water across a field, land managers often employ intensive grid sampling. However, time and cost required to conduct grid sampling often compel managers to use less-intensive, sometimes haphazard methods of measuring or estimating soil water status. Management zones delineated from these methods can be vague and can misrepresent actual conditions in the field. The spatial distribution and variability of other environmental properties, such as soil and terrain attributes, may be related to spatial variation of soil water, and in many cases these are more easily measured (Trangmar et al., 1986). Identification of terrain features related to soil water variation across fields would be valuable to land managers. Quantified relationships between soil wetness and soil or terrain attributes could aid in estimating the distribution of soil water across landscapes and in delineating zones having similar soil water status.

Soil Water and Plant Available Water

Water affects plant growth by influencing physiological processes within the plant. Water acts as an essential constituent that drives physiological activity in the plant, as a solvent in which minerals, nutrients, and other solutes enter plants and move between cells and organs, and as a reactant in important plant processes such as photosynthesis (Kramer and Boyer, 1995). As water becomes limited, plant functions suffer and economic yields decrease.

Plant available water refers to soil water held between field capacity and permanent wilting point. Permanent wilting point refers to the soil water content at which plants irreversibly wilt and fail to recover. Field capacity refers to the soil water content after free drainage has essentially ceased (Or and Wraith, 2000). Soil water held below wilting point or above field capacity is not available for use by plants in most cases (Kramer and Boyer, 1995; Brady and Weil, 1999).

There are numerous ways to measure or estimate plant available soil water content. Soil water can be measured gravimetrically based on soil samples taken to the average rooting depth of a particular crop of interest (Cook and Veseth, 1991). Soil water content is often calculated as a decimal fraction of the dry weight of the soil sample. However, this method results in significant disturbance to the soil, as many samples are required to accurately characterize soil water across a field.

Soil water can also be measured, with less destruction to the soil, through the use of sensors such as neutron moisture meters, gamma ray attenuation, and time domain reflectometry (Gardner, 1986; Or and Wraith, 2000). All of these methods are useful for measuring soil water at various depths in the soil (Kramer and Boyer, 1995). However, neutron moisture meters and gamma ray attenuation require training and licensing for safe use due to radiation hazard, and calibration for different soils. The considerable expense involved with using these methods may limit their feasibility for use by land managers.

Many sampling strategies have been applied to measure soil attributes and soil water, including regular grid-based (Odeh et al., 1994; Western et al., 1999) as well as random or stratified random sampling designs (Bell et al., 1994; McKenzie and Ryan, 1999). These methods can potentially assess and spatially represent soil water across a field with high accuracy, but are often field intensive and expensive, and therefore may not be feasible for a farmer or land manager.

Spatial Variation of Soil Water and Soil Properties

Many soil and environmental properties vary substantially across a field or landscape, and studies that model or predict environmental conditions should take into account spatial heterogeneity in geology, soils, and landforms (McLaughlin et al., 1993).

Soil water content and related soil properties often exhibit extreme variability over distances of about 1 to 100 m (Yates and Warrick, 1987; Moore et al., 1993; Western et al., 1999). At small catchment and hillslope scales soil water distribution varies as a result of water routing processes, due to terrain and landscape, heterogeneity in vegetation and soil characteristics, and other factors such as microclimate (Gessler et al., 1995; Western et al., 1999).

Soil properties such as horizonation, texture, and effective porosity can affect lateral flow and accumulation of soil water by impeding vertical water flow or through their influences on soil hydraulic properties (Bell et al., 1994; Gessler et al., 1995; Or and Wraith, 2000). Terrain modifies these effects. Further, variability in soils is substantially influenced by terrain, as topography is a basic soil forming factor (Brady and Weil, 1999). Soil depth, and soil physical and chemical properties, varies with landscape position. Variation of soil properties with landscape position can thereby affect water flow patterns (Afyuni et al., 1994).

Spatial variability of soil water can be random or organized (Bloschl, 1999; Western et al., 1999). The degree of organization in spatial variability of soil water is largely related to soil properties and terrain (Western et al., 1999). For dry soils near wilting point, spatial variability is primarily random as local soil properties hold primary influence on water flow. Capillary forces exerted by the soil matrix resist displacement of water (Philip, 1957; Hillel, 1980). This effectively opposes gravitational forces inherent in terrain-driven lateral flow (Yeh and Eltahir, 1998). Hydraulic conductivity, a primary soil hydraulic property, increases exponentially as soils wet (Bouma and Anderson, 1973). Spatial patterns in soil water distribution might then be increasingly influenced by terrain-driven lateral forces and impediments to vertical water flow (Gessler et al., 1995; Grayson et al., 1997). This can lead towards high organization in the spatial pattern of soil water.

Site Specific Agriculture

Interest in precision agriculture has arisen from the realization that significant yield increases can not be efficiently obtained through additional chemical applications, and the desire to simultaneously maintain or increase yields while reducing chemical inputs into the system due to economic and environmental concerns (Bell et al., 1995; Brown, 1995). This relatively new practice incorporates the use of geographic information systems (GIS), remote sensing, and global positioning systems (GPS) to more efficiently manage farm fields on a site-specific basis. Global positioning systems provide the location for data being recorded in the field. Geographic information systems provide a method for linking, displaying, and analyzing GPS-generated and remotely-sensed data for decision support applications (Burrough and McDonnell, 1998). These systems are often used directly on farm machinery, and the farmer may conduct specific analyses or utilize consultants.

Defining and managing soil and landscape spatial variability is crucial for precision agriculture. Managers aim to characterize the spatial distribution of soil and other environmental properties as precisely as possible so they can vary their management techniques across space, maximizing management effectiveness (Bell et al., 1995). To this end a farmer may be interested in partitioning fields into management zones. Delineation of management zones is often achieved by characterizing spatial variability of one or more soil properties or crop yield. Within these zones variability of the soil property of interest is low relative to its variability across the field. Management techniques within zones are similar, yet unique with respect to the rest of the field (Goddard et al., 1999).

Within this context, integrated GIS/modeling programs must be capable of identifying the best possible management practices for a given combination of soils, topography, and any other factors relevant to the field. Concurrently, these programs must be accessible for use by a manager who might have limited expertise using such programs (Frida, 1993; Parks 1993). A computer model that requires extensive training might be prohibitive to a majority of managers, and therefore of little practical use. Models to be used for site-specific agriculture should therefore be designed for application by users beyond the researcher developing them (Parks, 1993). Within such systems, a manager could identify and delineate management zones based on having similar soil water properties. Crop yields could be maintained or enhanced while inputs such as fertilizer, pesticides, and herbicides could be optimized across the field. Consequences of such a system would include potentially favorable effects on the environment and on economic return (Power and Schepers, 1989).

Soil Survey and Terrain Analysis

Explanatory variables used to model soil water variability must be easier to obtain than soil water measurements, if these variables are to simplify the task of increasing efficiency and productivity (McKenzie and Ryan, 1999). Increasingly, easily obtained soil survey maps are displayed in a GIS for management purposes (Keck, 1998). Soil survey map units encompass a range of individual soil properties within specified limits of variation. Map units can be used as a template for soil water sampling and as management zones for use in crop yield models (Decker, 2000). A soil water sample may be taken within each soil map unit, and, based on soil properties defined in the map unit, a value for plant available water could be calculated and assigned to the map unit. Plant available water could then be used, along with other soil and climatic factors, in making crop yield predictions in a GIS.

Conventional soil survey maps, however, do not delineate all of a field's inherent variability nor represent specific soil attribute variation (Moore et al., 1993). Inferred homogeneities within soil map units do not exist for many physical and chemical attributes that affect environmental modeling and soil-specific management (Moore et al., 1993). Point samples often do not fit within the range of values assigned to a given soil series or map unit (Nettleton et al., 1991). Thus actual plant available water may vary significantly within the map unit to which only one value for plant available water has been assigned. This can lead to variation of actual crop yield within the map unit, yet not predicted in a crop yield model.

Environmental factors that might influence within-unit soil water variability include topography and geologic processes (Verhagen et al., 1995). In mountainous or hilly terrain, soil water distribution is controlled largely by vertical and horizontal water divergence and convergence (Odeh et al., 1994; Moore et al., 1993b). Two areas where soil water storage might be high due to lateral subsurface flow are hillslope hollows and low-gradient slopes. Alternatively, it could be expected that hillslope ridges might have lower soil water storage due to lack of contribution from lateral flow. This might vary with different soils (Burt and Butcher, 1985). Soil-terrain modeling incorporates soils and terrain to identify portions of the landscape where water might move predominantly in the lateral, as opposed to vertical, direction.

Digital Elevation Models

MacMillan et al. (2000) suggest it is possible to transfer manual rule-based approaches for interpreting and classifying landscapes into computer based procedures that use artificial intelligence. In doing so, the capture and application of tacit knowledge of experts in the fields of soil and landform modeling could be automated and repeatable across space (i.e. different sites) and time.

Digital elevation models (DEMs) depict a landscape by representing the spatial distribution of elevation above some arbitrary datum, usually as a grid within a GIS framework (Moore et al., 1991). Elevation contour maps or elevation data points collected with a GPS are two sources of input elevation data. As part of the classification procedure DEMs can calculate quantitative terrain attributes for each grid cell that characterize the surface shape of the landscape. The attributes can then be used for statistical correlation with other environmental properties at these nodes.

Quantitative attributes that are derived from a DEM can be divided into primary and secondary, or compound, attributes. Primary indices are calculated directly from a DEM, and four that have been correlated extensively with soil water content include local slope, aspect, plan curvature (a measure of the rate of flow convergence and divergence), and profile curvature (water concentrates where slopes flatten out) (Burt and Butcher, 1985; Moore et al., 1993b; Odeh et al., 1994; Gessler et al., 1995). A fifth primary topographic attribute considered by many researchers to be of fundamental importance in modeling soil water content is specific catchment area (Moore et al., 1993c; Western et al., 1999). This attribute is an approximate measure of runoff per unit width above a given point in a landscape, therefore estimating contributing flow to that point.

Compound attributes are generated through the combination of two or more primary attributes. The intent is to characterize and model more precisely specific processes occurring in the landscape (Gallant and Wilson, 1996). Various forms of wetness indices, the stream power index, and sediment transport capacity indices are examples of process-based secondary attributes. The compound topographic index (CTI), or steady-state wetness index, incorporates many pedological-transfer functions across landscapes that influence soil spatial variability. Therefore it can be used to capture spatial variability and distribution of select soil properties and attributes (Burt and Butcher, 1985; Moore et al., 1993c; Odeh et al., 1994; Barling et al., 1994). The spatial distribution of soil water has been extensively modeled using CTI (Burt and Butcher, 1985; Jones, 1986; Moore et al., 1988, 1993b).

Topographic Region Partitioning

An alternative approach to terrain analysis involves topographic region partitioning. This approach is based on separating a landscape into distinct sections or regions based on position or shape, i.e. ridge, shoulder, backslope, toeslope, etc., often within a GIS.

The region-partitioning approach incorporates a deterministic, expert knowledge based procedure to model the spatial distribution of soil water. Landscapes can be partitioned into any number of classes, through the separation or combination of any kind and number of terrain features (Pennock et al., 1987; Zhu et al., 1997; Nolan et al., 2000). The partitioning is based, in part, on presumed knowledge of processes occurring across a landscape and the effects of these processes on soil water distribution. As contrasted with stochastic statistical analysis, the use of expert knowledge to define landform elements permits definition of a standard set of spatial entities that can be expected to exhibit predictable behaviors (with respect to water) across a wide range of landscapes (MacMillan et al., 2000).

The methods and scales at which topography has been used for region-partitioning have been varied. Leavesley and Stannard (1990) assumed that watersheds could be divided into sub-areas, called hydrologic response units (HRU), based on homogeneity in hydrologic response. This approach emphasized that HRUs should be defined through matching the similarity of many topographic and environmental (e.g. soil, vegetation) variables.

Wood et al. (1988, 1990) introduced the idea of the representative element area (REA) to address within-unit variability. The basis of the REA concept is identification of upper and lower bounds of spatial variability of environmental variables that yield a specific homogenous hydrologic response. This is also called the critical area. At the critical area scale, the effects at the point scale are attenuated or completely submerged (Grayson et al., 1992).

Use of topographic and soil survey information for region partitioning has been conducted at relatively small, farm field scales with varying degrees of success. In one case, attributes computed from a DEM and a fuzzy rule base were integrated to identify

15 morphologically defined landform facets (MacMillan et al., 2000). The 15 facets were grouped into fewer classes to stratify soil properties. Using topographically derived regions, McBratney et al. (1991) claimed to improve representation of geostatistically mapped soil attributes. Odeh (1994) illustrated that optimal sampling patterns could be designed to reduce representative error of samples. Nolan et al. (2000), however, suggested that the success of topographic region partitioning varied from site to site and year to year, predominantly as a function of the influence other environmental variables have over the variable being stratified.

Other studies maintain that multivariate statistics such as discriminant analysis and fuzzy-k means clustering of quantitative terrain attribute data can be used to partition regions (Webster and Burrough, 1974; Bell et al., 1994; Thomas et al., 1998; Sinowski and Auerswald, 1999). The terrain data are grouped into classes so that "similar" data are in the same class (Manly, 2000). De Bruin and Stein (1997) maintain that this method enhances soil-landscape modeling because it allows representation of fuzziness inherent to soil landscape units.

Expert knowledge is incorporated into multivariate analysis in one of two ways, depending on the method used. In discriminant analysis, a user-defined number of classes are "seeded" with specific values of terrain and environmental variables used in the partitioning process. These values are pre-determined by the user to be representative of their respective classes. Subsequent assignment of dataset individuals is based on statistical distance of each individual to these values (Manly, 2000). For fuzzy k-means cluster analysis, the user defines the optimum number of classes to be determined for a landscape. Classification is based on statistical distances calculated between individuals in the dataset (MacMillan et al., 2000; Manly, 2000).

Models and Classification

Models that incorporate soils and terrain to characterize soil water variability can be classified into two groups: probability, or stochastic, and deterministic models. Stochastic models do not necessarily rely on understanding of processes involved with soil water variability. These models instead typically assume that small-scale water flow and accumulation can be described as random functions with known statistical properties (McLaughlin et al., 1993). These statistics are then used to calculate the probability that a given soil water value will occur. A comparison between estimates of soil water status developed from regression equations and validation samples in the field is a relatively simple stochastic method that has been attempted with variable success (Moore et al., 1993; Barling et al., 1994; Western et al., 1999).

In contrast, deterministic models incorporate mass water conservation and flux laws into the predictive process. Predicted values are thus a function of space and time. In this sense, deterministic models require an understanding, or expert knowledge, of the underlying environmental and systematic processes involved in soil water distribution and variability. Buckingham-Darcy's Law for unsaturated flow in porous media is an example of this type of model. There are two general classes of deterministic models. Quantitative models use mathematic, often differential and/or numerical, equations to characterize the underlying process. Qualitative models often use expert knowledge to produce results in the form of abstract class designations rather than numerical results (Keck, 1998).

A model at best only represents reality by capturing some aspect, or essence, of the reality it attempts to represent (Fdida and Pujolle, 1987). Natural processes that occur in an environmental system can be highly complex and involve many factors. Most models are based on a set of simplifying assumptions that allow some environmental factor to serve as a surrogate for multiple other factors, thus reducing complexity (Keck, 1998). However, outputs from such a model can only be as accurate as these assumptions are appropriate (Keck, 1998). The simplifying assumptions must capture appropriate elements of reality in a manner that is not distorted or biased. A soil-terrain model for predicting soil water distribution will not be useful to farmers if spatial estimates are incorrect.

Scope and Purpose

The work presented in this thesis contributes to a larger effort to incorporate site-specific management practices into agriculture. Research conducted for this thesis was based on the hypothesis that the integration of soil survey and terrain analysis in a GIS format could be used to delineate distribution of soil water content across landscapes. An inherent assumption was that topography is integral to modeling soil water distribution and variability across agricultural fields such as these studied, which had moderate topographic relief. The goal of the project was to increase understanding of the practice of using terrain to model soil water distribution and spatio-temporal variability, and to determine if terrain analysis might be useful to producers for identification of management zones based on soil water content. These management zones could be used to aid the farmer in optimally allocating chemical application rates, while maintaining or increasing yield and thereby reducing likelihood of groundwater pollution. Additionally, management zones could be used as a template for benchmark sampling of soil water, which is more feasible than traditional grid sampling schemes.

Objectives

Two aspects of the overall project are described in this thesis. Chapter 2 addresses two objectives: 1) to characterize and describe the spatial distribution and variability of soil water on four Montana farm fields of moderate (15-30m) relief; and 2) to evaluate the feasibility of region partitioning, through terrain analysis and soil survey, to delineate management zones based on soil water content in these four fields. This aspect of the project incorporates a qualitative deterministic modeling approach to delineate the regions. Chapter 3 addresses a single objective: to determine the correlation between soil water content and topographically-derived quantitative indices calculated at 5m grid scales. The empirical, stochastic approach used in Chapter 3 assumes that terrain attributes function as surrogates for the processes underlying soil water distribution.

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CHAPTER 2

TOPOGRAPHIC REGION PARTITIONING WITHIN FARM FIELDS AND ANALYSIS OF SOIL WATER CONTENT WITHIN AND BETWEEN REGIONS

Introduction

Soil water is integral to many processes that occur within and across landscapes, including plant growth and crop yields. Land managers, however, often find it difficult to assess the distribution and variability of soil water content in an efficient and reliable manner. Topography can influence the distribution of soil water by influencing surface and subsurface flow (Burt and Butcher, 1986; Moore et al., 1991; Grayson et al., 1997). Terrain analysis may therefore be a useful tool for delineating soil water spatial distribution and variability across landscapes.

Approaches that use terrain analysis to infer soil water attributes assume that terrain modifies soil and parent materials and can therefore serve as a surrogate by integrating many landscape processes that influence soil water patterns (Gessler et al., 1995). Region partitioning is based on separating a landscape into distinct sections or regions based on landscape position (upper, mid, and lower) or shape (convexity and concavity). If successful, variation in an environmental variable of interest, such as soil water content, is smaller within any particular region than between regions or across the landscape (Ovalles and Collins, 1986).

For modeling soil water distribution, three or four class groupings seem to offer an optimal combination of simplicity, spatial consistence, and meaningful differences in terrain and soil properties (Pennock et al., 1987; Burrough et al., 1992; MacMillan et al., 2000). Region partitioning might be useful to managers who would like to apply spatially variable management strategies based on soil water status. An assumed relationship between soil water and terrain, and the need to define effective agricultural management zones, provide motivation for the use of a terrain-based region-partitioning approach.

The purpose of this study was to evaluate the potential to delineate soil water management zones as an aid to farmers and land managers. Such zones might be used to optimize application rates and as templates for benchmark soil sampling. This study encompassed two main objectives: 1) to measure soil water content at multiple locations on four Montana farm fields several times during the growing season; and 2) to test the utility of three terrain and soil-based region-partitioning methods to delineate the measured soil water distribution and variability.

Materials and Methods

Study Sites

The study was conducted at four locations, each comprising a 25 to 60 ha portion of farm fields located across the "Hi-Line" agricultural region of north central Montana.

Liberty County Site. The study area consisted of about 25 ha within a farm field having gently rolling terrain of moderate (20m) relief and located approximately 21 km north of Chester, MT (T34N, R7E, Section 17; 48°42'30" 110°51'30") (Fig. 1). The predominant aspect trended to the south, with a moderate draw running in a south-southwesterly direction (Fig. 2a). The area has a cool, semi-arid climate, with mean annual precipitation of 31 to 43 cm (Caprio et al., 1994). However, the research site commonly receives lower amounts of annual precipitation, possibly due to its location in a rain shadow to the east south east of the Sweetgrass Hills (Janice Mattson, 2000). The field was dryland farmed by the Mattson family with an alternate wheat/fallow rotation.

The underlying geologic materials at the liberty site are primarily glacial till derived from the Bear Paw formation (Veseth and Montagne, 1980). Soils are mapped as a complex of Joplin loams (a fine-loamy, mixed, frigid Aridic Argiustoll) formed on till, and Hillon loams (fine-loamy, mixed, calcareous, frigid Aridic Ustorthent) (National Soil Survey Staff, 1998a; 1998b).

Hill County Site. The study area was a 15 ha portion of a farm field located in Hill County, approximately 16 km west of Havre, MT (T32N, R14E, Section 17; 48°31'30" 109°57') (Fig. 1). This field is characterized by a knoll of moderate relief (~15m) running west-east across the southern portion, and a knoll of lower relief (~5m) running west-east across the northern portion of the site. The remainder of the field is relatively flat (Fig. 2b). The area has a cool, semi-arid climate with mean annual precipitation of 31 to 43 cm and (Caprio et al., 1994). The field was dryland farmed by the Kaercher family with an alternate wheat/fallow rotation.

Underlying geologic materials are glacial till derived from the Bear Paw and Judith River formations (Veseth and Montagne, 1980). This site consists of three mapped soils. Soils in the southern portion (Map unit 701D), along the knoll, are a complex of Yetull loamy sands (mixed, frigid Aridic Ustipsamments) formed in sandy alluvium and/or eolian deposits, and Busby fine sandy loams (coarse-loamy, mixed, frigid Haplocalcidic Haplustepts). Just to the north is a complex (331B) of Phillips loams (fine, frigid Aridic Haplustalfs) and Elloam clay loams (fine, frigid Aridic Natrustalfs), both formed in till on plains. In the northern portion of the field, soils (421C) are the Joplin loams (fine-loamy, mixed, frigid Aridic Argiustoll) formed on till, and the Hillon loams (fine-loamy, mixed, calcareous, frigid Aridic Ustorthent) (National Soil Survey Staff, 1998c; 1999; 1998d; 1996; 1998a; 1998b).

Phillips County Sites. The remaining two study sites were neighboring strips of the same field that are dryland farmed in alternate years by the Anderson and Mavencamp families using an alternate wheat/fallow rotation. "Phillips 1" consisted of 25 ha, and the second site, "Phillips 2", consisted of 12 ha of the field, approximately 22.5 km east of Malta, MT (T31N, R32E, Section 20; 48°25'30" 107°35'30") (Fig. 1). This site has moderate relief (~30m) with uneven rolling topography and occasional severe undulations (Fig. 3). The climate is cool, semi-arid with mean annual precipitation of about 31 to 43 cm (Caprio et al., 1994).

The underlying geologic materials are primarily glacial till from the Clagget formation (Veseth and Montagne, 1980). Soils are mapped as a complex of Scobey clay loams (fine, smectitic, frigid Aridic Argiustoll), and Kevin clay loams (fine-loamy, mixed, frigid Aridic Argiustoll), formed on till plains, hills, and moraines (National Soil Survey Staff, 1998e; 1998f).