



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

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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 Row 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 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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WITHIN FOUR MONTANA FARM FIELDS

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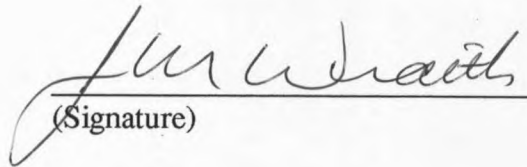
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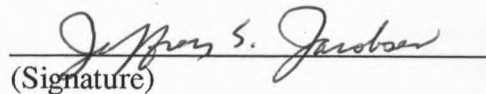
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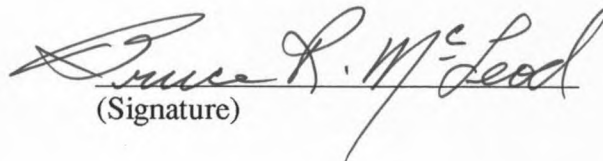
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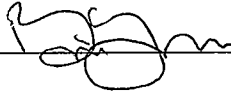
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ABSTRACT

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 Eltahan, 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-south-

westerly 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).

Figure 1. Location of the four sites used in this study. Two adjacent fields in Phillips County near Malta were utilized.

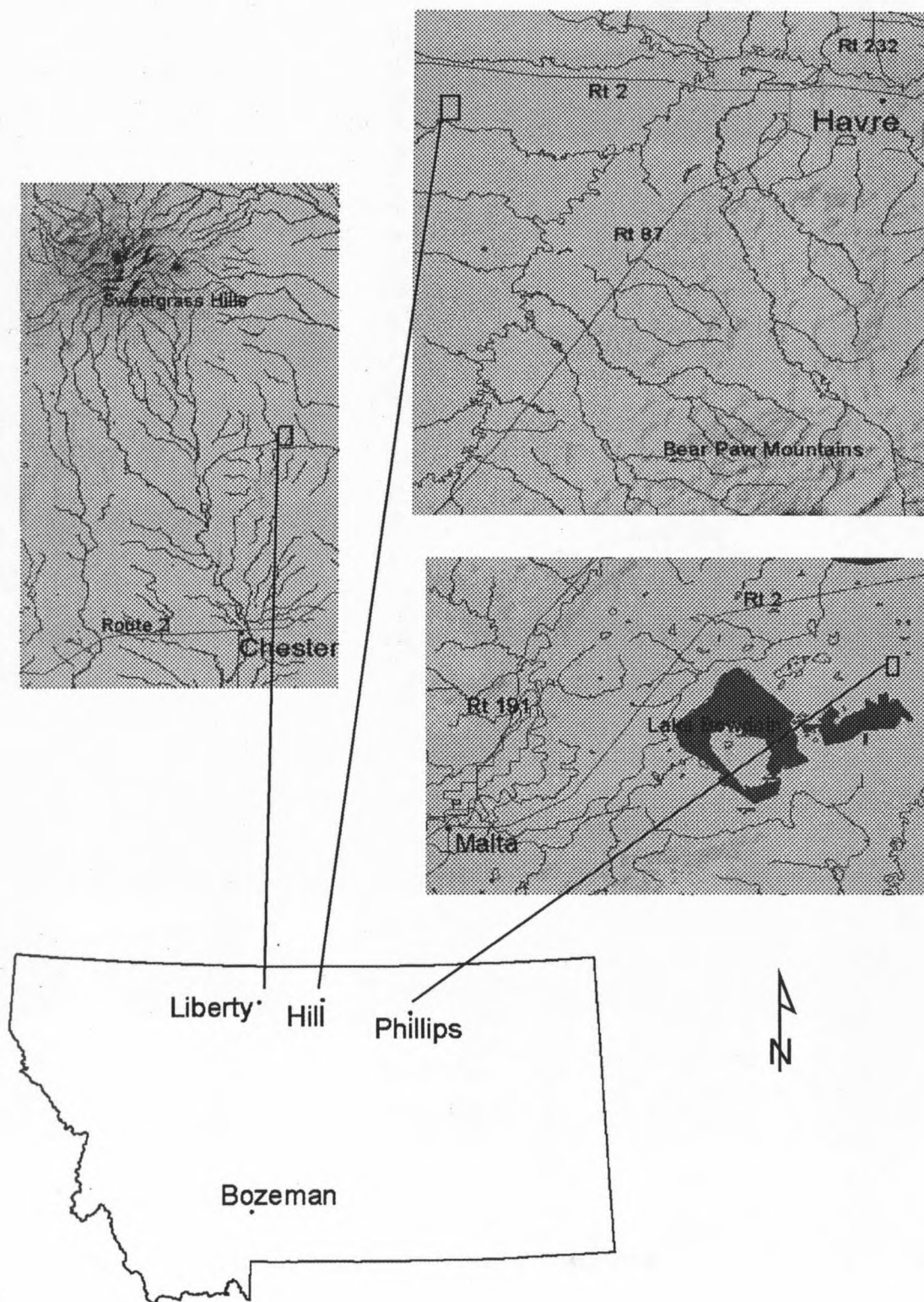
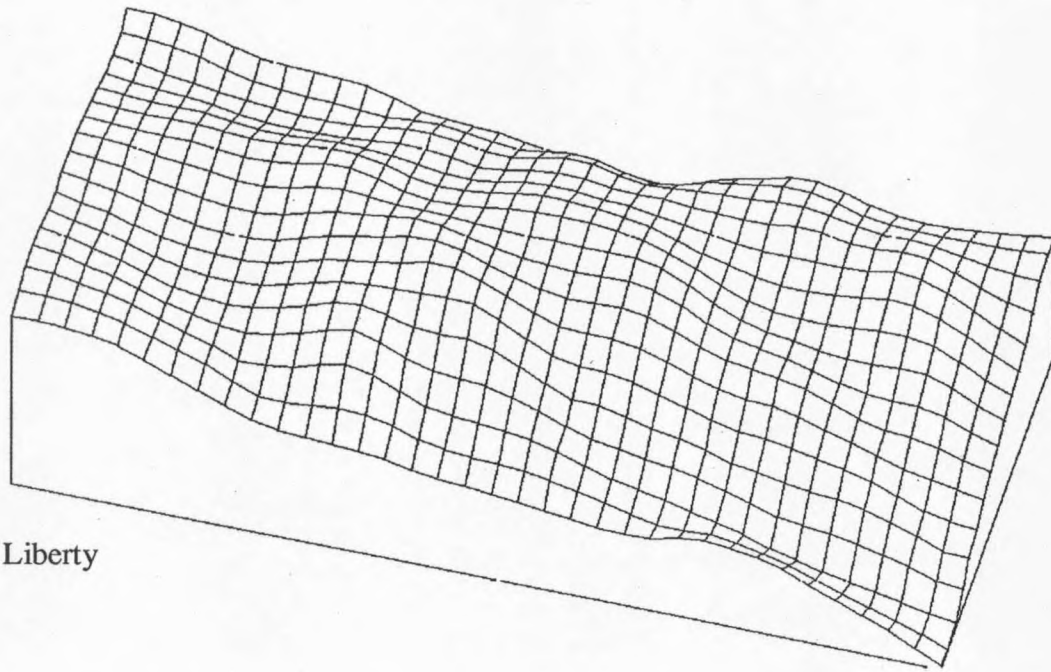
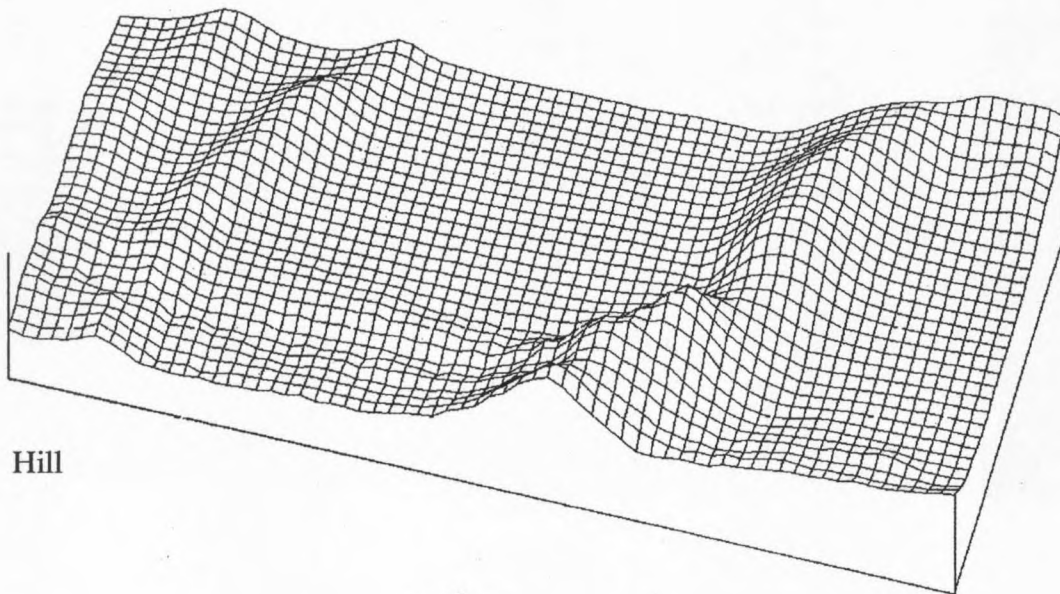


Figure 2. Interpolated 10m elevation grid surfaces for the Liberty and Hill field sites.



Liberty

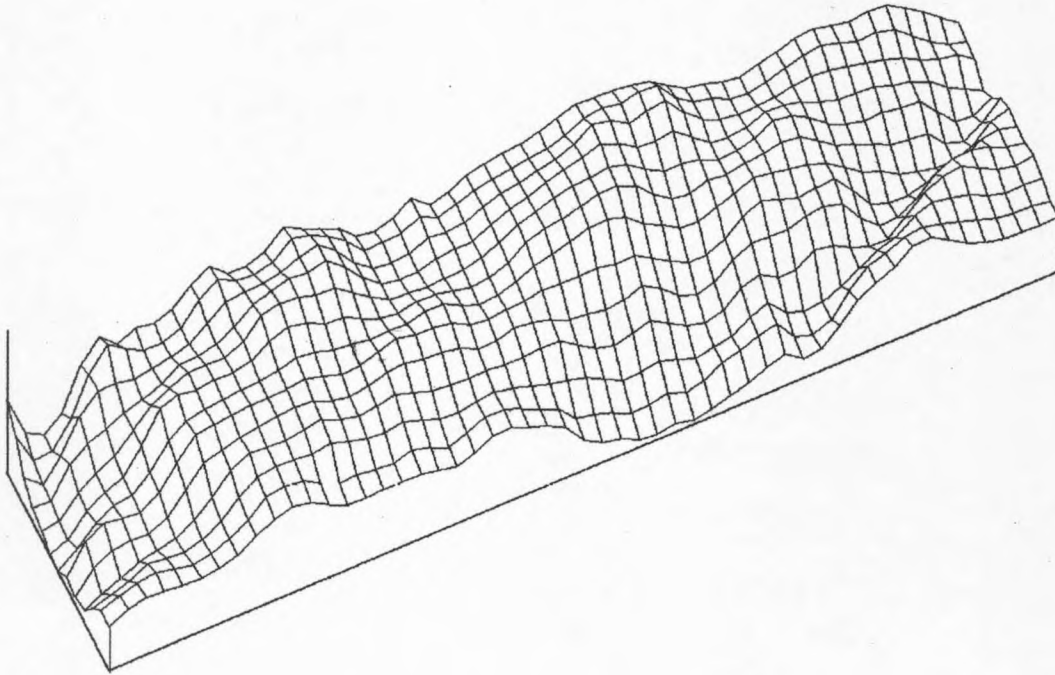


Hill

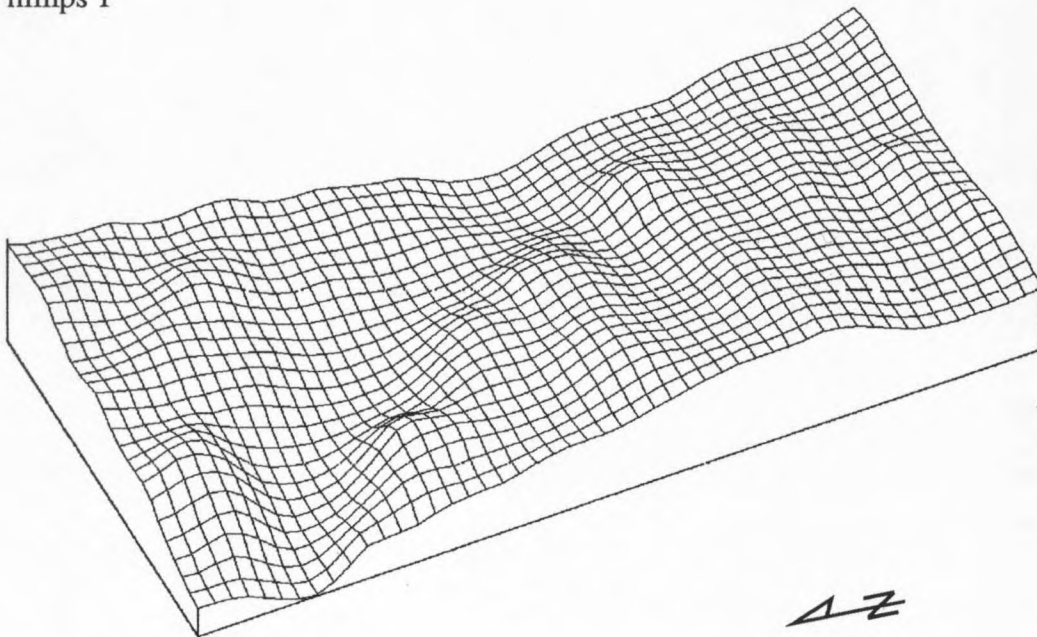


1 mesh cell = 10 by 10 m

Figure 3. Interpolated 10m elevation grid surfaces for Phillips field sites.



Phillips 1



Phillips 2

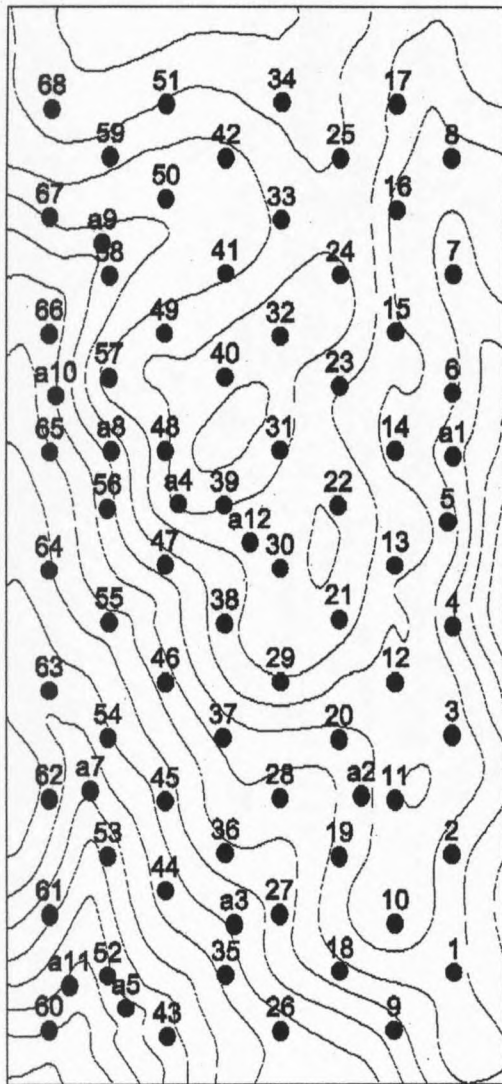
1 mesh cell = 10 by 10 m

GPS Survey and Soil Water Sample Grids

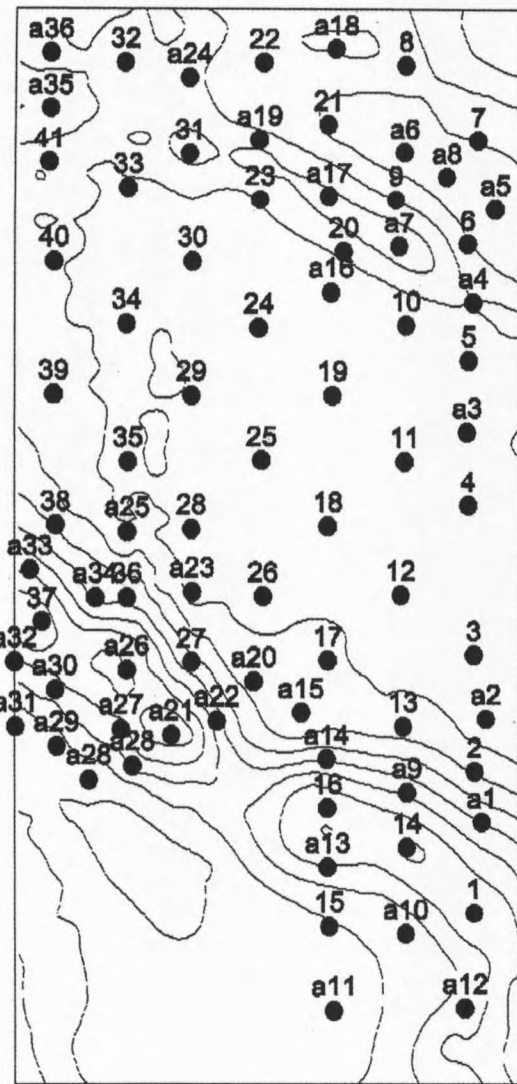
Field elevations were collected over each study site in the fall of 2000 (Liberty and Phillips) and in the fall of 2001 (Hill). A Novatel model 3151R GPS receiver (24-channel, single-frequency, L1 carrier phase) was mounted on an all-terrain vehicle and measured elevation at roughly 10-m intervals along a series of parallel transects. A second Novatel receiver was located at a base station in the same field. The raw elevation measurements were corrected in the laboratory with the commercial post-processing software GravNav (Waypoint Consulting, Inc., Calgary, Alberta, Canada) to a positional accuracy of within ± 4 -cm in both the horizontal and vertical planes, relative to the location of the base station. An Ashtech AgNavigator consisting of a 486 computer, light-bar, and navigation-grade GPS receiver (12 channel, L1 C/A code) was used to provide guidance along the parallel transects within ± 1 -m of positional accuracy.

A permanent, augmented sampling grid of 78 to 80 points was established in each field for the purpose of measuring soil water contents (Fig. 4, 5). 50 to 65 equally spaced sample points were established in an offset grid-like pattern. The GPS system was used to develop the grid and to mark the points in each field. An additional 15 to 30 points were added to augment the grid, in order to better represent the range of soils and terrain features (e.g. areas of convergence and divergence) across the study site. The combination of grid points and augment points in any field was a product of the size of the field and visual estimation of topographic variability within the field. To insure adequate coverage, the larger plots included more points in the offset grid.

Figure 4. Permanent soil water content sampling grid for the Liberty and Hill sites.



Liberty



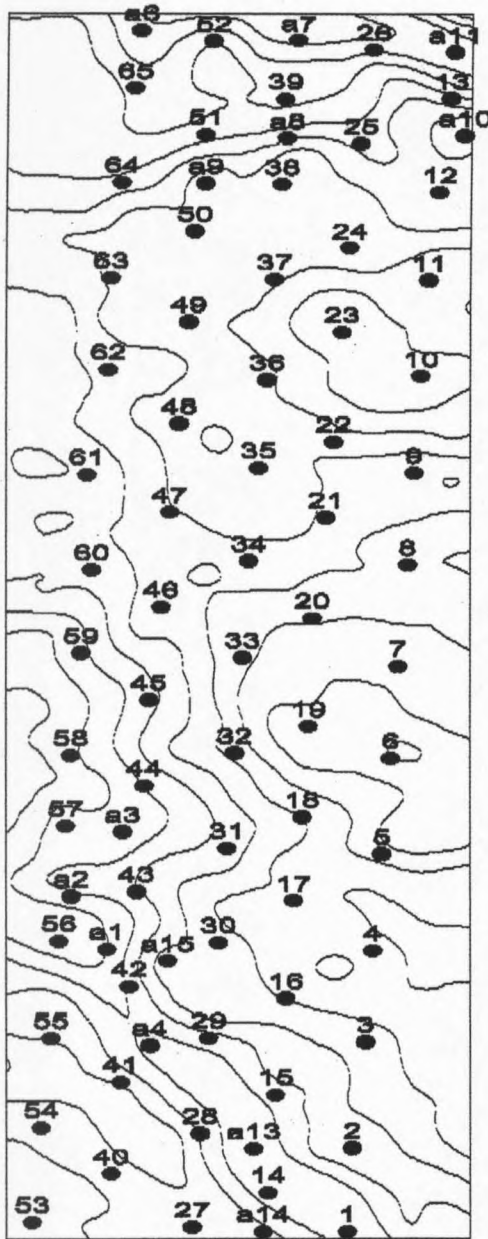
Hill

Fields not to scale

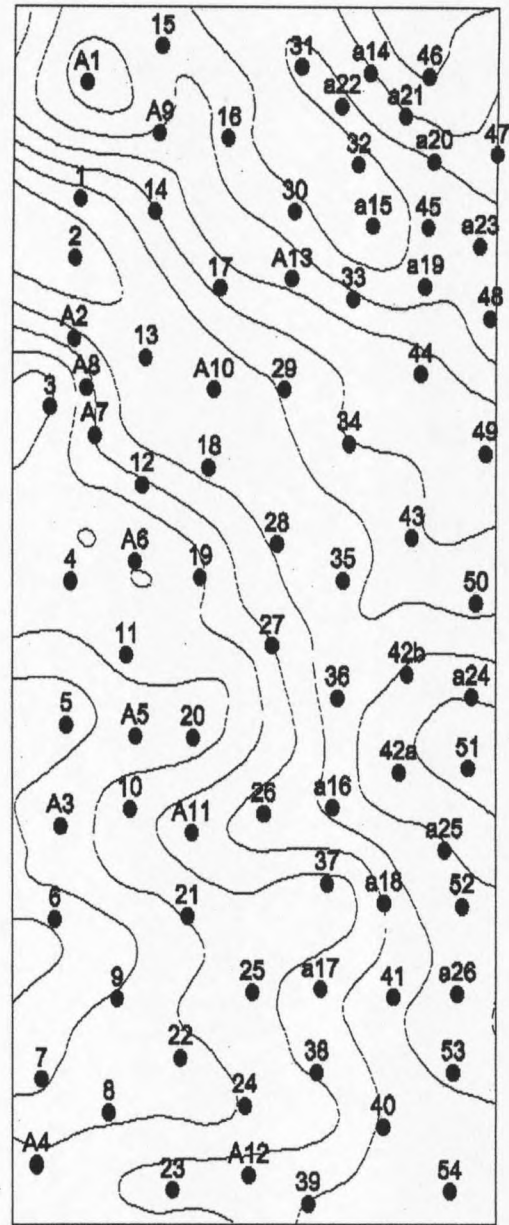
"a" indicates augment point



Figure 5. Permanent soil water content sampling grid for the Phillips sites.



Phillips 1



Phillips 2

Fields not to scale
 "a" indicates augment point



At each sample point a thin-wall PVC access tube was installed to 80 cm depth to measure soil water content with a neutron moisture meter (503DR, CPN Co., Martinez, CA) (Gardner, 1986). Following access tube installation the locations and elevations of each point were resurveyed using the GPS.

Soil Sampling and Field Characterization

Soils information used in this project was obtained through the National Cooperative Soil Survey and select field samples. All fields were mapped as complexes of soil series by the National Resource Conservation Service staff. Soil pits were excavated to investigate spatial distribution of soil series across the landscape. For every field, at least one soil pit was excavated on the upland, mid-slope, and lowland landscape positions, as well as in areas of convergence and divergence. Soil profiles were described for the sampled locations within fields (Appendix B), including some soil characteristics considered to be related or correlated to soil water storage, flow, and spatial distribution (Or and Wraith, 2000). The soils information was used in interpreting results of the region-partitioning approaches described below.

Generation of Topographic Regions

Two of the methods for partitioning landscape regions in order to model soil water distribution were landscape models that classify terrain attributes using a rule-based approach. The third method used multivariate statistical cluster analysis to numerically classify terrain attributes. The GPS elevation data for each field were converted to a regular, equally-spaced 5 m digital elevation model (DEM) grid using the interpolation software package ANUDEM (Hutchinson, 1989). ANUDEM takes as input

irregularly spaced elevation point data and creates grid based DEMs using a series of smoothing operators.

Rule-Based Landscape Region-Partitioning. The interpolated 5 m elevation data were imported into Arcview Spatial Analyst v3.2 (Environmental Systems Research Institute, Inc., Redlands, CA) as an ASCII file, converted to an Arcview grid, then imported into LandMapR (MacMillan et al., 2000) to generate landscape classes. LandMapR computed quantitative terrain attributes such as slope, profile curvature, and plan curvature, for every cell in a DEM, and converted them to any of 20 basic fuzzy landform attributes. These attributes are “fuzzy” because, among other reasons, they describe the terrain in terms of relative shape (convex_down, rel_steep, etc.) and location (near_top, near_bottom, etc.). The landform attributes were used in various combinations to define 15 basic landform element classes, e.g. convergent backslope, toe-slope, etc.

The converted landform element class data was extracted from LandMapR, imported into Arcview Spatial Analyst v3.2, and converted to a 5 m grid. Using the reclassify function, the 15 landform elements were grouped into fewer classes (3-4) to reduce complexity and spatial fragmentation, using two different approaches.

One approach, termed the Flow Method, was based on empirical concepts of surface and subsurface water flow across a landscape. This approach created four classes: divergent (water shedding), convergent (water receiving), planar or flat (water neutral), and depressions (water retaining) as outlined in MacMillan et al., 2000. The second grouping method, Soil-Landscape, was based on topography and relative position in the landscape as reflections of soil spatial patterns. Three generalized classes were

-recognized: upper, mid, and lower as outlined in Appendix E. Soil formation as a function of one attribute of landscape, and resultant variability in soils across a landscape, were represented in this approach.

Multivariate Statistical Region-Partitioning. The 5 m interpolated data from ANUDEM were entered into the Terrain Analysis Program for the Environmental Sciences (TAPES) (Gallant and Wilson, 1996) software program to calculate terrain attributes for each 25 m² cell, for the four study sites. Four primary attributes correlated with soil water content in other studies (Burt and Butcher, 1985; Moore et al., 1993b; Odeh et al., 1994) were generated: slope, elevation, profile (down-slope convergence and divergence) curvature, and plan (across-slope) curvature. The finite differences (FD option) approach, rather than the approximate (D8) approach, was used to calculate slopes for this project.

The terrain attributes calculated by TAPES, along with associated coordinate data, were imported into Minitab statistical software (Minitab Inc., State College, PA). Fuzzy-k means cluster analysis was performed using the four terrain attributes. The program delineated three (upper, mid, and lower) landscape position classes for each of the four study sites. The complete dataset with class designations was imported into Arcview Spatial Analyst v3.2 where it was converted to a grid based on class designations.

In Arcview, neutron moisture meter sample point coordinates were overlaid on their respective Flow, Soil-Landscape, and cluster analysis class grids. A get-grid function was performed to determine cells in which the sample points were located. Class information for each cell containing a sample point was assigned to the sample points.

Soil Water Content

Soil water content measurements were used to evaluate efficacy of region partitioning to designate soil water management zones. Neutron moisture meters were used to measure water content at 20 cm depth intervals to 80 cm. Calibration relationships for the neutron meters were developed at each study site. Measurements were obtained five times during the growing season at each site. Some sample points were not monitored on specific dates due to equipment malfunction. The earliest measurement occurred immediately following seeding of the fields. Therefore, the influence of the crop on soil water would be minimal or nonexistent at that time. The last measurement of the growing season was collected at harvest, and more strongly reflected crop impacts on soil water status.

For all field sample points at all depths at each measurement date equivalent depth of soil water (cm) was calculated as the product of measured volume water content ($\text{cm}^3 / \text{cm}^3$) and the corresponding measurement depth interval (cm). Thus, measurements at 20 cm were converted to equivalent depth of soil water in the top 30 cm of soil. Measurements at 40 cm, 60 cm, and 80 cm depths were converted to equivalent depth of soil water at the 30 - 50 cm, 50 - 70 cm, and 70 - 90 cm soil depth intervals, respectively. Total soil water integrated over the top 70 cm of soil were also calculated. Soil water was not summed over the top 90 cm because several neutron access tubes were not installed to sufficient depth as a result of rocks or other obstructions. All access tubes allowed measurement to the 60 cm depth.

Statistical Analysis

Excel (Microsoft Corporation, Redmond, WA 98052) spreadsheet software was used to calculate summary statistics for soil water. Tables 14 - 17 in Appendix A provide designated region classes for soil water point measurements in each field. These were linked with measured soil water contents to create composite data files for analysis of variance (ANOVA) and for calculation of relative variance in soil water contents. Analyses at depths of 20 cm (i.e. 0 – 30 cm depth interval), 60 cm (50 – 70 cm interval), and top 70 cm were performed. Analysis at 80 cm was not performed due to lack of data.

To test for differences in mean soil water content between the delineated regions, ANOVA (Minitab) was conducted for each site and for all collection dates. Semivariograms were used to evaluate autocorrelation in each water content dataset. A normal probability plot of residuals was created to test for normality in the data. The F-test with a significance P-value of 0.05 was used to find differences between at least two of the region mean soil water values. To determine which regions differed significantly, the Tukey-Kramer multiple comparison procedure was used (Devore and Peck, 2001), with a simultaneous confidence interval of 90% (family error rate of 10%). This corresponded to an individual confidence level of 97.8% (individual error rate of 2.2%).

Relative variance of composite data files was evaluated for all collection dates. This characterized map precision by expressing the percentage of variability within regions that was less than variability across the entire study field, and is calculated from the pooled variance, S_p^2 , expressed as

$$S_p^2 = \frac{\sum (x_{1j} - \bar{x}_1)^2 + \sum (x_{2j} - \bar{x}_2)^2 + \dots + \sum (x_{ij} - \bar{x}_i)^2}{n_1 + n_2 + \dots - n_i}$$

where $\sum (x_{ij} - \bar{x}_i)^2$ is the sum of squares for the i th region, n_i is the number of water content observations in the i th region, and n_t is the total number of regions (Beckett and Burrough, 1971, Long et al., 1995). Relative variance R_s^2 is then expressed as

$$R_s^2 = \frac{(S_t^2 - S_p^2)}{S_t^2}$$

where S_p^2 is the pooled variance and S_t^2 is total across-study-site variance.

Results

Soil Water Content and Precipitation

Soil water content mean values for each site for the first and last measurement dates of the growing season at three representative depths: 20 cm (0 – 30 cm depth interval), 60 cm (50 – 70 cm depth interval), and top 70 cm (0 – 70 cm depth interval), illustrated similarity in soil water content from site to site (Table 1). Of particular interest was the coefficient of variation (CV), which gives a relative measure of variability in soil water content by expressing standard deviation as a proportion of the mean. Variability in soil water content increases with CV (range 0 – 1.0). CV values of around 0.5 suggest moderate variance in a data set (Rozgonyi, 1995; Weisstein, 1999).

Soil water content CV values on the first measurement date at each depth at all sites were consistently low (CV values 0.08 - 0.15), except for the Hill County site (CV values 0.23 - 0.31). This indicates a substantial lack of variance in soil water content at the beginning of the growing season. For all study sites at all depths, CVs were greater on the last measurement date than on the first, suggesting an increase in soil water content

variance as the growing season progressed. End of season CV at Liberty and Phillips 1 remained rather low (0.22 - 0.27), however. End of season CV at Phillips 2 varied with depth, and suggested moderate soil water variance (CV = 0.48) at 20 cm, but lower variance (CV = 0.22) at 60 cm depth. CVs at Hill on the last measurement date (0.38 - 0.46) indicated moderate soil water variance.

High variance in soil water content was not indicated at any depth at any of the study sites based on CV values (Rozgonyi, 1995; Weisstein, 1999). A consistent trend of decreasing CV values with depth was noted for the last measurement date at the Hill (0.46 to 0.38) and Phillips 2 (0.48 - 0.29) locations. CV values for Liberty (0.25 - 0.23) and Phillips 1 (0.27 - 0.26) on the last measurement date were uniform with depth

Table 1. Summary statistics for measured soil water contents on first and last measurement dates, at three depths, for the four study sites.

	----- 20 cm -----		----- 60 cm -----		--- Top 70 cm ---	
Liberty						
	May 18	Aug 7	May18	Aug 7	May 18	Aug 7
n	79	77	79	78	79	77
Min	5.14	1.65	3.64	1.41	13.65	5.08
Max	8.55	5.34	7.85	4.56	22.40	13.72
Mean	7.11	3.09	5.19	2.69	17.38	8.34
S.D.	0.77	0.76	0.61	0.61	1.57	1.65
C.V.	0.11	0.25	0.12	0.23	0.09	0.20
Hill						
	May 19	Aug 2	May 19	Aug 2	May 19	Aug 2
n	78	77	78	77	78	77
Min	2.98	0.35	2.20	0.77	8.82	1.64
Max	11.56	11.27	7.46	6.08	24.52	23.28
Mean	6.56	4.05	4.59	3.14	16.05	9.84
S.D.	2.01	1.88	1.12	1.20	3.63	4.00
C.V.	0.31	0.46	0.24	0.38	0.23	0.41
Philips 1						
	May 19	Aug 9	May 19	Aug 9	May 19	Aug 9
n	78	77	77	75	77	75
Min	5.75	1.66	4.19	1.57	15.28	5.60
Max	9.91	6.17	6.73	4.90	23.28	14.16
Mean	7.76	3.35	5.37	2.91	18.52	8.99
S.D.	0.73	0.89	0.58	0.75	1.39	1.54
C.V.	0.09	0.27	0.11	0.26	0.08	0.17
Philips 2						
	May 18	Aug 1	May 18	Aug 1	May 18	Aug 1
n	81	81	81	81	81	81
Min	4.06	1.71	2.86	1.27	10.55	3.85
Max	7.87	7.38	6.29	5.64	20.02	16.44
Mean	6.39	5.02	4.59	3.17	15.70	11.31
S.D.	0.89	1.32	0.70	0.92	1.78	2.56
C.V.	0.14	0.48	0.15	0.29	0.11	0.23

Little precipitation occurred during the 2000 field season, and annual precipitation was below normal for both Liberty (43% of long-term average) and Phillips 1 (71%) (Fig. 6, Table 2). Precipitation at Liberty occurred primarily during a single event that delivered less than 0.5 cm. Phillips 1 received most of its precipitation prior to July, and total seasonal rainfall was significantly greater than at Liberty (10.54 vs. 0.76 cm).

Precipitation during 2001 was also below normal at Hill (61% of long-term average) and Phillips 2 (68%) (Fig. 6, Table 2). Two separate growing season precipitation events of nearly 2.5 cm occurred at Phillips 2, one on June 4-6, and the second on August 1.

Figure 6. Daily growing season precipitation for the four study sites. Liberty and Phillips1 represent 2000, while Hill and Phillips 2 represent 2001. Note different scales on precipitation axes.

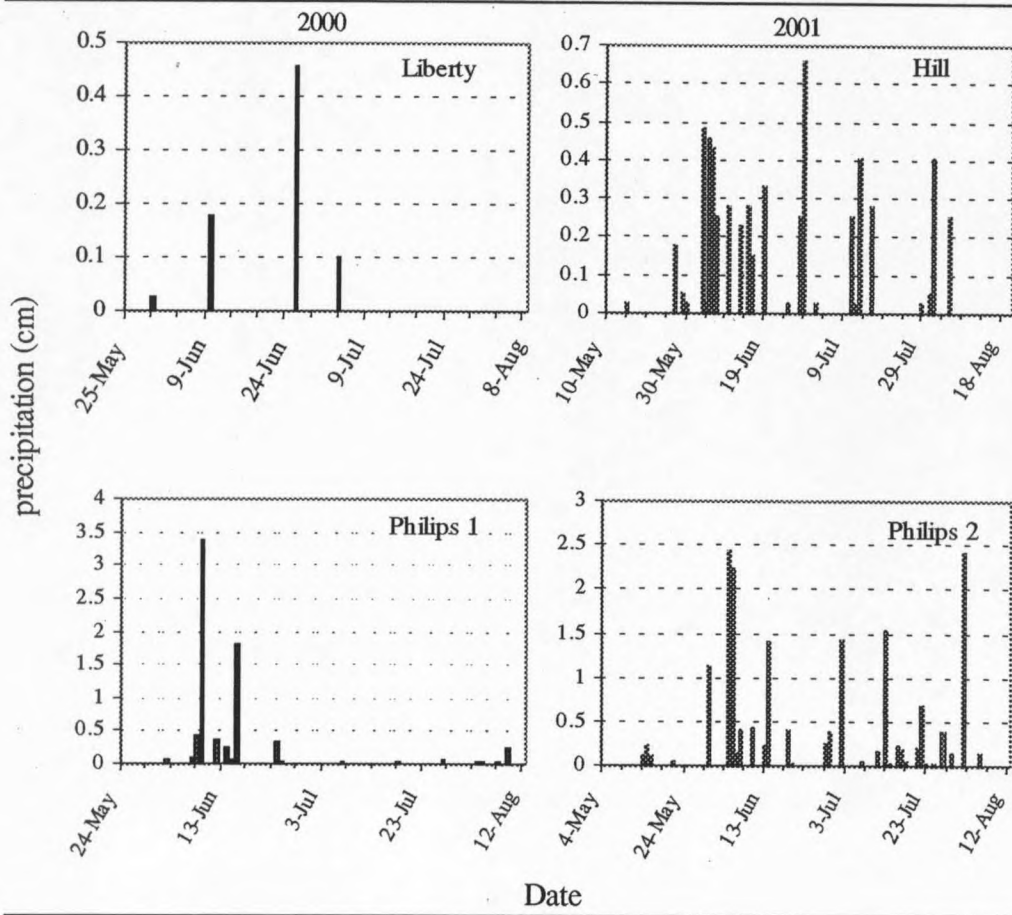


Table 2. Monthly growing season and annual precipitation amounts for the three field locations. Yearly and mean precipitation data were taken from closest weather stations at Chester, Havre, and Malta, MT for the Liberty, Hill, and Philips sites, respectively. Precipitation measured at the study sites are also included for comparative purposes. "---" indicates precipitation data not available for that time period.

Location	Year	Precipitation (cm)				
		May	June	July	August	Annual
Liberty	2000	1.98	1.91	1.29	0.46	11.79
	2000 (site)	---	0.64	0.10	---	---
	Mean	4.34	6.10	3.84	3.05	27.10
Hill	2001	1.55	3.68	7.54	0.46	17.63
	2001 (site)	1.20	3.86	4.02	---	---
	Mean	4.11	5.21	3.94	3.02	28.83
Philips	2000	2.77	6.3	4.29	0.10	22.59
	2000 (site)	---	6.71	0.16	0.24	---
	2001	2.16	7.34	5.28	2.16	21.77
	2001 (site)	1.82	8.33	5.08	2.47	---
	Mean	5.68	6.45	4.67	3.05	31.90

Soils

Appendix B contains partial descriptions of soil pits excavated. Soil series within complexes were assigned to specific regions based on the general landscape position of each excavated soil pit to assist in interpretation of region partitioning results.

In general, at Liberty, Phillips 1, and Phillips 2, convex and upper areas in the landscape exhibited thinner mollic epipedons, shallower depth to carbonates, and higher clay contents at shallow depths than concave and lower areas in the landscape. At Hill, sandy loam to sand textures and absence of a mollic epipedon characterized the upper landscape positions. Clays to clay loam soils with well-defined mollic epipedons and depth to carbonates approaching 25 cm were found in lower, level areas in the landscape.

Region Partitioning

Figure 7 illustrates how each region-partitioning method divided the field at the Liberty site. The other three sites are illustrated in Figs 19-21 in Appendix C. Patterns of

region delineation for each of the three methods were similar across the four sites.

However, the Cluster Method had the largest contiguous regions. Conversely, the Flow Method produced more numerous, smaller regions. Since the Flow Method partitioned the landscape based on water receiving and water shedding characteristics, differences in elevation did not necessarily result in different regions.

Soil-Landscape was most similar to the Cluster Method in size of regions delineated, but regions lacked the spatial continuity of those based on the Cluster Method. The Soil-Landscape Method was most different from the other methods in terms of the large area that was classified as mid landscape position. This large area resulted in inclusion of 40% to 45% of soil water sample points within the mid landscape position across all sites. This is contrasted with a maximum 36% of soil water sample points included in upper or lower Soil-Landscape regions across all sites.

Region Soil Water Dynamics

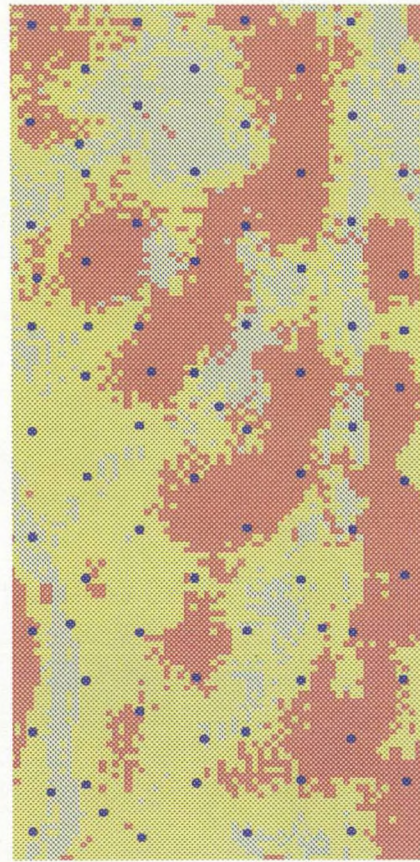
Liberty Site. At Liberty, differences in mean soil water content between regions varied with depth for the Flow and Soil-Landscape Methods, but remained relatively similar for the Cluster method. To a depth of 30 cm (20 cm), there were no significant differences in mean soil water content between regions for any method throughout the growing season (Table 3; Fig. 8, 9). No differences between Cluster region means were evident at the 50 – 70 cm (60 cm) or top 70 cm depths either.

At 60 cm depth, Flow method depression regions and the Soil-Landscape method lower regions had the highest mean soil water content throughout the growing season.

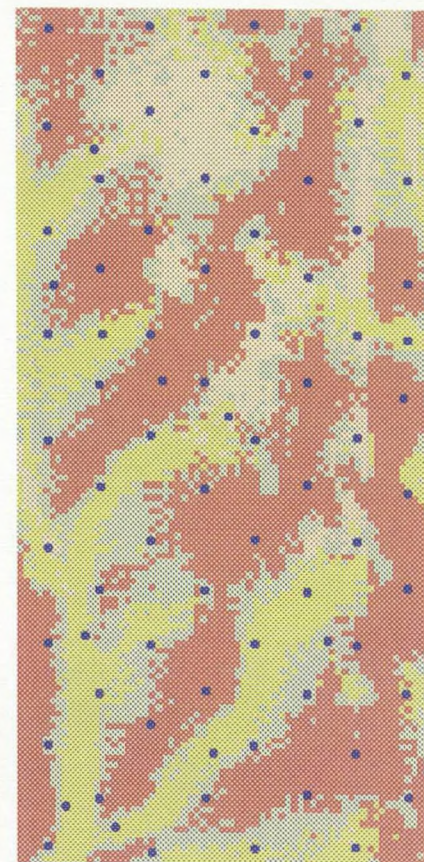
Figure 7. Results of three partitioning schemes for the Liberty site. The three partitioning methods are listed at the bottom left of the respective panels.



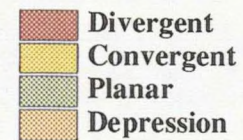
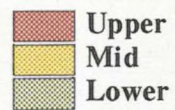
Cluster



Soil-Landscape



Flow



Depression and lower mean soil water contents were significantly different from divergent and upper regions, respectively, on May 18 and August 7 (Table 3).

For the top 70 cm, mean soil water content was highest in Flow Method depressions throughout the growing season, but significant differences were evident only on August 7 (Table 3). Soil-Landscape regions had similar soil water contents from May 18 to July 12. Between July 12 and August 7 loss in mean soil water content was greater in upper regions than lower regions, resulting in a significant difference on August 7 between the lower and upper regions in this attribute.

Table 3. ANOVA summary for region beginning and ending growing season soil water content means at Liberty. Within rows, asterisk in p-value column highlights significance at 0.05 level, and region mean values followed by the same letter are different at the 5% significance level.

Depth	Date	P-value	Region means			
			Flow			
			Divergent	Convergent	Planar	Depression
20 cm	May 18	0.564	7.07	6.91	6.85	7.20
	Aug 7	0.542	3.02	3.22	2.90	3.26
60 cm	May 18	0.022*	5.05a	5.16	5.16b	5.67ab
	Aug 7	0.002*	2.46a	2.69b	2.81	3.23ab
top 70 cm	May 18	0.124	17.22	17.1	17.27	18.38
	Aug 7	0.011*	7.86a	8.45	8.35b	9.79ab
Soil-Landscape						
			Lower	Mid	Upper	
20 cm	May 18	0.904	7.06	6.96	7.03	
	Aug 7	0.274	3.37	2.99	3.04	
60 cm	May 18	0.053*	5.48a	5.19	5.03a	
	Aug 7	0.057*	2.97a	2.72	2.52a	
top 70 cm	May 18	0.326	17.85	17.37	17.13	
	Aug 7	0.053*	9.23a	8.25	7.99a	
Cluster						
			Lower	Mid	Upper	
20 cm	May 18	0.668	7.07	6.93	7.09	
	Aug 7	0.42	3.30	3.01	3.05	
60 cm	May 18	0.097	5.43	5.06	5.19	
	Aug 7	0.063	2.99a	2.59a	2.64	
top 70 cm	May 18	0.382	17.78	17.15	17.42	
	Aug 7	0.067	9.16a	8.08a	8.15	

Figure 8. Mean soil water content expressed as equivalent depth of water for three measurement depths, for sample locations allocated within two different partitioning methods, at the Liberty site.

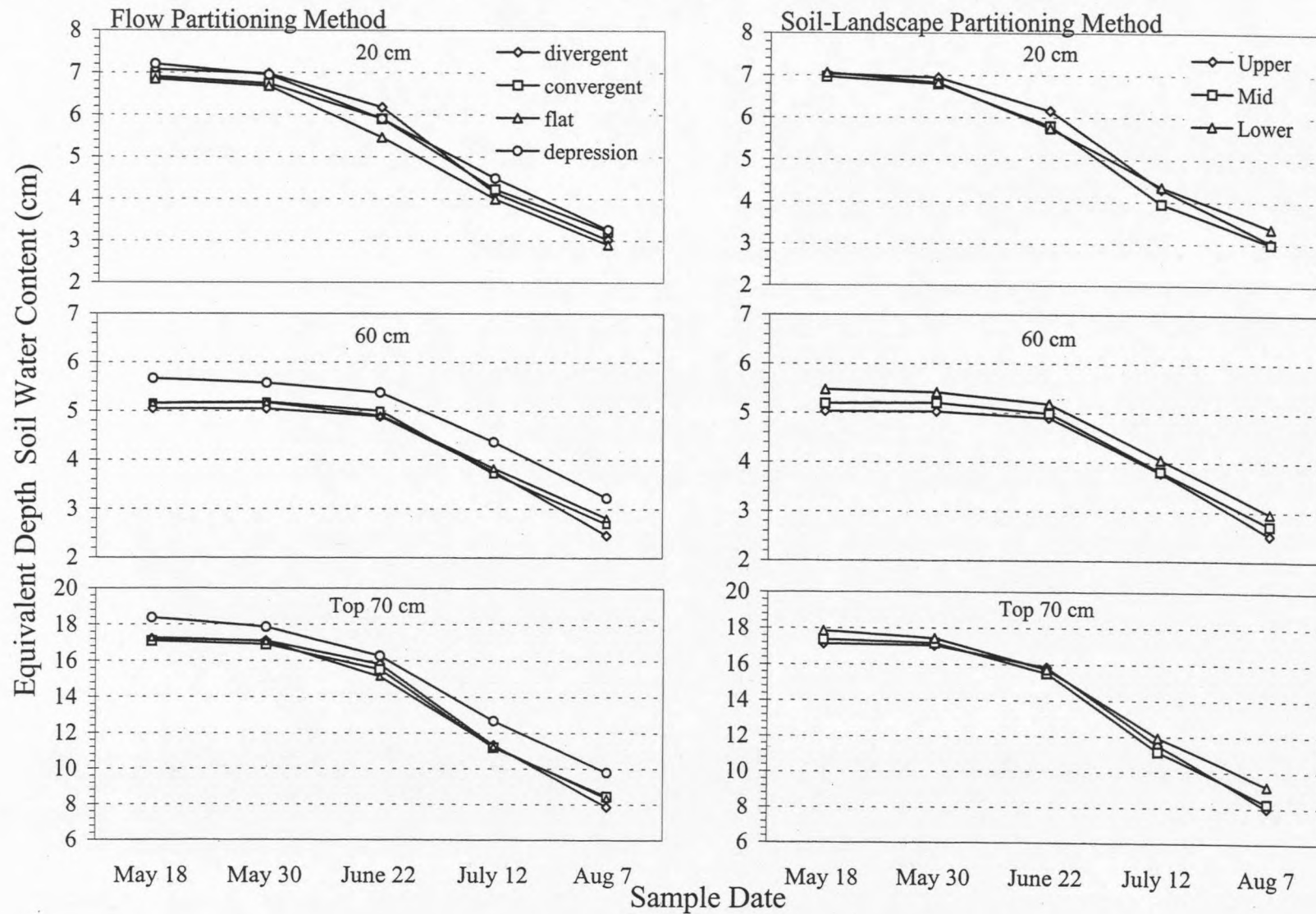
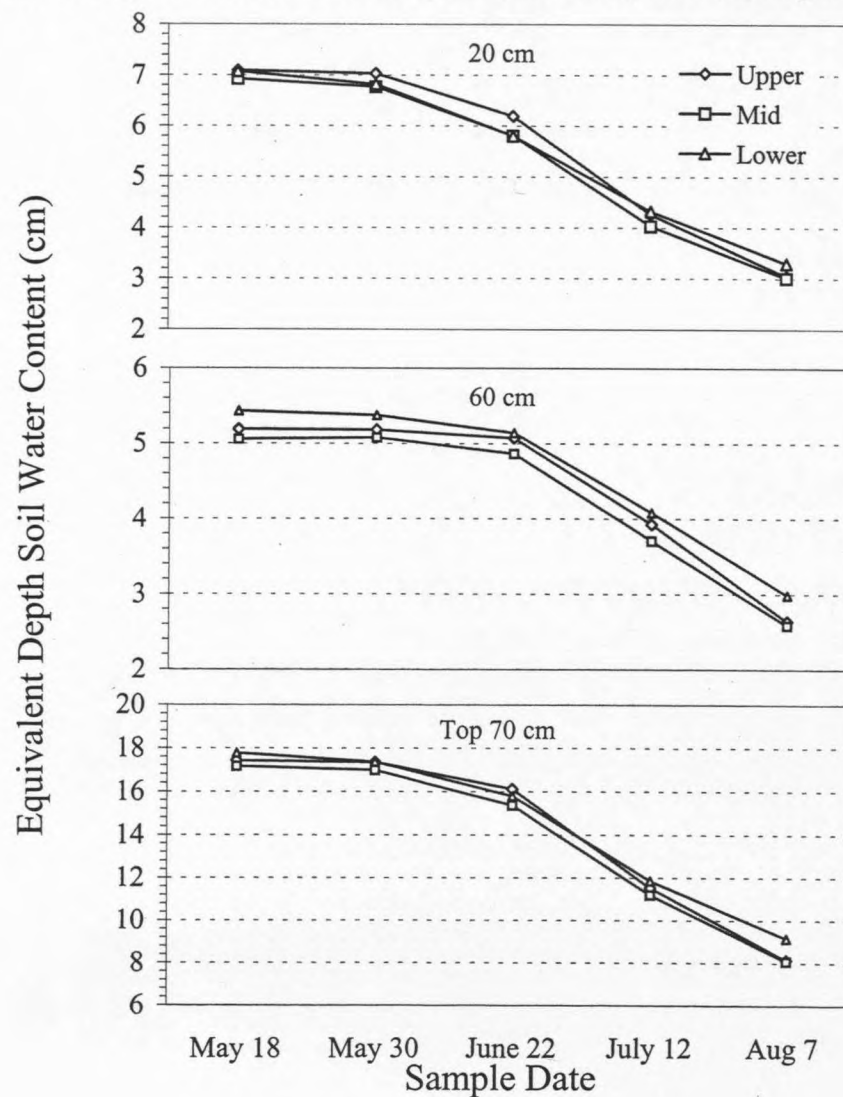


Figure 9. Mean soil water content expressed as equivalent depth of water for three measurement depths, for sample locations allocated within regions delineated at the Liberty site using the Cluster partitioning method.



Hill Site. Observed patterns in region mean soil water content were similar between the three partitioning methods at all depths at Hill (Fig. 10, 11). Increased soil water contents between July 20 and August 2 resulting from precipitation during July (Fig. 6) were evident for all regions at all depths. At the end of the growing season (August 2) at all depths, significant differences in mean soil water content were exhibited between regions in all partitioning methods (Table 4).

For the Flow partitioning method planar regions had the highest and divergent regions the lowest mean soil water contents at all depths (Fig. 10). Except for the beginning of the growing season (May 19) at 20 cm, planar and divergent region mean soil water contents were significantly different at all depths and dates (Table 4).

Soil-Landscape lower regions predominantly had the highest mean soil water content throughout the growing season at all depths for Hill (Fig.10). However, lower region mean soil water content differed significantly from other regions (mid and upper) only at the end of the growing season (August 2) (Table 4).

For the Cluster Method, lower regions predominantly had the highest soil water contents throughout the growing season at all depths. Except at 60 cm, Lower significantly differed from mid and upper on May 19 and August 2. At 60 cm depth, lower differed only from mid on August 2 (Table 4).

Figure 10. Mean soil water content expressed as equivalent depth of water for three measurement depths, for sample locations allocated within two different partitioning methods, at the Hill site.

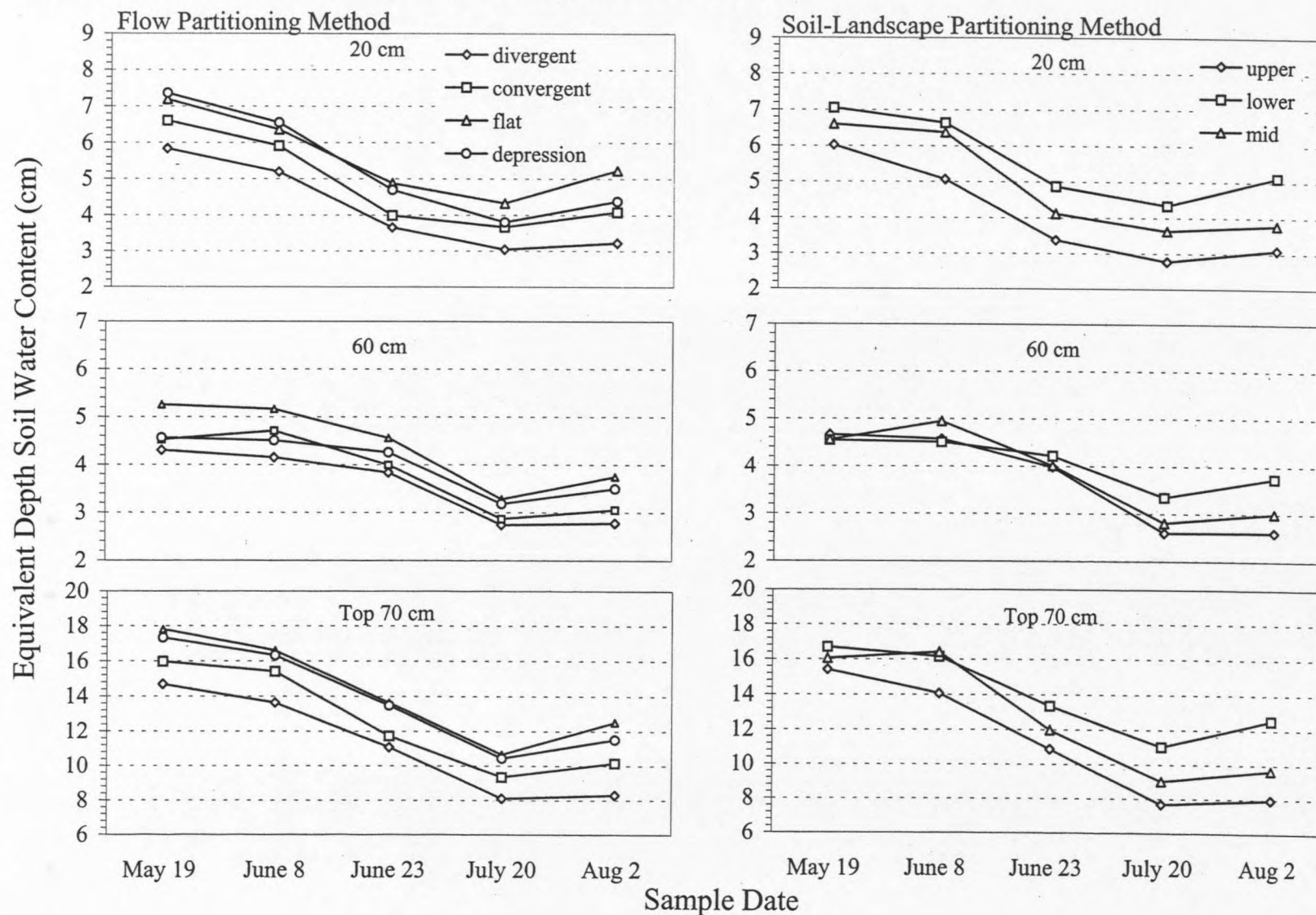


Figure 11. Mean soil water content expressed as equivalent depth of water for three measurement depths, for sample locations allocated within regions delineated at the Hill site using the Cluster partitioning method.

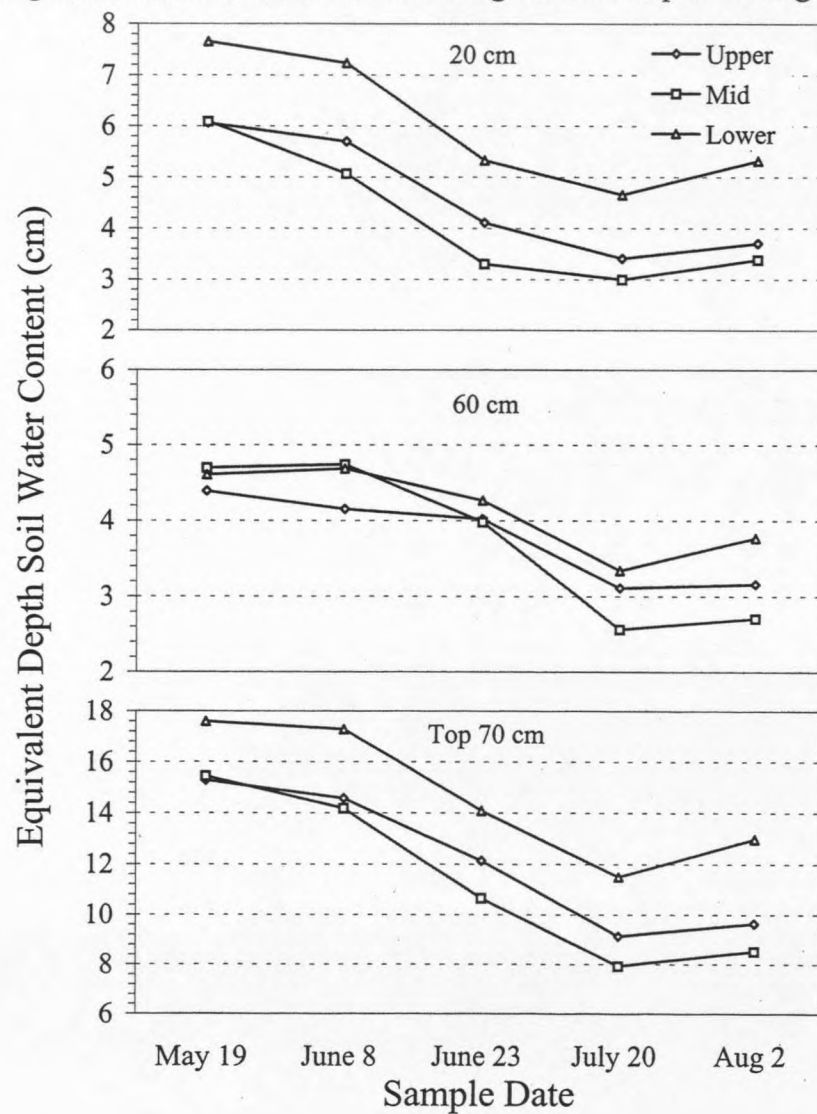


Table 4. ANOVA summary for region beginning and ending growing season soil water content means at Hill. Within rows, asterisk in p-value column highlights significance at 0.05 level, and region mean values followed by the same letter are different at the 5% significance level.

Depth	Date	P-value	Region means			
			Flow			
			Divergent	Convergent	Planar	Depression
20 cm	May 19	0.102	5.84	6.61	7.19	7.36
	Aug 2	0.010*	3.22a	4.09	5.23a	4.38
60 cm	May 19	0.080*	4.30a	4.53	5.25a	4.56
	Aug 2	0.072*	2.78a	3.06	3.75a	3.50
top 70 cm	May 19	0.042*	14.68a	15.98	17.80a	17.32
	Aug 2	0.008*	8.30a	10.18	12.52a	11.52
Soil-Landscape						
			Lower	Mid	Upper	
20 cm	May 19	0.153	7.06	6.60	6.02	
	Aug 2	0.001*	5.12ab	3.79a	3.09b	
60 cm	May 19	0.907	4.54	4.55	4.66	
	Aug 2	0.001*	3.75ab	3.00a	2.61b	
top 70 cm	May 19	0.417	16.69	16.10	15.41	
	Aug 2	0.001*	12.55ab	9.67a	7.96b	
Cluster						
			Lower	Mid	Upper	
20 cm	May 19	0.005*	7.65ab	6.09a	6.06b	
	Aug 2	0.001*	5.32ab	3.39a	3.71b	
60 cm	May 19	0.634	4.61	4.69	4.39	
	Aug 2	0.003*	3.77a	2.71a	3.16	
top 70 cm	May 19	0.044*	17.59ab	15.44a	15.28b	
	Aug 2	0.001*	12.98ab	8.53a	9.94b	

Phillips 1. At Phillips 1, soil water content patterns varied with depth for all three partitioning methods (Fig.12, 13). At 20 cm, soil water content increased for most regions between June 23 and July 13 due to precipitation (Fig. 6). However, there were no significant differences between regions for any method throughout the growing season at 20cm (Table 5).

At 60 cm, Flow Method depression regions had the highest and divergent regions the lowest soil water content throughout the growing season. Soil-Landscape and Cluster Method lower and upper regions exhibited the same pattern (Fig. 12, 13). Significant

differences in mean soil water content were evident on May 19 between regions for all partitioning methods, but only for the Cluster method on August 9. Lack of significant differences on August 9 is due to large variability in soil water content within regions.

Mean soil water contents in the top 70 cm were similar between regions for the Flow and Cluster methods through July 13 (Fig.12, 13). After this date, change in soil water storage varied between regions. Depressions differ significantly from divergent regions, and lower regions differ from mid and upper regions, on Aug 9 (Table 5). Soil-Landscape Method lower regions differed from upper regions only on May 19.

Table 5. ANOVA summary for region beginning and ending growing season soil water content means at Phillips 1. Within rows, asterisk in p-value column highlights significance at 0.05 level, and region mean values followed by the same letter are different at the 5% significance level.

Depth	Date	P-value	Region means			
			Flow			
			Divergent	Convergent	Planar	Depression
20 cm	May 19	0.662	7.69	7.73	7.90	8.04
	Aug 9	0.275	3.27	3.24	3.51	3.96
60 cm	May 19	0.025*	5.18ab	5.52a	5.31	5.83b
	Aug 9	0.096	2.76	2.99	2.85	3.63
top 70 cm	May 19	0.134	18.23	18.65	18.47	19.63
	Aug 9	0.049*	8.64a	9.15	8.90	10.63a
Soil-Landscape						
			Lower	Mid	Upper	
20 cm	May 19	0.087	7.62	7.96	7.58	
	Aug 9	0.403	3.19	3.49	3.26	
60 cm	May 19	0.002*	5.73a	5.31	5.13a	
	Aug 9	0.16	3.20	2.85	2.77	
top 70 cm	May 19	0.041*	18.94a	18.66	17.92a	
	Aug 9	0.313	9.31	9.07	8.60	
Cluster						
			Lower	Mid	Upper	
20 cm	May 19	0.901	7.71	7.79	7.78	
	Aug 9	0.838	3.42	3.29	3.32	
60 cm	May 19	0.010*	5.62a	5.31	5.13a	
	Aug 9	0.005*	3.27ab	2.84a	2.58b	
top 70 cm	May 19	0.347	18.80	18.45	18.22	
	Aug 9	0.006*	9.71ab	8.81a	8.35b	

Figure 12. Mean soil water content expressed as equivalent depth of water for three measurement depths, for sample locations allocated within two different partitioning methods, at the Phillips 1 site.

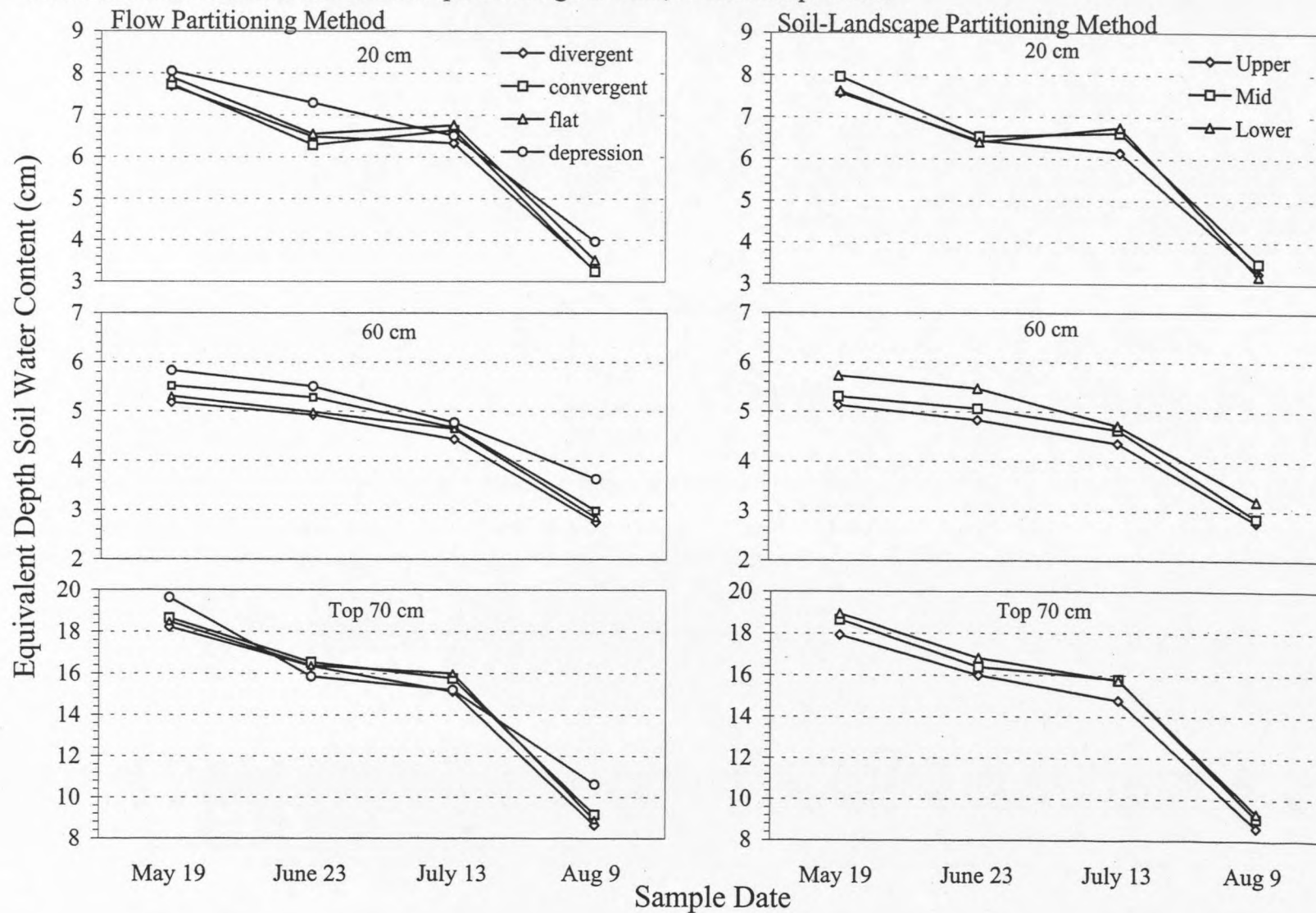
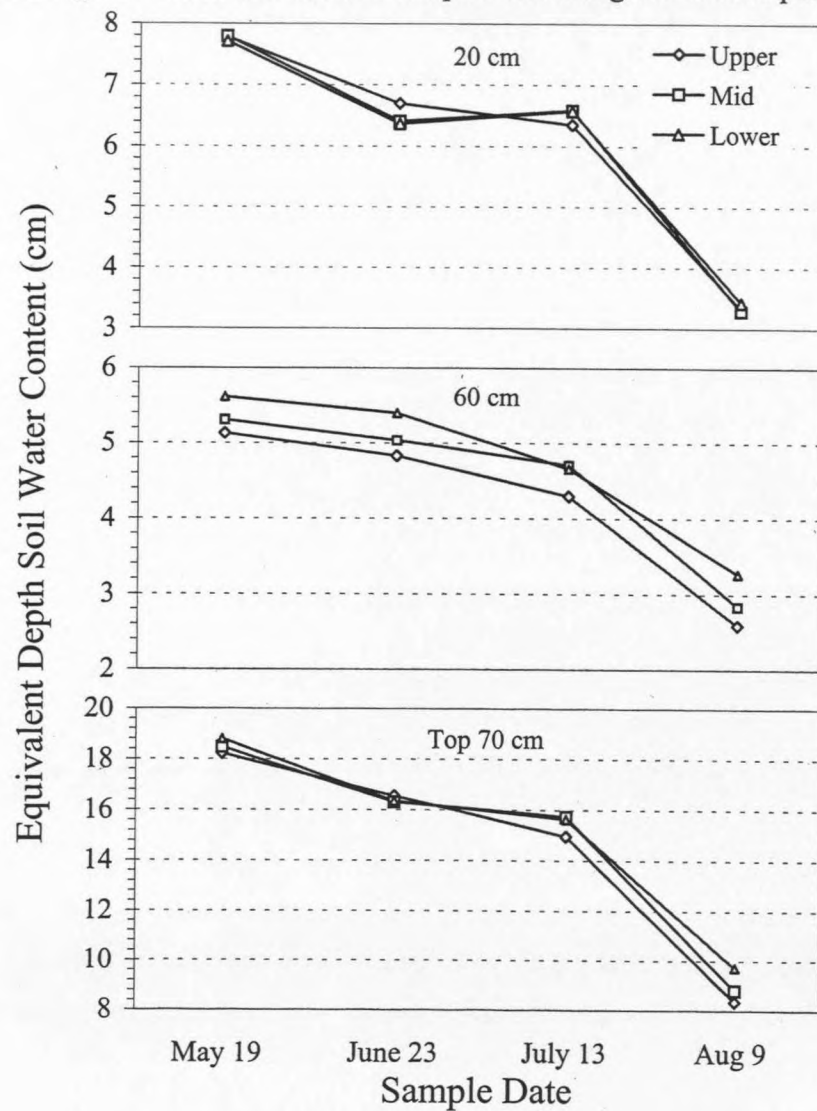


Figure 13. Mean soil water content expressed as equivalent depth of water for three measurement depths, for sample locations allocated within regions delineated at the Phillips 1 site using the Cluster partitioning method.



Phillips 2. Patterns in mean soil water content varied similarly with depth for the three partitioning methods (Fig. 14, 15). Mean soil water content increased in all regions at all depths on June 7 as a result of precipitation. Mean soil water content also increased in all regions at the 20 cm depth on August 1 due to precipitation. Significant differences between any regions at Phillips 2 were found only at 20 cm depth (Table 6).

At 20 cm, Flow Method divergent regions had the highest and convergent regions the lowest mean soil water content throughout the growing season. Similarly, Cluster Method upper regions had the highest and lower regions the lowest mean soil water content throughout the growing season. Significant differences in mean soil water content were exhibited between these respective regions on May 18 and on August 1. No significant differences were evident between Soil-Landscape regions.

Although no significant differences between mean soil water contents were present at a depth of 60 cm, there was an inversion in region soil water content relationships from the 20 cm depth. The regions that had the highest soil water contents at 20 cm depth (divergent and upper) had the lowest soil water contents at 60 cm depth. Conversely, regions that had the lowest soil water contents at 20 cm (convergent and lower) had the highest soil water contents at 60 cm depth.

Figure 14. Mean soil water content expressed as equivalent depth of water for three measurement depths, for sample locations allocated within two different partitioning methods, at the Phillips 2 site.

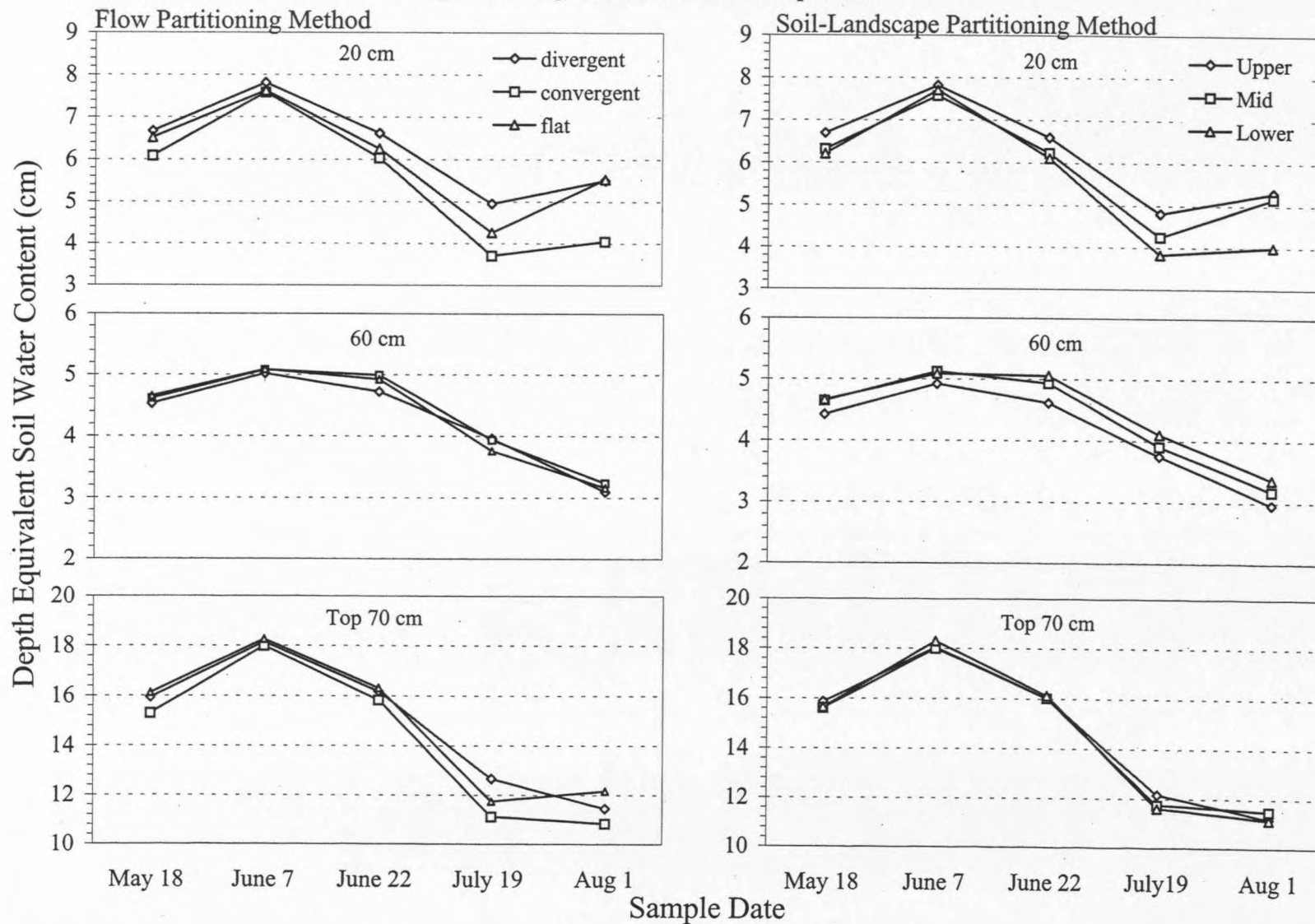


Figure 15. Mean soil water content expressed as equivalent depth of water for three measurement depths, for sample locations allocated within regions delineated at the Phillips 2 site using the Cluster partitioning method.

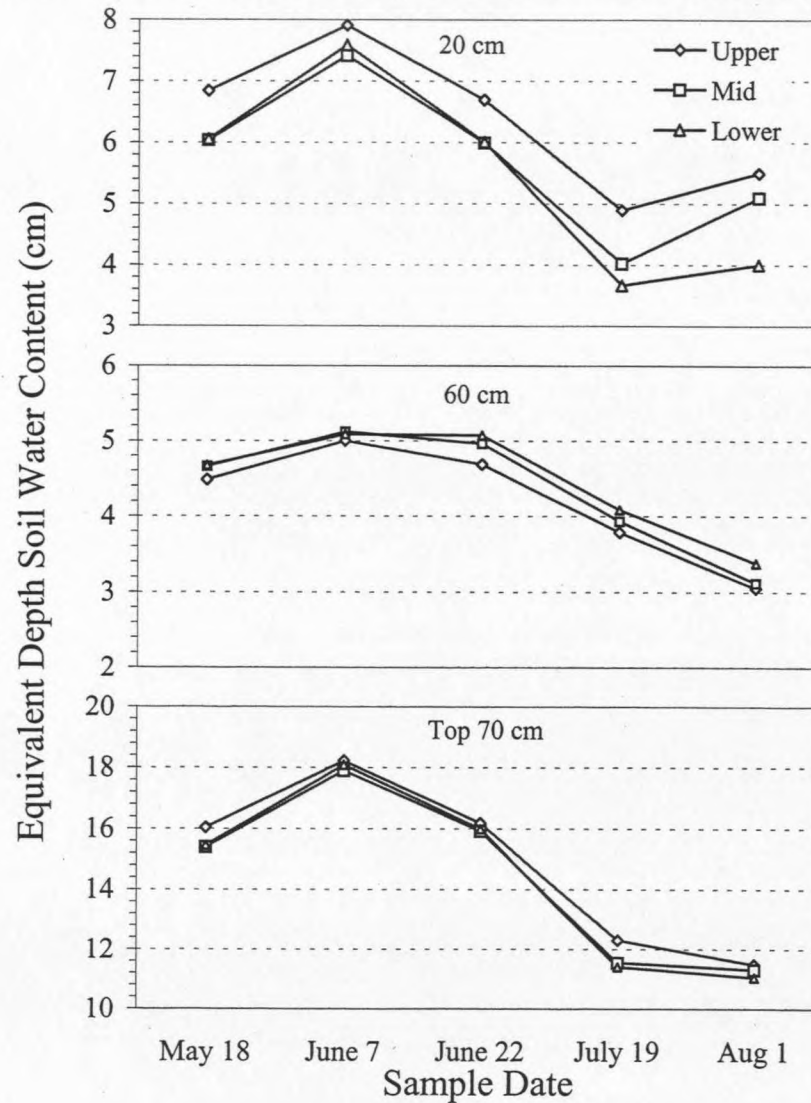


Table 6. ANOVA summary for region beginning and ending growing season soil water content means at Phillips 2. Within rows, asterisk in p-value column highlights significance at 0.05 level, and region mean values followed by the same letter are different at the 5% significance level.

Depth	Date	P-value	Region means		
			Flow		
			Divergent	Convergent	Planar
20 cm	May 18	0.021*	6.67a	6.09a	6.51
	Aug 1	0.028*	5.47a	4.18ab	5.53b
60 cm	May 18	0.824	4.53	4.61	4.65
	Aug 1	0.828	3.09	3.23	3.16
top 70 cm	May 18	0.206	15.94	15.3	16.13
	Aug 1	0.241	11.45	10.84	12.17
Soil-Landscape					
			Lower	Mid	Upper
20 cm	May 18	0.148	6.20	6.31	6.69
	Aug 1	0.196	4.58	5.17	5.20
60 cm	May 18	0.421	4.66	4.65	4.42
	Aug 1	0.337	3.37	3.18	2.96
top 70 cm	May 18	0.863	15.65	15.62	15.87
	Aug 1	0.850	11.14	11.50	11.18
Cluster					
			Lower	Mid	Upper
20 cm	May 18	0.001*	6.06a	6.04b	6.84ab
	Aug 1	0.043*	4.17a	5.09	5.42a
60 cm	May 18	0.512	4.67	4.66	4.48
	Aug 1	0.382	3.38	3.12	3.05
top 70 cm	May 18	0.301	15.46	15.40	16.05
	Aug 1	0.820	11.05	11.31	11.49

Region Partitioning Method Performance Across Sites

The effectiveness of the region-partitioning methods used to identify and delineate spatial variability in soil water content across multiple fields is important in terms of their potential practical utility in farm or land management. Performance of the Flow, Soil-Landscape, and Cluster partitioning methods at the four study sites is summarized in Table 7, which includes only time of the season and depths where at least one partitioning method had at least two topographic regions that were significantly different in measured mean soil water content.

Of the three methods, Flow most frequently had significant differences in region mean soil water contents (Table 7). In addition, differences in soil water contents between Flow Method regions occurred at all study sites, in contrast to the Soil-Landscape and Cluster Methods. However, for every method, the specific regions that exhibited significant differences from each other varied from site to site (Tables 3-6). For example, significant differences between Flow Method regions were exhibited at 20 cm at both Hill and Phillips 2 (Table 7). While at Hill divergent regions differed from planar regions, at Phillips 2 divergent regions did not differ from planar regions, but rather from convergent regions. This illustrates that no method uniformly delineated differences in soil water content across all sites.

Table 7. Region partitioning method performance at each field location. Only listed are those depths where significant differences in mean soil water content between regions were evident for at least one partitioning method. Asterisk indicates ANOVA significant difference between regions for that partitioning method at $p < 0.05$.

Site	Depth	Date	Partitioning Scheme		
			Flow	Soil/landscape	Cluster
Liberty	60 cm	May 18	*	*	
		Aug 8	*	*	
	Top 70 cm	Aug 8	*	*	
Hill	20 cm	May 19			*
		Aug 2	*	*	*
	60 cm	May 19	*		
		Aug 2	*	*	*
	Top 70 cm	May 19	*		*
		Aug 2	*	*	*
Philips 1	60 cm	May 19	*	*	*
		Aug 9			*
	Top 70 cm	May 19	*	*	
		Aug 9	*		*
Philips 2	20 cm	May 18	*		*
		Aug 1	*		*

Reduction of Soil Water Variance Through Region Partitioning

The percent reduction in field-wide measured soil water content variance by delineating discrete regions is shown in Table 8. Across all four fields the largest value of relative variance was 21% for the Cluster method at the Hill site. This means that soil water content variability was 21% less in Cluster regions than across the entire site. The majority of relative variance values were between 5% and 13%, indicating that overall study-site, field-wide variability in measured soil water content was reduced only 5% to 13% by identification of discrete field regions.

At Liberty, the Flow method was most precise in delineating regions, with relative variances of 8% to 15%. The Cluster method was generally more precise than the Flow or Soil-Landscape methods, which did not differ significantly, at Hill and Phillips 1. At Phillips 2, all methods performed similarly, with relative variance values of 4% to 7%.

Table 8. Percent reduction in field-wide measured soil water content variance by delineating regions through each of the partitioning methods. Only dates and depths shown are those with significant difference in soil water content between at least two regions.

Site	Depth	Date	Partitioning Scheme		
			Flow	Soil/landscape	Cluster
Liberty	60 cm	May 18	8	5	4
		Aug 8	15	5	5
	Top 70 cm	Aug 8	10	5	5
Hill	20 cm	May 19	5	8	11
		Aug 2	11	11	19
	60 cm	May 19	5	4	4
		Aug 2	5	5	12
	Top 70 cm	May 19	7	6	5
		Aug 2	11	13	21
Phillips 1	60 cm	May 19	8	13	10
		Aug 9	5	5	11
	Top 70 cm	May 19	5	6	6
		Aug 9	7	3	11
Phillips 2	20 cm	May 18	7	4	5
		Aug 1	6	4	6

Discussion

Measured Soil Water Contents

The general lack of variability in soil water contents early in the growing season at all sites and depths indicates that little topographical redistribution of water had occurred during the previous two years when these fields were in fallow. Precipitation must be received at a rate higher than the potential final infiltration rate of the soil, for a sufficient period of time, for ponding and overland flow to occur (Or and Wraith, 2000). There were no visual indications of lateral flow across the soil surface (e.g. rills) prior to the 2000 or 2001 growing seasons.

Increased variability in soil water status at the end of the growing seasons might be indicative of topographical re-distribution of water in response to growing season precipitation. Alternatively, spatial differences in clay contents and their effects on soil water retention may have exerted primary influence as soils dried throughout the growing season. Plant water uptake may also have varied spatially, in part as a result of variation in soil water retention, but also because evaporative water demand probably varied with topography because of differences in microclimatic conditions (Campbell and Norman, 1998). A potential role of the wheat crop is supported by the reduction in spatial differences in soil water content with depth at the end of the growing seasons. Plants may not have been able to extract water from 60 cm depth as efficiently as from 20 cm, because of expected lower root densities and ability of higher clay contents at 60 cm to retain water at low matric potentials.

Topographic Region Soil Water Dynamics

The results of this study suggest that region partitioning may have some potential to delineate variability in soil water content within agricultural fields in North Central Montana. However, none of the methods consistently identified variability across all four field sites, indicating that routine use of any one method may not be feasible. When differences in soil water content between regions were identified at multiple sites using the same region partitioning method, patterns varied between the topographic regions from field to field. Additionally, some ANOVA results were not intuitive in that they were inconsistent with expected relationships between topography and soil water distribution.

Across sites, when field-scale spatial variability in soil water content was low, differences in soil water content between partitioned regions only sometimes were evident. This suggests that the nature of soil water spatial organization may have varied when overall soil water variability was low. Region partitioning more readily delineates soil water variability when spatial organization is high, rather than when it is scattered and random (Western et al., 1999). In all cases when measured soil water variability was moderate, significant differences were identified between some topographic regions.

The question remains whether the terrain models can be routinely applied across many landscapes, land uses, and climatic regimes or seasons. Topography has been demonstrated to play an important role in the distribution of soil water in many cases (Barling et al., 1994). However, soil properties such as soil water retention and hydraulic conductivity relationships (Or and Wraith, 2000) also play a crucial role in saturated and

unsaturated water flow, and can therefore modify topographic influence. As these soil properties vary across space, then, processes such as terrain-driven redistribution of soil water may vary (Kachanoski, 1992).

Precipitation and Soil Property Influences. It seems likely that precipitation patterns may influence the relative degree of control exerted over soil water status by terrain and soils. During wet years, or as soil water status locally approaches or exceeds the gravitational water holding capacity, the terrain component may directly influence soil water distribution based on hillslope hydrologic processes related to land surface form (Grayson et al., 1997; Western et al., 1999). When precipitation is less abundant and when soils are drier, soil properties might hold primary influence and inhibit topographical control of soil water redistribution (Yeh and Eltahir, 1998). The growing seasons of 2000 and 2001 were substantially drier than normal at the four sites used in this study (Table 2). There was no visual indication of surface lateral flow during the growing seasons at any of our sites. Therefore, differences in soil water content between the delineated topographic regions at my study sites likely were the result of spatial variability in soils rather than in topography.

Soil water retention and water flow are related to pore size distribution under relatively wet conditions (matric potentials greater than about -0.1 Mpa), and to the smaller pore sizes as well as to the area of solid surfaces as soils dry (matric potentials less than about -0.1 Mpa) (Or and Wraith, 2000). Silty and sandy soil textures facilitate vertical infiltration of water (Philip, 1969; Stephens, 1995; Hillel, 1998). Smaller particle size and high soil surface areas associated with clayey soils promote retention of soil

water through adsorption and capillarity (Or and Wraith, 2000). Presence of calcium carbonates in soil profiles, while not impeding vertical infiltration of water, indicates that over many years high vertical infiltration rates of water generally may not have occurred past depths at which they are found (Brady and Weil, 1999).

At Hill, overall spatial variability of soil water and soil properties was greatest of all the sites. Unlike the other sites, predominant landscape features were mapped as different soil series. Cluster Method lower regions and Flow Method planar regions, which coincided spatially with soil map unit 331B, consistently had the highest soil water contents at all depths. Heavy clays in the top 70 cm associated with these soils may have acted to retain soil water. Alternatively, upper and divergent regions coincided with soil map unit 701D, and had lower measured soil water contents. The high sand content in these soils may have allowed precipitation received prior to our study to redistribute more evenly within the soil profile, or to infiltrate to depths greater than that to which we measured.

Soil properties may have also had predominant influence on soil water distribution at Phillips 2. At 20 cm depth an unexpected pattern was observed, with conceptually water-shedding divergent and upper regions having the highest soil water contents throughout the growing season, and 'water-collecting' convergent and lower regions having the lowest soil water contents. These patterns were reversed at the 60 cm depth, perhaps reflecting long-term subsurface lateral flow due to topography. Differential crop uptake of water may also have contributed to these patterns. However, differences in depth to clay between regions offer a likely explanation. Shallower depth to clay in convex, upper landscape areas than in concave, lower landscape areas may be

expected, particularly if erosive loss of upper soil horizons in upper areas and deposition in lower areas has occurred (Walker et al., 1968; Kreznor, et al., 1989; Moore et al., 1993; Gessler et al., 1995). At Phillips 1 and 2, sampling revealed that clay content was higher near the soil surface in the upper landscape positions than in lower landscape positions. Presence of calcium carbonates at 20 cm depth in upper areas further suggests that water would accumulate nearer the surface. For the lower regions having greater depth to clay, soil water would be expected to drain to deeper depth more readily and thus to accumulate deeper in the profile, consistent with measured patterns (Fig. 14, 15).

At Phillips 1, soil water content patterns at 60 cm depth between the delineated regions were similar to Phillips 2. In contrast to conditions at Phillips 2, however, near surface (20 cm) soil water content for Phillips 1 showed no differences between the topographic regions. This may have been because precipitation during the 2000 growing season was lower than for 2001 (Fig. 6, Table 2), reducing soil water recharge. Similar trends in soil water content and precipitation were present at Liberty, which shared general similarity in soil textures with the Phillips 1 and Phillips 2 sites.

Although terrain-based region-partitioning methods demonstrated some success in delineating soil water variability in this study, this did not appear to be a result of modeling direct terrain influences on surface and subsurface lateral water flow. However, variability in soil properties across landscapes is partially a function of topography (Moore et al., 1993; Brady and Weil, 1999). For drier regions or during periods of low precipitation, terrain might thereby exert only an indirect influence over soil water distribution through its effects on soil property (i.e. texture) distribution. Further complicating this relationship, terrain form can be influenced by myriad types of

erosional and depositional processes (i.e. colluvium, wind, glacial) (Keck, 2002).

Differences in terrain forming factors can therefore have substantial impact on soil properties and water transport characteristics of a hillslope. This was evident in the differences in soil characteristics at similar landscape positions between Hill and the other sites.

Sampling and Measured Differences in Soil Wetness. To represent soil water status over my relatively large field study sites, soil water measurement locations were spaced at a minimum of 70 meters. Whether this resulted in loss of important information regarding spatial properties of soil water status at smaller scales is not known. Secondly, boundaries between soil-landscape regions may be fuzzy transition zones (Bruin and Stein, 1998). Therefore, it may be arbitrary to assign a location within a transition zone to any soil-landscape region (Bruin and Stein, 1998). The region-partitioning method assumes that regions are internally homogenous units separated by discrete boundaries. Soil water measurements taken within a transition zone but assigned to a particular region would result in increased apparent soil water variability for that region.

Magnitudes of statistically significant differences in soil water content between regions were relatively small. The maximum difference of 3 cm water per 70 cm soil depth found at Hill translates to 25% of the total water in the profile at the end of the growing season, but this was not the norm across all fields, which generally had substantially smaller relative differences. Further, this 3 cm water might translate into a wheat yield difference of about 4.5 bushels per acre (Bauder et al., 1987), and probably only if the difference was present early in the growing season. The low relative variance

values also suggested that soil water content variability was not much lower within regions than across the study sites. Given the fairly low overall variability at each of the sites it is not surprising that statistically reducing the variance might be difficult.

Further Application of Topographic Region-Partitioning. Whether the regional relationships elucidated in this study might hold for the same fields during years of normal rainfall, or for different soil types under similar weather patterns, is not known. However, even during years having more typical rainfall patterns, similar results may be expected because of the semi-arid climate in this area. Based on results of this study, topographic region partitioning might be expected to become useful in an agricultural management context only under conditions of moderate to high field-wide soil water content variability, such as may be expected under higher rainfall.

Further, terrain-based models should be effective for prediction of soil water distribution only if inherent model assumptions, primarily concerning homogeneity of soil properties such as texture across landscapes, are met for a particular system. Landon (1995) reached a similar conclusion based on a lack of correlation between terrain and soil water in deep, well-drained silty soils near Bozeman, MT. Because factors that affect soil water distribution vary across space and time, any region-partitioning method may have variable utility from field to field or from year to year. For example, Nolan et al. (2000) found that correlations between crop yield and several various terrain-based region partitioning methods varied from year to year in Canada.

Conclusions

An attempt was made to identify and delineate variability in soil water content within four farm fields in north central Montana through partitioning the fields into discrete regions based on topographic position. Although some differences in soil water content were found between the regions, their small magnitude and lack of consistency infer questionable significance in terms of practical application to field management.

Due to apparent minimal lateral redistribution of soil water under the field conditions studied (low precipitation, well-developed soils), differences in water content between regions may have been influenced more by soil properties and plant uptake of soil water across the field that varied with terrain, rather than by direct terrain influences. Variation in the nature of how soil water contents differed between regions, across fields, and with soil depth supports this speculation.

Under conditions not found in this study (i.e. higher precipitation), region partitioning approaches may provide a potentially effective option for delineation of soil water spatial variability, and subsequently agricultural management zones, across farm field landscapes. However, these techniques will only be beneficial if they can accurately model the systems to which they are being applied. Therefore, integration of site-specific information regarding soils and other factors with terrain models should be pursued in order to increase efficacy of terrain-based region partitioning methods. Soil texture, particularly clay content, presence and depth of impeding layers in the soil profile, and precipitation patterns may be important factors to consider.

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CHAPTER 3

COMPARISON OF MEASURED SOIL WATER CONTENT AND A QUANTITATIVE COMPOUND TOPOGRAPHIC INDEX DERIVED FROM A DEM

Introduction

Quantitative models that relate terrain to soil properties have been developed by many researchers (e.g., Burt and Butcher, 1985; Moore et al., 1993, 1993b; Odeh et al., 1994; Gessler et al., 1995, 1998, 2000). Based on consideration of topographic control on hydrological processes, numerous studies have maintained that topography is a primary influence on soil water spatial distribution and variability through its effect on surface runoff and subsurface water flow (Anderson and Burt, 1978; Hanna et al., 1982; Burt and Butcher, 1985; Moore et al., 1993; Western et al., 1999). Terrain attributes can provide a quantification of landform shape and connectivity that can help define water flow patterns, and subsequent soil water distribution (Gessler et al., 2000).

The compound topographic index (CTI), or steady-state wetness index, is a quantitative, process-based secondary terrain attribute that has been used to capture spatial distribution and variability of select soil properties (Burt and Butcher, 1985; Moore et al., 1993c; Odeh et al., 1994; Barling et al., 1994) and of soil water content (Burt and Butcher, 1985; Jones, 1986; Moore et al., 1993b).

CTI incorporates two primary topographic attributes, specific catchment area and slope, that are integral to soil water flow and accumulation. CTI is defined as

$$CTI = \ln (A_s / \tan \beta)$$

where A_s is specific catchment area ($m^2 m^{-1}$), and β is slope (degrees). CTI values are relative to the area encompassed by the DEM, and increase with increasing catchment area and/or decreasing slope. According to this method, locations lower in the catchment or landscape, and particularly those nearest the outlet of drainage-ways, will be the wettest. The CTI specifies that soil water content will decrease as flow lines are re-traced upslope (Barling et al., 1994).

Five implicit assumptions are inherent in the derivation of the CTI: 1) uniform infiltration capacity across the catchment; 2) uniform drainage losses to groundwater; 3) uniform soil transmissivity; 4) direction of subsurface flow, dictated by the gradient of the piezometric head, is parallel to surface topography; and 5) steady-state conditions apply (i.e. every spatial point in the landscape is receiving flow from its entire upslope contributing area) (Jones, 1986). The applications of CTI in situations where these assumptions are violated weaken its capability as a predictor of soil water content. When assumptions are violated, Barling et al. (1994) stated that "the distribution of soil water becomes a balance between the topography and the soil water potential, and simple indices may not be applicable".

The hydrologic processes addressed in assumptions 1 - 4 are affected to some extent by soil properties such as texture and structure, and by soil profile depth (Moore et al., 1993b). As spatial variability in soil properties increases, the assumption of spatial

uniformity in these processes becomes increasingly problematic. Further, locations across a landscape that have similar CTI values may behave differently because of their landscape position (MacMillan et al., 2000). For example, a DEM grid cell with a moderate CTI value located in a convex area lower in the landscape may have shallower and perhaps coarser soils than a cell having similar CTI and located in a linear area higher in the landscape. Because CTI does not consider the nature of topography contained within area A_s (specific catchment area), it may not provide adequate prediction of soil water content (Burt and Butcher, 1986).

Provision of information regarding landscape position into CTI-based soil water content correlation models could help better identify how CTI and soil water content correlations vary across a field. The objective of this study was to test whether the secondary quantitative compound topographic index (CTI) was correlated to measured soil water content in agricultural fields typical of those found in north-central Montana, USA. To evaluate differences in correlation between and within fields, sites and landscape regions were incorporated into the analysis as covariate predictor variables.

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" 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-south-easterly 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, this site commonly receives lower amounts of annual precipitation, possibly due to its location in a rain shadow to the south east of the Sweetgrass Hills (Mattson, 2000). The field was dryland farmed by the Mattson family with a 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, superactive, frigid Aridic Argiustoll) formed on till, and Hillon loams (fine-loamy, mixed, calcareous, superactive, 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 rainfall of 31 to 43 cm (Caprio et al., 1994). The field was dryland farmed by the Kaercher family with a 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, smectitic, frigid Aridic HaplustalFs) and Elloam clay loams (fine, smectitic, 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, superactive, frigid Aridic Argiustoll), and the Hillon loams (fine-loamy, mixed, calcareous, superactive, 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 using a wheat/fallow rotation. The Phillips location is approximately 22.5 km east of Malta, MT (T31N, R32E, Section 20; 48°25'30" 107°35'30") (Fig. 1). One site, "Phillips 1", incorporated 25 ha and was sampled during 2000. The second site, "Phillips 2", incorporated 12 ha of the field and was sampled in 2001. This site has moderate relief (~30m) with uneven rolling topography and occasional severe undulations (Fig. 3). The area has a cool, semi-arid climate with mean annual rainfall 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, superactive, frigid Aridic Argiustoll), formed on till plains, hills, and moraines (National Soil Survey Staff, 1998e; 1998f).

GPS Survey and Soil Water Sample Grid

Field elevations were collected over each study site in the fall of 2000 (Liberty and Phillips) and in the fall of 2001 (Hill). A Novatel model 3151R GPS receiver (24-channel, single-frequency, L1 carrier phase) was mounted on an all-terrain vehicle and measured elevation at roughly 10-m intervals along a series of parallel transects. A second Novatel receiver was located at a base station in the same field. The raw elevation measurements were corrected in the laboratory with the commercial post-processing software GravNav (Waypoint Consulting, Inc. Calgary, Alberta, Canada) to a positional accuracy of within ± 4 -cm in both the horizontal and vertical planes, relative to the location of the base station. An Ashtech AgNavigator consisting of a 486 computer, light-bar, and navigation-grade GPS receiver (12 channel, L1 C/A code) was used to provide guidance along the parallel transects within ± 1 -m of positional accuracy.

A permanent, augmented sampling grid of 78 to 80 points was established in each field for the purpose of measuring soil water content (Fig. 4, 5). Of these, 50 to 65 equally spaced sample points were established in an offset grid-like pattern. The GPS system was used to develop the grid and to mark the points in each field. An additional 15 to 30 points were added to augment the grid, in order to adequately represent the range of soils and terrain features (e.g. areas of convergence and divergence) across the study site. The combination of grid points and augment points in each field was based on field area and visual estimation of its topographic variability. To insure adequate coverage, the larger plots included more points in the offset grid.

At each sample point a PVC access tube was installed to 80 cm depth to measure soil water content with a neutron moisture meter (Model 503DR, CPN, Martinez, CA).

Following access tube installation the locations and elevations of each sample point were resurveyed using the GPS.

Generation of Terrain Attributes

The GPS elevation data for the four study sites were converted to square, equally spaced 10 m DEM grids using Surfer software (Golden Software, Inc., Golden, CO 80401). Geostatistical kriging methods were used in Surfer to act as smoothing interpolators of irregularly spaced point data. This procedure eliminated presence of vertical elevation bands in the 5 m DEM grids created from irregularly sampled point data spaced 10 m apart. The smoothed XYZ data contained at each grid node in the Surfer grid was input into the interpolation software package ANUDEM (Hutchinson, 1989) and converted to square, regularly spaced 5 m grids. The interpolated 5 m elevation lattice data were imported into the grid version of the Terrain Analysis Program for the Environmental Sciences (TAPES) program (Moore, 1992; Gallant and Wilson, 1996). TAPES generated 14 primary terrain attributes for each of the 25 m² DEM cells. Two of the 14 primary terrain attributes, slope and specific catchment area (SCA), were used in this study. CTI was calculated for each cell based on these values.

The TAPES default mode is for a depressionless DEM. However, depressions may naturally occur and they behave uniquely in terms of soil water content at the scale at which we were modeling, so the default feature was disabled. Slope was calculated using the finite differences (FD option) approach. The FRho8 algorithm was used to calculate SCA in this study because it allowed flow in upland cells to be distributed simultaneously to multiple surrounding cells on a slope-weighted basis. This allowed for

distributed water flow, rather than routing of water based on defined stream channels. This was important because there were no defined stream channels in the study areas.

The terrain attributes calculated by TAPES were imported into ARC/INFO (Environmental Sciences Research Institute, Inc., Redlands, CA 92373) to create grids for use in ArcView Spatial Analyst v 3.2 (Environmental Sciences Research Institute, Inc.). Each study site's grid was overlain with the soil water sample point coordinates for that site. A get-grid function determined grid cells in which sample points were located. The terrain attributes for each cell containing a sample point were then extracted from the grid and linked with the data table for the soil water sample point coordinates.

Generation of Topographic Regions

The GPS elevations for each field were converted to 5 m DEM grids in ANUDEM as per the procedure previously described for creating terrain attributes. The interpolated 5 m elevations were imported into Arcview Spatial Analyst v3.2 as an ASCII file, converted into a grid, and then imported into the landscape analysis program LandMapR (MacMillan et al., 2000) to generate landscape classes. LandMapR defined 15 basic landform element classes, e.g. convergent backslope, toe-slope, etc., for every grid cell in the DEM using a fuzzy rule-based procedure. The converted landform element class data was extracted from LandMapR, imported into Arcview Spatial Analyst v3.2 as a table, and converted to a 5 m grid. A reclassify function was performed to group the 15 landform elements into fewer classes, hence increasing spatial coherence, using two different rule-based methods: one based on contextual landscape position, and one based on assumed soil variability as reflected in topography.

The first approach, termed the Flow method, was based on empirical concepts of surface water flow across landscapes. This approach created four classes: divergent (water shedding), convergent (water receiving), planar or flat (water neutral), and depressions, as outlined in MacMillan et al., 2000. The second grouping method, Soil-Landscape, was based on relative position in the landscape and topography as indicators of soil spatial patterns. Three generalized classes were created: upper, mid, and lower. Soil formation as a function of landscape, and resultant variability in soils across landscapes, are presumably represented by this approach.

Neutron moisture meter sample point coordinates for each site were overlain on the respective Flow and Soil-Landscape class grids. A get-grid function was performed in Arcview 3.2 to determine cells in which the sample points were located. Class information for each cell containing a sample point was assigned to the sample points.

Soil Water Content

Neutron moisture meter (Gardner, 1986) measurements were used to correlate CTI to soil water content at the four study sites. Water content was measured at 20 cm depth intervals to 80 cm. Calibration relationships for the neutron meters were developed at each study site. Measurements were obtained five times during a single growing season at each site. Some sample points were not monitored on specific dates due to equipment malfunction. The earliest measurement occurred immediately following seeding of the field. This was considered as an indication of soil water distribution with minimal vegetative influence, as the fields were fallowed the previous year. The last measurement

of the growing season was collected at harvest, and could be used to assess changes in soil water status as affected by growing season influences.

For all depths at all sample points at each measurement date, the equivalent depth of soil water (cm) was calculated as the product of measured volume water content ($\text{cm}^3 / \text{cm}^3$) and the corresponding measurement depth interval (cm). Thus, measurements at 20 cm were converted to equivalent depth of soil water in the top 30 cm of soil. Measurements at 40 cm, 60 cm, and 80 cm were converted to equivalent depth of soil water at the 30 - 50 cm, 50 - 70 cm, and 70 - 90 cm soil depth intervals, respectively. Total soil water to 70 cm depth of soil was also calculated by integrating the 20 cm, 40 cm, and 60 cm measurements. In addition, for all depths including the top 70 cm, a seasonal average soil water content was estimated using the five seasonal measurements.

Statistical Analysis

Tables 13 - 16 (Appendix A) present complete lists of calculated terrain attributes and class values for each field. These data files were linked with soil water measurements for each field and imported for regression analysis into S-Plus (Mathsoft, Seattle, WA 98109) as ASCII data files. Regression analyses at the 20 cm, 60 cm, and top 70 cm depths were performed for the first and last measurement dates, and for season average soil water contents, to determine if soil water content was correlated to CTI. These depths were considered as representative of field conditions.

Simple linear regression was performed to determine correlation between measured soil water content, the dependent variable, and CTI, the independent variable. An F-test with significance p-value of 0.05 was applied to this procedure. To

accommodate potential differences between study sites due to climate, soils, and other factors, study sites were included as independent, indicator variables in multiple linear regression analyses. Further, since we presumed that differences between topographic regions affected the correlation between CTI and soil water content, landscape regions were also used as independent, indicator predictor variables. Indicator variables and CTI parameters can be crossed, or interacted, to test for heterogeneity of slope in the model. The model regression equation for CTI with indicator and interaction variables was:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_1 X_2 + \beta_5 X_1 X_3 + \beta_6 X_2 X_3 + \ell_i$$

where Y is soil water content, X_1 is CTI, X_2, X_3 are region and study site indicator variables, respectively, and β are model coefficients. CTI is a quantitative value and indicator parameters are classificatory, qualitative values. The inclusion of the region, study site, and interaction was determined by a partial F-test evaluating significance in the full model, with $P = 0.05$ the criterion for inclusion of the parameters in the model. Plots of regression residuals were evaluated for possible trends in the data and for presence of outliers. Models that indicated lack of significance in the addition of region and/or interaction variables reverted to the simple regression analysis that tested correlation between CTI and soil water content.

Results

Soil Water Content and Precipitation

Mean soil water content values for each site for all measurement periods at three representative depths: 20 cm (0 – 30 cm depth interval), 60 cm (50 – 70 cm depth interval), and top 70 cm, illustrate similarity in soil water content from site to site (Table 9). Most depths at all sites exhibited low to moderately-low variance in soil water content as evidenced by the small coefficients of variation (CV) (0.09 – 0.29). However, Hill exhibited moderate variance at the end of the growing season at all depths. Phillips 2 exhibited moderate variability at the end of the growing season at 20 cm (CV = 0.48). Variance in soil water content was greater at the end of the growing season than at the beginning of the growing season at all depths for all sites.

Little precipitation occurred during the 2000 field season, and annual precipitation was below normal for both Liberty (43% of long-term average) and Phillips 1 (71%) (Chapter 2: Fig. 6, Table 2). Precipitation at Liberty occurred primarily during a single event that delivered less than 0.5 cm. Phillips 1 received most of its precipitation prior to July, and total seasonal rainfall was significantly greater than at Liberty (10.54 vs. 0.76 cm). Precipitation during 2001 was also below normal at Hill (61% of long-term average) and Phillips 2 (68%). Two separate growing season precipitation events of nearly 2.5 cm occurred at Phillips 2, one on June 4-6, and the second on August 1.

Table 9. Summary statistics for soil water content depth equivalent (cm) on the first and last measurement dates, and for season-average, for the four study sites.

Soil Depth									
----- 20 cm -----			----- 60 cm -----			----- Upper 70 cm -----			
Liberty									
	May 18	Aug 7	Avg	May18	Aug 7	Avg	May 18	Aug 7	Avg
n	79	77	71	79	78	70	79	77	71
Min	5.14	1.65	3.67	3.64	1.41	3.04	13.65	5.08	10.72
Max	8.55	5.34	7.24	7.85	4.56	5.98	22.40	13.72	18.51
Mean	7.11	3.09	5.43	5.19	2.69	4.40	17.38	8.34	14.05
S.D.	0.77	0.76	0.76	0.61	0.61	0.56	1.57	1.65	1.59
C.V.	0.11	0.25	0.14	0.12	0.23	0.13	0.09	0.20	0.11
Hill									
	May 19	Aug 2	Avg	May 19	Aug 2	Avg	May 19	Aug 2	Avg
n	78	77	78	78	77	77	78	77	77
Min	2.98	0.35	2.09	2.20	0.77	1.85	8.82	1.64	6.60
Max	11.56	11.27	10.55	7.46	6.08	5.95	24.52	23.28	22.76
Mean	6.56	4.05	4.79	4.59	3.14	3.81	16.05	9.84	11.74
S.D.	2.01	1.87	1.77	1.12	1.20	1.00	3.63	4.00	3.33
C.V.	0.31	0.46	0.37	0.24	0.38	0.38	0.23	0.41	0.28
Philips 1									
	May 19	Aug 9	Avg	May 19	Aug 9	Avg	May 19	Aug 9	Avg
n	78	77	70	77	75	68	77	75	69
Min	5.75	1.66	4.15	4.19	1.57	3.53	15.28	5.60	12.10
Max	9.91	6.17	8.30	6.73	4.90	6.12	23.28	14.16	19.27
Mean	7.76	3.35	6.05	5.37	2.91	4.46	18.52	8.99	14.74
S.D.	0.73	0.89	0.72	0.58	0.75	0.56	1.39	1.54	1.28
C.V.	0.09	0.27	0.12	0.11	0.26	0.13	0.08	0.17	0.09
Philips 2									
	May 18	Aug 1	Avg	May 18	Aug 1	Avg	May 18	Aug 1	Avg
n	81	81	81	81	81	81	81	81	81
Min	4.06	1.71	4.39	2.86	1.27	2.72	10.55	3.85	10.42
Max	7.87	7.38	7.71	6.29	5.64	6.21	20.02	16.44	18.51
Mean	6.39	5.02	5.94	4.59	3.17	4.32	15.70	11.31	14.60
S.D.	0.89	1.32	0.83	0.70	0.92	0.71	1.78	2.56	1.75
C.V.	0.14	0.48	0.14	0.15	0.29	0.16	0.11	0.23	0.12

Compound Topographic Index

The mean and minimum values for CTI at all sites were similar (Table 10).

Liberty had the largest CTI value, but the lowest standard deviation from the mean,

indicating that this large CTI value may be an outlier. The other three sites had similar

CTI maximum and standard deviation values. The coefficient of variation (CV), or relative measure of variability in the data, was similar for all sites and indicated that variability in CTI across all our study sites was low to moderate.

Table 10. Summary statistics for CTI for the four study sites. n = sample number, SD = standard deviation, CV = coefficient of variation.

	Liberty	Hill	Philips 1	Philips 2
n	79	78	78	81
Min	5.43	4.58	4.59	4.62
Max	14.51	12.75	13.20	11.18
Mean	7.42	7.15	7.28	7.08
S.D.	1.42	1.76	1.70	1.71
C.V.	0.19	0.25	0.23	0.24

Soil Water Content – CTI Parameter Relationships

Regression analyses that incorporated Flow regions as covariate predictors showed statistical significance between CTI and soil water at all depths and measurement periods ($p < 0.05$)(Table 11). At 20 cm, correlation between CTI and soil water content was stronger at the end of the growing season than at the beginning, and exhibited the greatest range in R^2 values throughout the growing season (adjusted $R^2 = 0.265$ and 0.402 for beginning and end, respectively). At 60 cm depths, the opposite effect was exhibited (adjusted $R^2 = 0.296$ and 0.216 for beginning and end, respectively).

Correlations were unchanged throughout the growing season in the top 70 cm (beginning adjusted $R^2 = 0.324$, ending adjusted $R^2 = 0.359$, season-average adjusted $R^2 = 0.342$).

Study sites were significant at all depths and dates ($p < 0.05$) with the exception of the end of the growing season at 60 cm ($p = 0.096$), and therefore included in the final regression model. This indicates soil water content – CTI relationships varied from site to

site. Significant CTI - study site interactions were present for 20 cm and for the upper 70 cm ($p < 0.05$). This indicates that the differential effect of CTI on soil water content from site to site varied based on the value of CTI. Significance of Flow regions only at 20 cm for early, late, and season-average ($p < 0.005$), and for the end of the growing season in the upper 70 cm ($p < 0.05$) indicates that within-field differences in CTI - soil water content relationships were restricted largely to the 20 cm depth.

Regressions that incorporated Soil-Landscape regions as a covariate had R^2 values that were generally lower than those obtained using Flow region variables (Table 12). However, correlation patterns between CTI and soil water content with respect to depth were similar. 20 cm depths exhibited greater soil water content - CTI correlation at the end of the growing season than at the beginning (adjusted $R^2 = 0.35$ and 0.229 , respectively). The opposite was exhibited at 60 cm (adjusted $R^2 = 0.149$ and 0.254). Correlations were again most consistent in the upper 70 cm.

Similar to results for Flow regions, study sites were significant at all depths and for all measurement periods ($p < 0.05$) except at 60 cm at the end of the growing season ($p = 0.405$). CTI - study site interactions were only significant at 20 cm, for the beginning of the growing season ($p = 0.02$) and end of the growing season ($p = 0.027$). Soil-Landscape regions were not significant at any depth with the exception of average soil water content in the upper 70 cm ($p = 0.038$). Therefore, no Soil-Landscape regions or region interaction parameters are included in the regression model, indicating that soil water content - CTI relationships did not vary among Soil-Landscape regions.

Table 12. Soil water content - CTI parameter relationships for study sites with Flow regions. Asterisk (with p-value) indicates indicator and or interaction term included in final model. Tables include adjusted coefficient of determination (R), overall model p-value, and mean square error (MSE). DF = degrees of freedom.

Depth	Measurement Period	Adjusted R ²	p-value, full model	MSE, overall	p-value, study site	p-value, region	p-value, CTI/site interaction	p-value, CTI/region interaction	p-value, site/region interaction	DF
20 cm	first	0.265	0.001	1.383	0.005*	0.043*	0.028*	0.06	0.482	293
	last	0.402	0.001	1.423	0.0001*	0.043*	0.0001*	0.012*	0.039*	287
	average	0.324	0.001	1.095	0.0001*	0.011*	0.002*	0.003*	0.051	277
60 cm	first	0.296	0.001	0.552	0.024*	0.526	0.209	0.484	0.019*	292
	last	0.216	0.02	0.704	0.096	0.127	0.07	0.087	0.208	288
	average	0.253	0.023	0.488	0.006*	0.923	0.062	0.756	0.015*	273
Top 70 cm	first	0.324	0.001	4.635	0.003*	0.492	0.025*	0.255	0.111	292
	last	0.359	0.001	5.649	0.0001*	0.028*	0.0001*	0.006*	0.035*	287
	average	0.342	0.001	3.95	0.0001*	0.139	0.002*	0.028*	0.02*	275

Table 13 . Soil water content - CTI parameter relationships for study sites with Soil-Landscape regions. Asterisk (with p-value) indicates indicator and or interaction term included in final model. Tables include adjusted coefficient of determination (R), overall model p-value, and mean square error (MSE). DF = degrees of freedom.

Depth	Measurement Period	Adjusted R ²	p-value, full model	MSE, overall	p-value, study site	p-value, region	p-value, CTI/site interaction	p-value, CTI/region interaction	p-value, site/region interaction	DF
20 cm	first	0.229	0.0001	1.425	0.001*	0.5	0.020*	0.505	0.732	298
	last	0.35	0.0001	1.521	0.0001*	0.262	0.027*	0.323	0.268	294
	average	0.285	0.0001	1.138	0.002*	0.17	0.135	0.165	0.068	282
60 cm	first	0.254	0.0001	0.575	0.024*	0.617	0.371	0.74	0.382	297
	last	0.149	0.023	0.75	0.405	0.96	0.633	0.976	0.976	293
	average	0.253	0.0031	0.517	0.007*	0.338	0.791	0.356	0.969	278
Top 70 cm	first	0.279	0.0001	4.859	0.027*	0.202	0.192	0.21	0.831	297
	last	0.282	0.0001	6.222	0.003*	0.741	0.069	0.836	0.65	292
	average	0.29	0.0001	4.187	0.005*	0.038*	0.187	0.061	0.228	280

Analysis of Best Fit Regression Model Scatterplots

Scatterplots of the best fits for two soil water – CTI regression model types, one with study sites and Flow regions included as covariate predictors and one with just study sites included as covariate predictors, facilitated analysis of differences in soil water content – CTI relationships between sites and topographic regions, as well as presence of trends between topographic regions across study sites.

Figures 16 and 17 illustrate predicted soil water content slopes when including study sites and Flow regions as covariate predictors at 20 cm depth at the end of the growing season (full model adjusted $R^2 = 0.402$, $p = 0.001$). Study site and region variables were both significant and included in the model ($p = 0.0001$ and 0.043 , respectively). Also, study site - CTI, region - CTI, and study site - region interaction terms were significant and included ($p < 0.05$), resulting in slope differences between regions and study sites.

For Liberty and Hill, predicted soil water-CTI slopes were positive in all regions with the exception of Liberty depressions, which had flat slope. Positive slopes indicate that as CTI increases so to does soil water content. Predicted soil water slopes for divergent, convergent, and planar regions at Phillips 1 were also positive, but less so than for Liberty and Hill. The predicted soil water slopes were negative for Phillips 1 depressions, and for all regions at Phillips 2 with the exception of planar.

Across all fields, relative differences between regions in slopes of predicted soil water content based on calculated CTI exhibited a similar pattern. The predicted slope was most positive at all sites for planar regions, suggesting that for a unit increase in CTI the largest increase in measured soil water content occurred in planar areas of the field.

Figure 16. Predicted soil water content – CTI relationships within Flow regions at Liberty and Hill for the last measurement date of the growing season, at 20 cm depth. Model includes interaction terms. Adjusted $R^2 = 0.402$, $p = 0.001$.

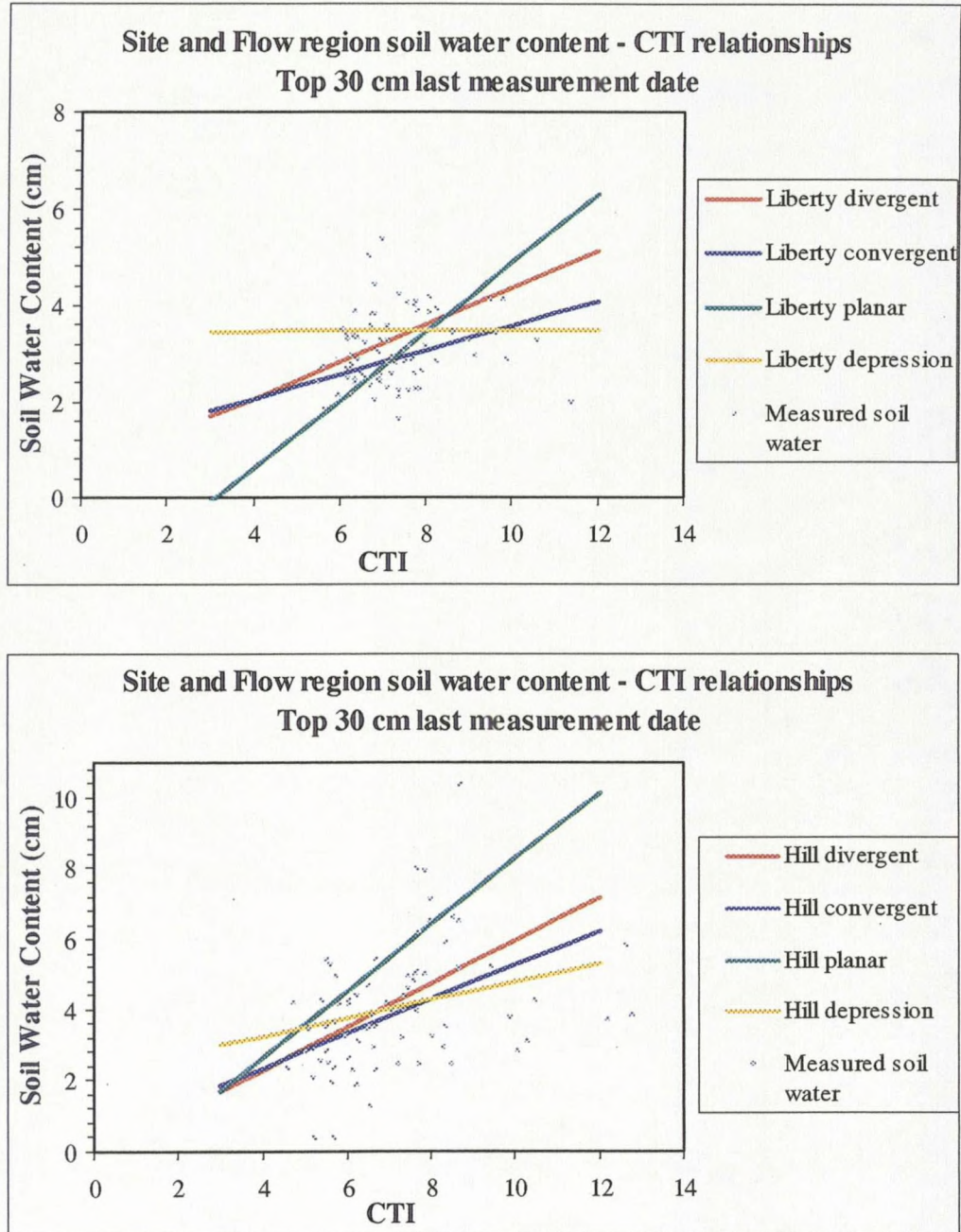
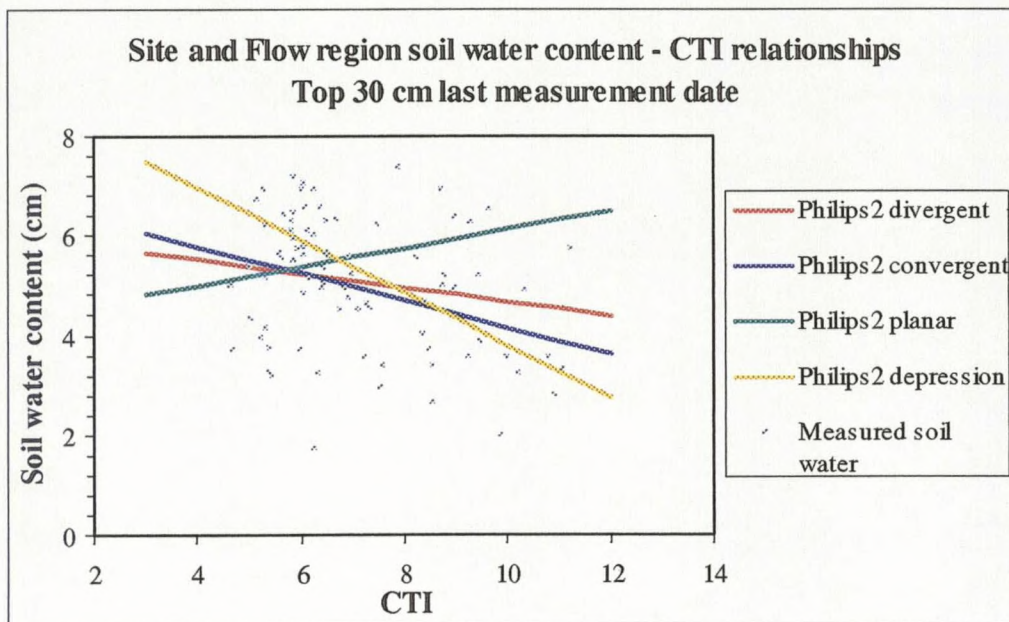
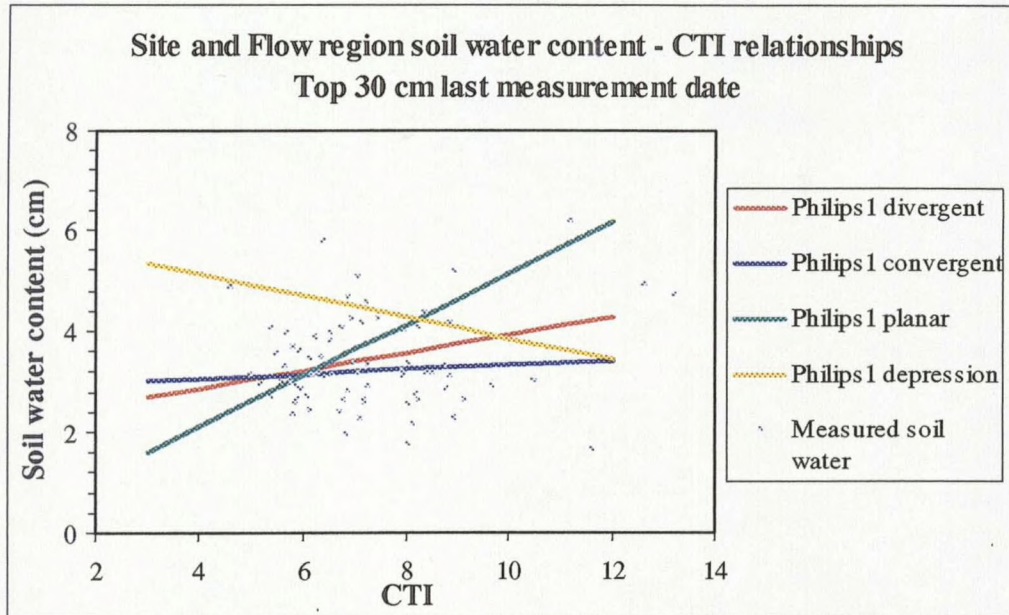


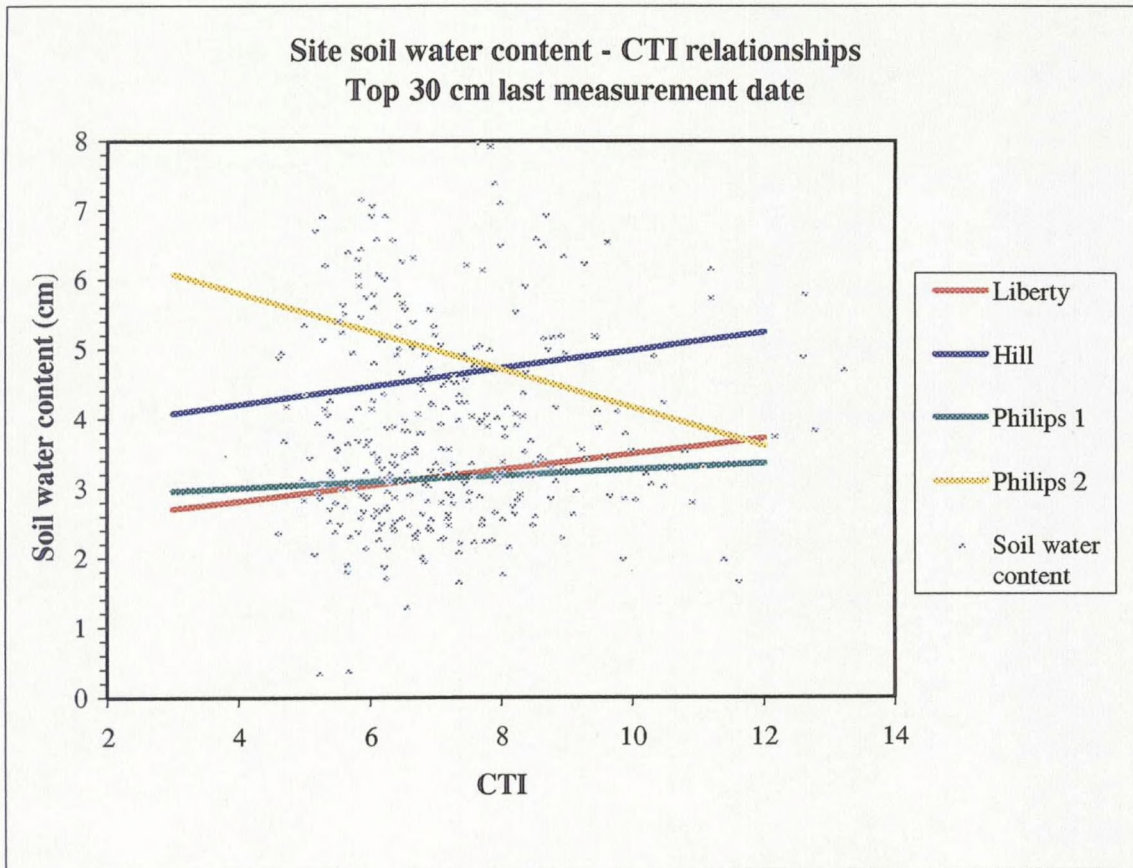
Figure 17. Predicted soil water content – CTI relationships within Flow regions Philips 1 and 2 for the last measurement date of the growing season, at 20 cm depth. Model includes interaction terms. Adjusted $R^2 = 0.402$, $p = 0.001$.



Predicted relationships then became increasingly flatter, or even negative, in order of divergent, convergent, and depression regions.

Figure 18 shows predicted soil water content slopes at 20 cm at the end of the growing season when including just study sites as a covariate predictor. This was the strongest relationship determined between CTI and soil water content when also attempting to include Soil-Landscape regions as a covariate predictor (adjusted $R^2 = 0.35$, $p = 0.0001$). The study site and study site - CTI interaction terms were significant and included in the model ($p = 0.0001$ and 0.027 , respectively). Region terms were not significant and were not included in the model. Thus the model reverted to differences in CTI - soil water content relationships only between fields. For this model, Hill and Liberty shared a moderately positive predicted soil water relationship (slope). Phillips 2 showed a strongly negative slope, implying that as CTI values increased predicted soil water content decreased. Phillips 1 had a much flatter prediction slope illustrating little relationship between CTI and measured soil water content.

Figure 18. Predicted study site soil water content – CTI relationships for Liberty, Hill, Philips 1, and Philips 2. Model includes interaction terms. Adjusted $R^2 = 0.35$, $p = 0.0001$.



Discussion

Regression analyses between soil water content and CTI demonstrated poor to moderate success in identifying such relationships on a farm field scale. Although most models were statistically significant, multiple coefficients of determination (R^2) were generally low, indicating that CTI did not explain a substantial portion of the variability in measured soil water contents. Further, the inverse relationship between soil water content and CTI found at the Phillips 2 site was contrary to what is expected when using CTI as a predictive attribute. Differences in CTI – soil water content relationships between and within fields also suggested that processes that influenced soil water distribution varied across space.

Quantitative topographic attributes are used as predictors of soil water content based on assumptions concerning water flow in response to hillslope surface form. As such, patterns of soil water are assumed to be similar across space in response to similar topographic controls, represented as topographic attributes. The relative nature of the soil water content - topographic relationship should remain constant if quantitative attributes are to effectively function as predictors of relative soil water content across space (i.e. multiple fields) and time. The present study found the soil wetness – CTI relationship to be inconsistent among and within fields.

Soil Water – CTI Relationship Across Space

When the best correlations between soil water content and CTI were exhibited (end of growing season at 20 cm depth), increased soil water content with increased CTI was observed at Liberty and Hill, and to a much lesser extent at Phillips 1. Results at

Phillips 2, however, were contrary to expectations in that an inverse relationship was found, with higher measured soil water contents higher up in the landscape. It is further perplexing that, while the strongest positive relationships between CTI and soil water content might be expected under abundant precipitation (Barling et al., 1994; Western et al., 1999), Phillips 2 had the highest precipitation of the four sites studied.

Inherent in the application of CTI is that soil properties and processes are assumed largely repeatable and therefore predictable across landscapes. However, soil properties typically exhibit complex scales of variation across space, and processes involving soils and landscapes likewise vary spatially (Burrough, 1993; Moore et al., 1993). Phillips 2 soils were formed on glacial till. Soils derived from till may be highly variable (Brady and Weil, 1999). According to the Official Series Descriptions, depth to clay as well as soil clay content at Phillips 2 varies with landscape position (National Soil Survey Staff, 1998a, 1998b). These conditions violate assumptions inherent in the CTI. Evidence of surface water flow was not visible, thus vertical infiltration of rainfall likely predominated at the Philips 2 site. Therefore, spatial variation in soil properties, e.g. clay content and its effects on water holding and infiltration capacities (Or and Wraith, 2000), may have held greater influence over soil water spatial distribution than did topography.

Within-field differences in CTI – soil water content relationships may occur on a different scale than for between-field differences. Such differences may be due to soil variability and also to position in the landscape. Barling et al. (1994) noted that different hillslope profiles and positions in the landscape could have identical values of topographic attributes such as slope and specific catchment area. According to the theory underlying CTI, these points should have similar relative soil water content. However,

due to expected differences in soils and other environmental factors between these positions, they would likely respond differently to the same hydrologic inputs. This might be why there were differences in soil water content – CTI relationships between Flow method topographic regions at all sites.

Planar regions exhibited the greatest positive correlations between CTI and soil water content at all sites. This might reflect that assumptions inherent in CTI were more appropriate for these positions as a result of greater uniformity of soil properties within these regions. Depressions consistently demonstrated the worst relationship between CTI and soil water content. At Phillips 1 and 2, predicted soil water content in depressional regions decreased with increasing CTI. Reasons for this are unclear, but one explanation might be that any water flowing laterally into depressional areas accumulated near the transition between the depression and contributing areas. Measurement points located at the interior of the depressions would thus have had higher CTI, but possibly lower soil water content.

A second issue pertains to spatial scale and concurrent effectiveness of terrain models. Moore et al. (1993) stated that a key problem in modeling environmental systems was the effects of scale and accuracy on computed terrain attributes. The values computed, and thus the processes modeled, for the grid cells of a DEM are assumed homogenous for that grid cell area (Moore et al., 1993). Therefore, predicted soil water is presumed uniform for the area encompassed by the grid cell. The size of the grid cell should then match as precisely as possible the scale of the process or attribute being modeled. Otherwise, any correlation between topographic attributes and the property (e.g. soil water content) would be weakened.

For our study, the 5 m grid cell size was the smallest feasible for representing the study sites' topography based on the elevation data available. Such grid cells were considered adequate to model processes at larger, watershed scales (Gessler et al., 1995; Western et al., 1999; Yu et al., 2001). It is possible that 5 m spacing may be insufficient to resolve spatial patterns in soil water at the site-specific scale of observation. Landon (1995) found that CTI values derived from 2 m and 10 m DEMs were only moderately correlated, and did not share similar patterns of spatial variability. Representation of the topography at our sites using smaller grid cell size DEMs (e.g. 2 m) would have required higher measurement density than the 10 m used for elevation sampling. Such sampling intensity does not seem feasible for routine land management purposes. More importantly, based on the apparent lack of lateral water flow at the four sites it seems unlikely that smaller grid size would alter the fundamental lack of correlation between soil water content and CTI.

Soil Water Variability, Precipitation, and Time Factors

Linkages between topography and soil water content might be weak in the absence of an adequate supply of water to the system. Further, Pachepsky et al. (2001) stated that correlation analysis between topographic variables and soil water content is justified only if soil water content varies significantly across the landscape. Soil water content did not exhibit high spatial variability at any of our sites, but spatial variability did increase at all depths by the end of the growing season. This increase could have been due to topographically influenced lateral surface and sub-surface redistribution of growing season precipitation. The strongest correlations between soil water content and

CTI were exhibited where spatial variability in soil water content was greatest, at 20 cm depth. However, the fact that correlations were not stronger at the end of the growing season at 60 cm and for the upper 70 cm depths, and that CTI and soil water content exhibited a moderately strong inverse relationship where growing season precipitation was highest, does not support a hypothesis of lateral water redistribution.

Alternately, increased spatial variability in soil water content may be due to spatial variation in crop water use. This could arise from differential evapo-transporative demands based on microclimate differences between landscape positions (Campbell and Norman, 1998). Another possibility is that variation in soil properties influenced spatial variation in soil water content through variable soil water retention, particularly as soils dried throughout the growing season (Or and Wraith, 2000). Interestingly, relationships between either one of these factors and soil water content could be modeled indirectly through soil water-CTI regression analyses, since variation in these factors is partially related to topography.

This study monitored the soil water – CTI relationship only during the growing season, but this covered the portion of the year in which at least half of yearly precipitation occurs for my study area. My measurements also captured the end of fallow periods for all the fields. Therefore, stronger correlations would be unlikely between soil water content and CTI at another time of the year in the semi-arid Northern Great Plains.

The CTI was not a good spatial indicator of relative soil water content at our study sites. Under the conditions of moderate variability in soil properties and low precipitation, three implicit assumptions of CTI were not met. The assumption of uniform infiltration capacity across the catchment implies spatial homogeneity in attributes,

including soil texture and soil hydraulic properties. According to the official series descriptions, this was not the case in my study fields (National Soil Survey Staff, 1996, etc.). The assumption that subsurface flow is parallel to surface topography infers the presence of an impeding layer in the soil profile at a similar depth across the landscape, which is not consistent with the relatively deep soils derived from glacial till at the study sites. Finally, the assumption of steady-state conditions was not met in the fields under the environmental conditions present. It is likely that not every point in the landscape received water flow from its entire upslope contributing area (Barling et al., 1994).

Conclusions

Measured soil water contents were correlated with a quantitative topographic attribute, the compound topographic index (CTI), across four dryland agricultural fields in north central Montana, USA. The analyses considered study sites and within-field topographic regions as co-predictors in an attempt to determine whether CTI might effectively be used to predict relative soil water content across multiple sites in the semi-arid agricultural areas of the Northern Great Plains.

Results indicated that CTI did not correlate well with soil water content at any of our sites. This may be partially due to the general lack of spatial variability in soil water content observed, a condition that is likely typical in the semi-arid climate of the region, but perhaps exacerbated by consecutive dry years during the study. Relatively weak relationships that were discerned between CTI and soil water content differed in character from site to site, indicating that governing processes also may have varied from site to site, regardless of overall soil water spatial variability. At one site where precipitation

was nearest to long-term average, the relationship between CTI and soil water content was inverse and therefore counter to expectations. These results suggest that CTI may not be an appropriate surrogate for predicting the distribution of soil water content under typical climatic and soil conditions found in the Northern Great Plains.

These results emphasize the difficulties encountered in modeling the complex processes that determine soil water spatial distribution through the use of simplified concepts such as compound topographic attributes. In the absence of abundant precipitation or shallow impeding layers, it is likely that other factors, predominantly soils and geology, may exert primary influence on soil water distribution. In order to model soil water distribution across multiple sites with topographic attributes such as CTI, identifying critical soil characteristics related to water flow, and their distribution in the system being modeled will be important.

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CHAPTER 4

SUMMARY

The objective of this study was to evaluate topographic influences on soil water content distribution across dryland agricultural fields representative of Montana's Golden Triangle region. This was part of a larger effort to develop site-specific environmental information systems to be used for field-scale management. To that end, we hypothesized that topography captures processes involving soils, geology, and other factors pertinent to soil water processes, and thus is a primary driver of soil water distribution. Topographic models, used in a GIS setting, could then be used to model and predict soil water distribution across multiple sites. If successful, a manager could assess soil water distribution across a field in a timely and effective manner while concurrently minimizing direct sampling efforts.

We used four sites across North-central Montana in an effort to test whether relationships between topography and soil water content would be consistent across space. Two approaches were taken: 1) the creation of topographic regions and the analysis of soil water content differences between the regions, and 2) direct correlation analysis between a quantitative topographic attribute, the compound topographic wetness index, and soil water content at specific field locations. Differences in soil water content between topographic regions within sites were absent to moderate at best. Correlations

between CTI and soil water content at all sites were not strong. Neither approach illustrated consistency in relationships across space.

Other researchers that used terrain to model soil water distribution in semi-arid environments also found little correlation between terrain and soil water. Landon (1995) found no relationship between a quantitative wetness index and soil water content across a hillslope consisting of deep, silty soils near Bozeman, MT. Nolan et al (2000) found that if relationships exist between topography and yield, universal applications across space and time were not attainable.

The growing seasons of 2000 and 2001 were dryer than normal. This may have played a role in the lack of strong topographic-soil water content relationships and the lack of similarity in relationships across the study sites. However, several assumptions concerning soil properties inherent in the calculation of CTI were likely not met at any of the sites. Thus even under normal precipitation conditions, it is unlikely that CTI would correlate well with soil water content under the semi-arid climatic conditions of central and eastern Montana.

Soils were variable across our study sites. In the absence of significant amounts of precipitation soil differences appear to have largely influenced soil water distribution. Further, soil-landscape processes that influence soil water distribution vary across space. Region-partitioning methods were an attempt at incorporating these processes into the soil water – CTI correlation model. The fact that results varied from site to site or within fields illustrates that modeling process across landscapes requires prior recognition of patterns between factors that affect the process, such as soils, geology, topography and others. Given increased understanding of patterns of topography and soils, and their

relation to soil water distribution, implementation of terrain-based region-partitioning methods that model process across multiple sites might be more attainable.

These results illustrate the difficulties that are often encountered in attempting to predict the result of complex processes with models that simplify those processes. Models that simplify processes to predict environmental responses only function properly if processes in a particular system being modeled are captured correctly. Since these processes generally vary across space, site-specific information should be integrated with these models.

APPENDICES

APPENDIX A

REGION CLASSES AND TOPOGRAPHIC ATTRIBUTE VALUES

Table 13. Liberty region classes and calculated topographic attributes for soil water content sample points.

Sample Point ID	Cluster	Soil/Landscape	Flow	Slope (%)	Profile curvature	Plan curvature	Aspect (deg)	CTI
1	upper	upper	divergent	1.30	-0.20	0.00	90.00	7.06
2	mid	upper	divergent	4.11	-0.04	2.97	108.44	7.06
3	upper	upper	divergent	2.92	-0.25	-2.34	59.04	6.33
4	mid	upper	divergent	7.43	-0.04	2.21	79.14	6.94
5	mid	upper	divergent	7.20	-0.08	-1.14	88.41	6.24
6	mid	upper	divergent	5.49	-0.14	-1.77	100.49	6.21
7	lower	lower	depression	0.36	0.01	75.95	146.31	14.51
8	lower	lower	convergent	2.16	0.08	3.90	193.39	9.74
9	mid	mid	convergent	4.98	0.02	2.79	231.52	7.88
10	upper	upper	divergent	2.00	-0.16	-4.00	180.00	6.33
11	mid	upper	divergent	3.83	-0.08	-5.16	254.88	5.43
12	lower	upper	planar	0.78	0.02	3.02	230.19	8.20
13	mid	lower	depression	2.59	0.29	8.77	117.55	8.02
14	lower	lower	depression	2.77	0.22	4.91	64.36	8.57
15	lower	lower	depression	2.93	0.25	1.01	82.15	7.39
16	mid	lower	depression	4.34	0.20	0.03	97.94	7.54
17	upper	mid	planar	3.47	0.07	3.75	101.63	8.06
18	mid	upper	divergent	5.46	-0.06	-1.93	208.44	6.24
19	mid	mid	planar	3.83	-0.11	-0.21	285.12	7.33
20	lower	mid	convergent	2.92	0.06	6.03	202.17	8.93
21	upper	upper	divergent	3.58	0.03	-0.89	116.57	6.35
22	upper	upper	divergent	2.82	-0.04	-1.42	62.53	6.29
23	lower	mid	planar	3.19	0.07	1.51	131.19	7.76
24	upper	upper	divergent	3.57	-0.11	-2.42	72.07	6.01
25	upper	upper	divergent	2.21	-0.11	-2.44	108.44	6.52
26	mid	lower	convergent	3.83	0.11	1.42	220.76	7.67
27	mid	mid	divergent	5.01	0.08	0.75	273.43	6.89
28	lower	mid	convergent	2.12	0.11	4.28	160.71	8.61
29	upper	upper	divergent	4.40	0.00	-0.93	181.30	6.16
30	upper	upper	divergent	2.01	-0.08	-3.88	264.29	6.86
31	upper	lower	depression	3.36	0.09	-2.53	112.75	6.66
32	upper	upper	planar	0.30	-0.12	26.67	180.00	7.96
33	upper	mid	convergent	2.43	-0.08	3.11	260.54	7.74
34	upper	upper	divergent	2.09	-0.11	-6.03	196.70	6.15
35	mid	mid	divergent	5.46	-0.04	-1.47	243.90	6.61
36	upper	upper	divergent	3.98	-0.02	-2.47	205.28	6.09
37	mid	mid	planar	4.60	-0.01	-0.59	225.88	6.86
38	mid	upper	divergent	4.00	0.00	-1.04	271.43	6.72
39	mid	mid	planar	3.48	0.16	2.42	161.57	6.76
40	upper	upper	divergent	2.66	0.03	-2.47	325.71	6.34

Table 13 continued. Liberty region classes and calculated topographic attributes for soil water content sample points.

Sample Point ID	Cluster	Soil/Landscape	Flow	Slope (%)	Profile curvature	Plan curvature	Aspect (deg)	CTI
41	lower	lower	depression	3.58	0.01	-0.22	333.43	7.55
42	lower	lower	depression	2.98	0.04	1.34	219.56	8.22
43	mid	mid	planar	4.40	-0.05	-1.54	248.68	7.73
44	mid	upper	divergent	4.66	-0.05	-1.61	247.29	6.75
45	mid	mid	planar	5.80	-0.09	-0.48	255.00	7.08
46	mid	mid	planar	6.36	0.15	1.35	245.85	6.75
47	mid	mid	convergent	5.80	0.09	1.94	215.88	6.89
48	mid	upper	divergent	6.10	-0.04	-0.63	269.06	6.11
49	upper	upper	divergent	2.94	-0.11	-2.96	342.18	7.33
50	lower	lower	depression	1.20	0.08	-2.98	184.76	9.44
51	upper	upper	divergent	2.95	-0.01	0.28	151.70	7.41
52	mid	mid	divergent	6.72	0.03	-0.42	247.25	7.68
53	mid	mid	convergent	6.18	0.09	1.74	247.17	7.52
54	mid	mid	planar	5.55	-0.09	-1.30	244.36	7.16
55	lower	mid	convergent	4.34	0.03	2.18	218.45	9.12
56	mid	mid	divergent	7.30	0.01	-0.09	260.54	6.45
57	upper	upper	divergent	6.10	-0.28	-3.96	268.12	5.61
58	mid	mid	planar	3.96	-0.07	-3.32	290.73	7.34
59	mid	upper	divergent	3.85	0.00	0.00	152.10	7.06
60	mid	mid	planar	4.70	0.00	-1.80	156.16	7.32
61	mid	mid	planar	6.93	0.03	-0.40	123.23	6.31
62	mid	mid	planar	6.77	-0.01	-0.50	102.80	5.91
63	lower	lower	depression	2.06	0.15	-1.24	219.09	10.54
64	mid	mid	divergent	4.85	0.04	-1.70	255.68	6.90
65	mid	mid	planar	5.90	0.07	-0.54	243.87	7.23
66	mid	lower	convergent	5.11	0.21	0.59	273.37	7.16
67	upper	upper	divergent	4.20	-0.10	-3.27	205.35	6.56
68	upper	upper	divergent	2.13	-0.07	-4.23	221.19	6.65
101	lower	mid	convergent	4.60	0.00	2.65	91.25	9.57
102	upper	mid	planar	3.60	-0.08	-1.10	271.59	6.80
103	lower	lower	convergent	3.70	0.15	5.77	251.08	9.28
104	upper	upper	divergent	4.74	-0.12	-5.03	225.86	5.58
105	lower	mid	convergent	5.46	0.02	1.08	235.44	9.85
107	lower	mid	planar	4.58	0.20	0.03	238.39	7.83
108	mid	mid	convergent	6.58	-0.05	1.30	245.77	7.46
109	upper	lower	depression	3.51	-0.05	-0.75	184.90	7.65
110	mid	mid	divergent	7.52	0.12	-1.07	265.43	6.23
111	lower	lower	convergent	3.22	0.21	8.36	150.26	11.37
112	lower	lower	depression	1.92	-0.08	1.83	231.34	9.31

Table 14. Hill region classes and calculated topographic attributes for soil water content sample points.

Sample Point ID	Cluster	Soil/Landscape	Flow	Slope (%)	Profile curvature	Plan curvature	Aspect (deg)	CTI
1	upper	upper	divergent	2.70	218.99	-0.42	-0.06	5.64
2	mid	lower	convergent	7.72	31.22	0.12	0.04	6.52
3	lower	lower	convergent	1.00	36.87	0.02	0.06	9.40
4	lower	lower	planar	1.12	79.70	0.04	0.01	7.79
5	lower	lower	convergent	1.02	191.31	0.10	0.06	8.61
6	mid	mid	planar	7.12	60.55	0.06	-0.10	5.63
7	mid	mid	planar	3.96	200.73	0.06	0.06	6.17
8	upper	mid	divergent	2.75	123.11	0.00	-0.32	5.49
9	mid	mid	divergent	7.16	26.57	-0.10	-0.06	5.54
10	lower	lower	convergent	1.39	210.26	0.19	0.01	7.68
11	lower	lower	depression	0.64	308.66	0.01	-0.05	7.58
12	lower	lower	divergent	0.45	63.44	0.00	0.00	7.96
13	mid	lower	planar	6.41	10.78	0.21	-0.09	6.65
14	upper	upper	divergent	1.71	249.44	-0.42	-0.38	5.20
15	lower	upper	convergent	1.98	220.91	0.05	0.03	8.32
16	upper	upper	divergent	5.10	357.75	-0.35	-0.25	5.13
17	lower	lower	planar	1.04	73.30	0.01	-0.05	8.69
18	lower	lower	depression	0.78	39.81	-0.03	-0.01	7.39
19	upper	lower	planar	0.89	63.44	-0.06	-0.02	7.56
20	mid	mid	planar	5.66	212.01	0.12	0.04	6.02
21	mid	mid	convergent	2.64	52.70	0.24	0.12	8.01
22	mid	mid	convergent	2.31	184.97	0.13	0.07	7.26
23	mid	mid	convergent	4.47	214.05	0.21	0.11	6.58
24	lower	lower	depression	0.30	90.00	-0.04	0.00	10.02
25	lower	lower	depression	0.20	0.00	0.00	0.00	10.25
26	lower	lower	depression	0.81	7.13	0.00	0.04	10.44
27	mid	upper	convergent	11.09	50.86	0.00	0.00	5.90
28	lower	lower	convergent	2.66	70.20	0.26	0.15	8.33
29	upper	lower	planar	2.11	121.43	-0.07	0.03	6.63
30	upper	lower	planar	0.63	71.57	-0.15	-0.01	7.79
31	upper	mid	divergent	2.61	212.47	-0.32	-0.16	5.36
32	lower	mid	convergent	2.00	126.87	0.14	0.18	8.46
33	lower	lower	convergent	2.00	182.86	0.17	0.19	8.63
34	lower	lower	convergent	0.36	326.31	0.10	0.26	12.59
35	lower	lower	depression	0.32	18.44	0.17	0.47	12.75
36	mid	upper	divergent	8.14	27.82	0.12	-0.12	6.01
37	upper	upper	divergent	2.98	103.57	-0.32	-0.64	4.71
38	mid	lower	convergent	7.72	42.37	0.11	0.01	6.54
39	upper	lower	planar	2.02	98.53	-0.08	0.04	7.65
40	upper	lower	divergent	1.80	70.56	0.00	-0.04	6.52

Table 14 continued. Hill region classes and calculated topographic attributes for soil water content sample points.

Sample Point ID	Cluster	Soil/Landscape	Flow	Slope (%)	Profile curvature	Plan curvature	Aspect (deg)	CTI
41	mid	lower	convergent	3.63	172.09	0.24	0.13	6.92
101	mid	upper	planar	8.51	33.50	0.03	0.05	6.09
102	lower	lower	convergent	2.06	39.09	0.17	0.03	8.51
103	lower	lower	depression	1.21	65.56	0.07	0.01	7.61
104	upper	mid	divergent	0.85	159.44	-0.06	-0.14	6.45
105	lower	mid	convergent	1.44	56.31	0.18	-0.02	7.95
106	mid	mid	convergent	1.88	25.20	0.25	-0.05	7.56
107	upper	mid	divergent	3.77	212.01	-0.48	-0.08	5.34
108	mid	mid	convergent	2.75	56.89	0.22	0.02	7.31
109	mid	upper	divergent	8.77	20.71	-0.09	-0.03	5.61
110	mid	upper	convergent	3.82	225.00	0.18	0.06	7.32
111	lower	upper	depression	0.80	270.00	0.00	0.00	9.81
112	mid	upper	convergent	4.36	306.61	0.03	0.17	7.65
113	mid	upper	divergent	7.08	193.06	0.03	-0.07	5.66
114	mid	upper	divergent	11.00	0.52	0.00	-0.12	5.51
115	mid	upper	convergent	3.91	13.32	0.37	0.23	8.27
116	lower	lower	depression	0.45	153.44	0.02	0.06	9.86
117	upper	mid	divergent	1.32	8.75	-0.43	-0.09	5.79
118	upper	mid	divergent	1.33	192.99	-0.27	-0.05	6.19
119	upper	mid	divergent	4.62	17.65	-0.44	-0.12	5.21
120	mid	upper	convergent	5.30	54.21	0.25	-0.09	6.66
121	upper	upper	divergent	2.89	165.96	-0.46	-0.70	4.58
122	mid	upper	divergent	11.39	69.97	-0.09	-0.15	4.96
123	mid	lower	convergent	5.80	46.40	0.38	0.17	7.17
124	upper	mid	divergent	1.53	121.61	-0.07	-0.05	6.48
125	mid	lower	convergent	5.24	28.52	0.23	0.13	7.68
126	upper	upper	divergent	2.69	68.20	-0.68	-0.32	5.06
127	mid	upper	planar	7.57	223.39	-0.07	0.03	5.99
1281	mid	upper	divergent	8.99	214.57	0.08	-0.12	5.45
1282	mid	upper	planar	3.92	199.36	0.13	-0.05	7.05
129	mid	upper	convergent	4.00	211.70	0.33	0.11	7.43
130	mid	upper	convergent	7.07	213.47	-0.02	0.10	6.24
131	lower	upper	depression	0.22	116.57	0.08	0.36	12.14
132	mid	upper	planar	8.10	205.62	0.08	0.00	5.70
133	mid	upper	divergent	8.83	30.63	-0.06	-0.06	5.47
134	mid	upper	convergent	8.90	38.16	0.12	0.24	6.35
135	upper	mid	divergent	2.84	140.71	-0.25	-0.23	5.23
136	lower	mid	convergent	1.91	353.99	0.18	0.18	8.03

Table 15. Phillips 1 region classes and calculated topographic attributes for soil water content sample points.

Sample Point ID	Cluster	Soil/Landscape	Flow	Slope (%)	Profile curvature	Plan curvature	Aspect (deg)	CTI
1	lower	lower	convergent	2.15	0.50	-8.52	68.20	6.83
2	upper	upper	divergent	3.09	-0.22	-3.12	209.05	8.72
3	lower	mid	convergent	2.56	0.01	2.67	231.34	8.19
4	upper	mid	divergent	3.12	0.01	-2.77	50.19	6.15
5	mid	mid	planar	5.72	0.05	-0.17	207.01	5.79
6	upper	upper	divergent	3.81	-0.18	-3.67	209.93	5.47
7	upper	mid	divergent	2.56	0.06	-0.90	30.58	6.90
8	lower	mid	planar	0.73	0.31	-4.35	344.05	8.89
9	lower	lower	depression	0.45	0.06	41.14	243.44	11.16
10	upper	upper	divergent	0.64	-0.15	-70.09	51.34	5.79
11	upper	upper	divergent	1.46	-0.41	0.88	164.05	5.84
12	lower	mid	depression	0.22	-0.03	32.20	333.43	12.58
13	mid	upper	divergent	9.96	-0.06	0.98	19.34	5.54
14	mid	lower	convergent	5.34	0.31	0.91	51.84	6.79
15	mid	mid	convergent	4.85	-0.01	2.68	248.20	8.47
16	mid	mid	planar	4.48	-0.01	-0.60	209.43	6.27
17	upper	mid	divergent	1.98	0.03	-5.51	49.09	6.33
18	lower	mid	convergent	4.08	-0.05	4.19	252.90	8.80
19	lower	upper	planar	1.04	-0.06	2.36	16.70	7.91
20	upper	upper	divergent	3.26	-0.02	3.04	349.38	7.18
21	lower	lower	depression	1.10	0.12	7.27	90.00	8.91
22	mid	lower	convergent	4.18	0.07	-2.62	191.04	6.52
23	upper	upper	divergent	0.99	-0.22	-10.10	225.00	6.10
24	lower	lower	convergent	1.70	0.08	9.16	40.24	8.74
25	lower	mid	convergent	2.69	0.04	2.97	21.80	8.00
26	mid	mid	divergent	7.40	0.08	-2.16	0.00	5.90
27	lower	mid	depression	1.77	0.13	1.70	196.39	7.03
28	mid	mid	planar	7.86	0.15	-1.47	78.26	5.69
29	mid	lower	convergent	6.75	0.09	0.39	207.32	6.71
30	mid	lower	convergent	3.89	0.08	2.09	244.09	7.12
31	mid	mid	convergent	5.28	0.07	1.66	294.62	6.83
32	mid	mid	planar	6.95	0.08	-0.64	239.74	5.94
33	upper	upper	divergent	4.20	-0.09	0.28	282.38	7.87
34	lower	lower	depression	0.71	0.04	5.26	81.87	9.07
35	lower	mid	divergent	2.19	-0.01	2.10	43.15	7.14
36	upper	mid	divergent	3.34	-0.04	-1.11	261.38	7.16
37	mid	upper	divergent	3.18	0.22	-0.65	316.27	6.69
38	upper	upper	divergent	2.43	-0.14	-4.31	260.54	5.81
39	lower	lower	convergent	2.69	0.24	1.61	344.93	8.18
40	mid	mid	planar	3.91	0.07	-0.65	230.19	6.48

Table 15 continued. Phillips 1 region classes and calculated topographic attributes for soil water content sample points.

Sample Point ID	Cluster	Soil/Landscape	Flow	Slope (%)	Profile curvature	Plan curvature	Aspect (deg)	CTI
41	mid	upper	divergent	6.95	-0.30	-2.51	49.67	5.35
42	mid	mid	planar	8.42	0.12	-1.88	256.95	5.61
43	mid	mid	convergent	5.55	0.02	-1.04	246.67	6.06
44	mid	mid	divergent	5.83	0.02	-0.41	239.04	6.96
45	mid	mid	convergent	5.84	0.00	2.11	276.88	7.43
46	upper	mid	divergent	2.12	0.02	-2.86	250.71	7.23
47	mid	upper	divergent	4.20	0.06	-2.45	231.77	6.21
48	upper	upper	divergent	3.20	0.01	-4.08	284.47	5.66
49	upper	mid	convergent	2.76	-0.09	-1.20	226.47	6.49
50	upper	upper	divergent	2.24	0.00	0.00	296.57	6.42
51	mid	mid	divergent	5.83	0.15	-1.15	337.83	8.00
52	mid	upper	divergent	5.95	-0.15	-6.87	16.61	4.94
53	lower	mid	depression	0.89	0.14	1.79	243.44	8.16
54	lower	mid	convergent	2.69	-0.02	0.74	221.99	7.88
55	upper	upper	divergent	3.75	-0.01	-3.03	43.92	6.09
56	lower	lower	convergent	2.82	0.33	1.08	22.93	8.09
57	upper	lower	divergent	1.30	-0.05	-27.11	355.60	5.91
58	mid	lower	divergent	5.25	0.05	-2.51	252.26	6.38
59	mid	mid	divergent	6.14	0.03	-1.87	250.97	6.75
60	lower	mid	convergent	3.20	-0.03	2.32	231.34	8.32
61	lower	mid	convergent	2.53	0.00	6.48	288.43	8.80
62	lower	mid	convergent	2.26	-0.19	6.63	257.20	10.45
63	lower	mid	planar	1.30	0.03	-5.35	292.62	7.91
64	mid	mid	planar	6.13	0.04	0.65	333.85	7.21
65	lower	lower	convergent	2.66	0.13	-0.57	55.71	7.04
101	mid	lower	convergent	7.40	0.35	0.13	279.34	7.05
102	mid	lower	convergent	6.15	-0.06	-0.31	201.97	5.86
103	lower	lower	convergent	3.69	0.16	1.01	302.83	8.36
104	lower	lower	convergent	1.08	0.05	40.21	158.20	10.41
106	lower	lower	convergent	2.92	-0.14	15.80	5.91	11.59
107	lower	mid	convergent	5.80	0.08	2.08	0.99	9.62
108	mid	upper	divergent	8.30	0.03	-1.81	347.47	5.34
109	upper	upper	divergent	3.11	-0.38	-10.93	315.00	5.17
110	upper	upper	divergent	1.98	-0.66	-39.42	139.09	4.59
111	lower	lower	convergent	1.01	0.07	68.57	264.29	13.20
113	lower	lower	convergent	2.84	0.44	-1.47	230.71	8.00
114	upper	upper	divergent	4.03	-0.35	-0.30	46.01	5.74
115	upper	upper	divergent	2.28	-0.29	-6.53	298.81	6.22

Table 16. Phillips 2 region classes and calculated topographic attributes for soil water content sample points.

Sample Point ID	Cluster	Soil/Landscape	Flow	Slope (%)	Profile curvature	Plan curvature	Aspect (deg)	CTI
1	mid	lower	convergent	8.95	0.24	0.39	205.13	6.15
2	lower	lower	convergent	1.53	0.41	9.86	348.69	10.88
3	upper	upper	divergent	6.94	-0.24	-3.40	78.37	4.99
4	lower	lower	convergent	1.32	0.24	27.32	261.25	9.25
5	upper	upper	divergent	3.19	-0.20	-6.22	122.20	5.38
6	upper	upper	divergent	4.33	-0.25	-3.49	33.69	5.37
7	upper	upper	divergent	4.02	-0.18	-6.46	161.11	5.95
8	upper	mid	planar	5.39	-0.05	0.18	169.32	6.40
9	mid	lower	convergent	3.97	0.12	-0.88	139.09	6.28
10	lower	mid	convergent	3.85	-0.01	6.38	117.90	8.75
11	mid	mid	convergent	4.69	0.21	1.51	33.69	6.50
12	upper	mid	planar	8.24	-0.04	0.52	29.05	5.78
13	mid	lower	convergent	2.06	0.42	-2.99	67.17	7.49
14	upper	mid	convergent	8.28	-0.03	1.83	227.45	7.86
15	lower	lower	convergent	1.14	0.26	12.32	105.26	8.50
16	mid	mid	divergent	5.25	0.05	-1.02	252.26	6.03
17	upper	mid	divergent	7.52	-0.02	-1.80	220.68	6.39
18	mid	lower	convergent	6.04	0.25	-0.11	28.69	6.31
19	upper	upper	divergent	5.95	-0.07	-3.57	82.28	5.37
20	upper	upper	divergent	5.12	-0.30	-3.43	141.34	5.29
21	upper	upper	divergent	4.61	-0.13	-1.62	40.60	6.09
22	upper	upper	divergent	1.70	-0.17	5.38	40.24	6.95
23	mid	lower	convergent	1.94	0.66	-3.08	348.11	7.51
24	upper	upper	divergent	3.84	-0.17	-8.18	141.34	5.28
25	lower	mid	convergent	2.91	-0.05	1.61	105.95	8.49
26	lower	lower	convergent	3.58	0.27	4.75	120.14	9.83
27	upper	mid	divergent	7.74	0.07	-1.48	61.45	5.56
28	mid	mid	planar	4.57	0.25	-0.26	61.19	7.18
29	lower	lower	convergent	3.58	0.13	4.18	239.86	8.92
30	upper	mid	planar	6.15	-0.04	0.02	224.34	6.06
31	lower	lower	convergent	1.66	0.16	9.83	64.98	7.24
32	upper	upper	divergent	3.47	-0.02	0.60	33.23	6.00
33	upper	mid	divergent	7.84	0.02	-1.76	203.29	5.62
34	mid	mid	divergent	4.46	-0.01	-4.28	225.91	6.79
35	lower	lower	convergent	1.25	0.10	1.53	298.61	7.43
36	mid	mid	planar	6.11	0.21	0.45	87.18	6.44
37	upper	upper	divergent	6.58	-0.27	-7.42	28.12	4.66
38	upper	upper	divergent	4.10	-0.05	-0.66	46.97	6.19
39	lower	lower	convergent	1.92	0.14	11.58	128.66	9.59
40	mid	mid	planar	4.46	0.13	-3.83	105.59	5.80

Table 16 continued. Phillips 2 region classes and calculated topographic attributes for soil water content sample points.

Sample Point ID	Cluster	Soil/Landscape	Flow	Slope (%)	Profile curvature	Plan curvature	Aspect (deg)	CTI
41	lower	mid	convergent	3.98	-0.04	8.07	101.59	9.46
42.1	lower	lower	convergent	3.88	0.08	6.30	55.49	10.18
42.2	mid	mid	convergent	5.20	0.07	2.58	142.03	6.87
43	mid	mid	divergent	4.13	0.06	-4.28	237.85	5.83
44	lower	mid	planar	2.25	0.19	-2.90	212.28	9.42
45	mid	mid	planar	4.33	0.18	-2.41	96.63	5.89
46	upper	upper	divergent	5.15	-0.36	-7.68	198.08	5.24
47	upper	upper	divergent	3.40	-0.51	-9.69	193.63	5.58
48	upper	upper	divergent	4.43	-0.16	-3.60	241.70	6.02
49	lower	mid	planar	1.30	0.06	-4.26	237.53	8.65
50	upper	upper	divergent	4.60	-0.24	-2.56	181.25	6.71
51	mid	lower	convergent	2.91	0.26	0.85	40.82	8.19
52	mid	mid	planar	3.09	0.18	-0.56	60.95	6.87
53	mid	mid	convergent	3.66	-0.02	3.74	34.99	7.28
54	lower	lower	convergent	0.85	0.02	-6.41	69.44	10.78
101	upper	upper	divergent	6.69	-0.19	-7.94	238.45	4.62
102	upper	mid	divergent	9.84	0.14	-2.27	37.57	5.26
103	lower	mid	convergent	3.20	-0.08	2.50	90.00	8.68
104	mid	lower	planar	2.16	0.11	-1.14	213.69	7.07
105	upper	upper	divergent	2.75	-0.44	-0.12	160.91	6.02
106	upper	upper	divergent	0.73	-0.28	-22.39	15.95	5.82
107	upper	mid	convergent	7.62	-0.01	1.14	76.33	6.20
108	upper	mid	divergent	9.53	0.03	-2.44	64.51	5.18
109	upper	upper	divergent	5.53	-0.14	-1.13	173.77	6.36
110	lower	lower	convergent	1.46	0.14	6.95	254.05	11.05
111	lower	mid	convergent	3.57	0.06	9.42	78.69	9.96
112	lower	lower	convergent	2.64	0.09	7.11	142.70	8.31
113	upper	mid	planar	6.80	0.07	0.18	208.07	6.19
114	upper	lower	convergent	7.40	0.10	-1.32	231.58	5.98
115	upper	upper	divergent	3.11	-0.38	-12.21	183.69	4.97
116	lower	mid	convergent	4.88	-0.06	5.33	42.51	9.22
117	lower	mid	convergent	3.61	-0.08	6.54	109.44	8.95
118	upper	upper	divergent	7.46	-0.08	-4.34	72.05	5.13
119	upper	upper	divergent	4.51	-0.14	-2.18	167.20	5.83
120	mid	mid	convergent	4.57	0.55	0.29	208.81	6.46
121	mid	mid	planar	6.69	0.22	-0.94	211.55	5.79
122	lower	lower	convergent	0.20	0.16	160.00	270.00	11.18
123	lower	mid	convergent	1.01	0.24	11.67	264.29	10.29
124	mid	lower	convergent	3.92	0.13	3.86	185.86	8.36
125	mid	mid	divergent	4.04	-0.02	-2.46	41.99	6.62
126	lower	mid	planar	3.26	0.07	-0.78	107.88	8.43

APPENDIX B

SOIL PROFILE DESCRIPTIONS

Site	Landscape Location	Depth (cm)	Horizon	Clay (%)	Color	Horizon notes	General notes
Liberty	concave linear	0 - 10	A	26	10YR 3/3 moist		* Resemblance of loess to 120 cm
		10 - 35	Bt	32	2.5Y 3/3 moist	clay films	* Depths > 120 cm heavy clay/rock layer
		35 - 68	Bk1	28	2.5Y 4/3 moist	es	
		68 - 120	Bk2	24	2.5Y 5.3 moist	es	
	linear midslope	0 - 10	A	na	10YR 3/3 moist		* Depths > 100 cm heavy clay/rock layer
		10 - 30	Bt	24	2.5Y 3/3 moist	some clay films	
		30 - 100	Bk	24 - 26		little clay increase	
	knoll convex	0 - 10	A	26	2.5Y 4/3 moist	ochric epipedon	* Prevalance of cobbles on surface
		10 - 25	Btk	30	2.5Y 4/2 moist	ES	* Depths > 65 cm heavy clay layer
		25 - 65	Bk	30	2.5Y 4/3 moist	secondary lime	* Calcareous to soil surface
		>65	By	>45		high levels gypsum	

Site	Landscape Location	Depth (cm)	Horizon	Clay (%)	Color	Horizon notes	General notes
Phillips	concave depositional	0 - 20	A	22	10YR 4/3 moist		* Relatively deep to carbonates
		20 - 60	Bt	36		coarse fragments	
		>60	Bk	34		strongly effervescent	
	linear concave	0 - 20	A	26	10YR 3/3 moist		
		20 - 38	Btk	42		coarse fragments	
		> 38	Bk	40			
	knoll convex	0 - 10	A	26	10YR 3/4	coarse fragments	* Gravel cap from 2 - 28 cm
		10 - 28	Bky	28		shales	* No argillic, calcareous to near surface
		28 - 75	Byz	32		calcium sulfates; salts	

Site	Landscape Location	Depth (cm)	Horizon	Clay (%)	Horizon notes	General notes
Hill	toeslope	0 - 15	A	26	10YR 3/2 moist	* South side of ridge on south end of field
		15 - 43	Bt	35	10YR 3/3 moist	
		43 - 60	Bk	22	10 YR 4/3 moist	
		60 - 122		22/45	stratified layers of sandy	
	backslope	0 - 12	A	18	10YR 4/2 moist	* Possible repetative deposition events indicated by stratified layers
		12 - 33	Bt	24	prismatic structure	
		33 - 45	Bk1	20		
		45 - 91	Bk2	24	secondary carbonates redox concentrations	
		>91	Bk3	18/24	stratified layers of fine sandy loams and loams	
	knoll convex	0 - 75	A	20 - 22	10YR 5/3 moist	* Ridge on south end of field (701D)
		> 75	C	26 - 34	evidence of carbonates stratified texture layers	* East side of study site
	knoll convex	0 - 10	A	10	10YR 5/2 moist	* Ridge on south end of field (701D)
		10 - 24	Bw	12 - 14		* West side of study site
		> 24	C	4 - 6		
far toeslope alluvial plain		0 - 10	A	30		* Middle portion of field (map unit 331B)
		10 - 33	Bt	36	pH 8.6	
		33 - 52	Bt/Bk	34	pH 8.6	
		>52	Bk	34	strongly effervescent	

APPENDIX C

REGION PARTITION MAPS

Figure 18. Results of three region partitioning schemes for the Hill site. The three partitioning methods are listed at the bottom left of the respective panels.

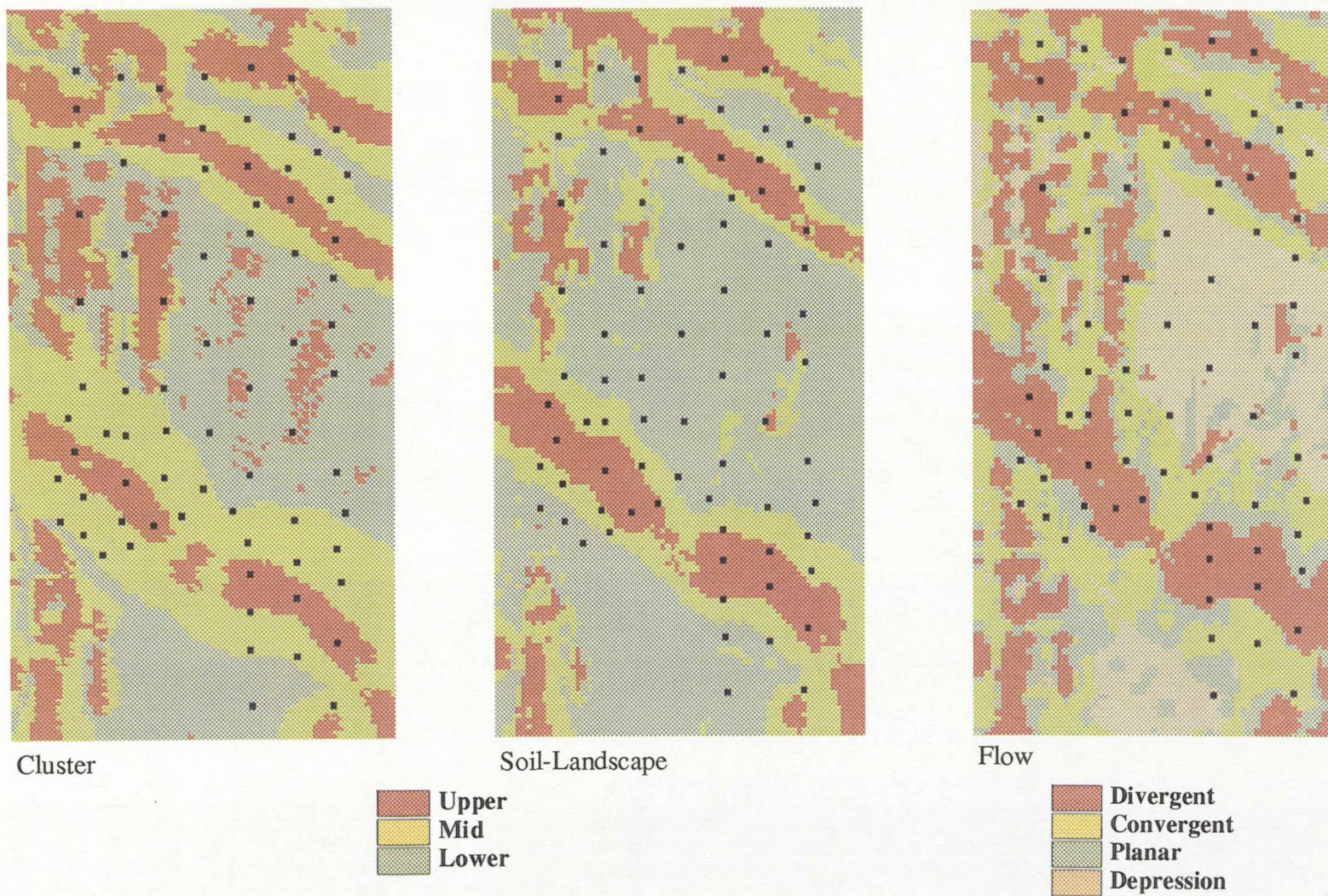


Figure 19. Results of three region partitioning schemes for the Philips 1 site. The three partitioning methods are listed at the bottom left of the respective panels.

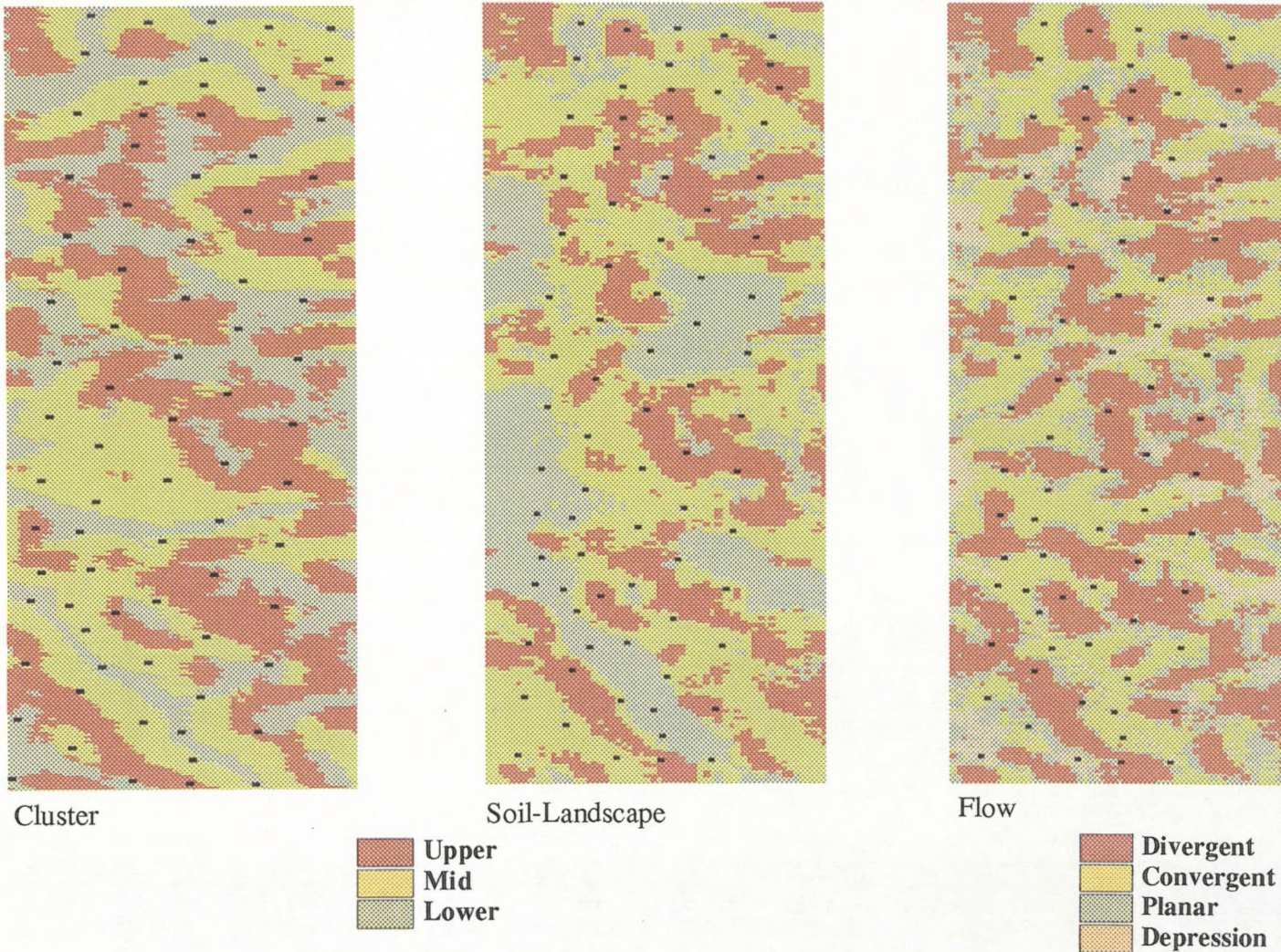
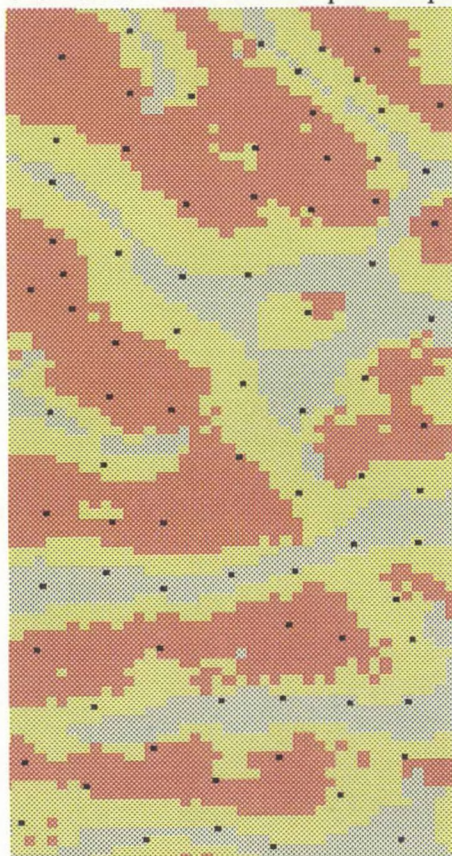
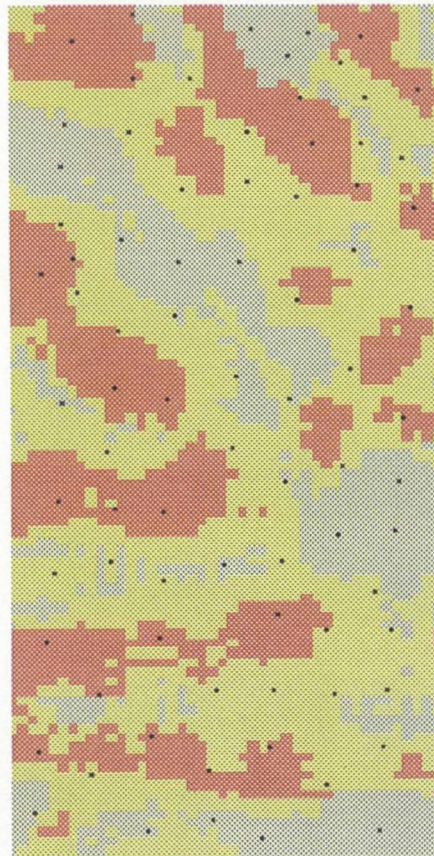


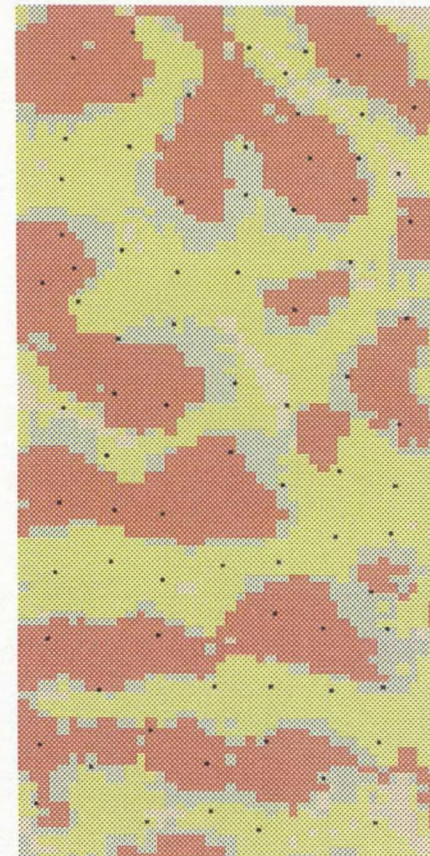
Figure 20. Results of three region partitioning schemes for the Philips 2 site. The three partitioning methods are listed at the bottom left of the respective panels.



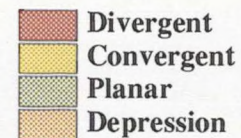
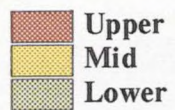
Cluster



Soil/landscape



Flow



APPENDIX D
ANOVA TABLES

Table 17. ANOVA summary for region soil water content means at Liberty. Within rows, asterisk in p-value column highlights significance at 0.05 level, and region mean values followed by the same letter are different at the 5% significance level.

Depth	Date	P-value	Region means (cm)			
			Flow			
			Divergent	Convergent	Planar	Depression
20 cm	May 30	0.535	6.97	6.74	6.68	6.95
	June 22	0.187	6.18	5.90	5.50	5.90
	July 12	0.680	4.14	4.22	3.99	4.49
60 cm	May 30	0.024*	5.04a	5.18	5.18	5.58a
	June 22	0.096	4.89	5.01	4.91	5.38
	July 12	0.055	3.77	3.72	3.83	4.37
top 70 cm	May 30	0.352	17.11	16.92	17.09	17.87
	June 22	0.484	15.80	15.30	15.14	16.27
	July 12	0.198	11.32	11.19	11.25	12.67
Soil-Landscape						
Depth	Date	P-value				
			Upper	Mid	Lower	
20 cm	May 30	0.737	6.95	6.79	6.83	
	June 22	0.339	6.16	5.85	5.75	
	July 12	0.320	4.29	3.96	4.35	
60 cm	May 30	0.043*	5.03a	5.21	5.42a	
	June 22	0.313	4.89	4.99	5.18	
	July 12	0.425	3.79	3.82	4.05	
top 70 cm	May 30	0.683	17.04	17.17	17.44	
	June 22	0.836	15.84	15.83	15.74	
	July 12	0.405	11.52	11.15	11.95	
Cluster						
Depth	Date	P-value				
			Upper	Mid	Lower	
20 cm	May 30	0.435	7.03	6.77	6.82	
	June 22	0.364	6.19	5.81	5.80	
	July 12	0.561	4.25	4.03	4.32	
60 cm	May 30	0.137	5.19	5.08	5.38	
	June 22	0.217	5.08	4.87	5.14	
	July 12	0.143	3.96	3.71	4.08	
top 70 cm	May 30	0.536	17.34	16.98	17.36	
	June 22	0.378	16.11	15.35	15.79	
	July 12	0.495	11.54	11.20	11.86	

Table 18. ANOVA summary for region soil water content means at Hill. Within rows, asterisk in p-value column highlights significance at 0.05 level, and region mean values followed by the same letter are different at the 5% significance level.

Depth	Date	P-value	Region means (cm)			
			Flow			
			Divergent	Convergent	Planar	Depression
20 cm	June 8	0.319	5.19	5.91	6.36	6.55
	June 23	0.198	3.65	3.98	4.88	4.69
	July 20	0.109	3.04	3.67	4.32	3.80
60 cm	June 8	0.117	4.16	4.71	4.16	4.51
	June 23	0.281	3.84	3.99	4.56	4.26
	July 20	0.400	2.70	2.87	3.28	3.18
top 70 cm	June 8	0.142	13.64	15.41	16.59	16.32
	June 23	0.118	11.09	11.74	13.64	13.48
	July 20	0.070	8.11	9.34	10.69	10.44
Soil-Landscape						
Depth	Date	P-value				
			Lower	Mid	Upper	
20 cm	June 8	0.015*	6.64a	6.37	5.07a	
	June 23	0.011*	4.87a	4.12	3.37a	
	July 20	0.001*	4.34a	3.63	2.78a	
60 cm	June 8	0.586	4.50	4.94	4.57	
	June 23	0.722	4.22	4.01	3.98	
	July 20	0.020*	3.35a	2.81	2.60a	
top 70 cm	June 8	0.084	16.16	16.41	14.07	
	June 23	0.041*	13.35a	11.98	10.87a	
	July 20	0.000*	11.03ab	9.02b	7.68a	
Cluster						
Depth	Date	P-value				
			Lower	Mid	Upper	
20 cm	June 8	0.001*	7.23ab	5.07b	5.69a	
	June 23	0.000*	5.33ab	3.30b	4.11a	
	July 20	0.000*	4.65ab	2.99b	3.41a	
60 cm	June 8	0.307	4.68	4.15	4.73	
	June 23	0.640	4.27	3.98	4.02	
	July 20	0.014*	3.34a	2.56a	3.11	
top 70 cm	June 8	0.013*	17.29a	14.18a	14.57	
	June 23	0.002*	14.09a	10.65a	12.14	
	July 20	0.000*	11.49ab	7.93b	9.14a	

Table 19. ANOVA summary for region soil water content means at Phillips 1. Within rows, asterisk in p-value column highlights significance at 0.05 level, and region mean values followed by the same letter are different at the 5% significance level.

Depth	Date	P-value	Region means (cm)			
			Flow			
			Divergent	Convergent	Planar	Depression
20 cm	June 23	0.137	6.49	6.29	6.55	7.29
	July 13	0.675	6.33	6.64	6.76	6.51
60 cm	June 23	0.076	4.93	5.28	4.99	5.50
	July 13	0.629	4.44	4.67	4.65	4.77
top 70 cm	June 23	0.886	16.36	16.54	16.38	15.86
	July 13	0.624	15.13	15.77	16.01	15.21
Soil-Landscape						
			Lower	Mid	Upper	
20 cm	June 23	0.841	6.40	6.64	6.44	
	July 13	0.191	6.75	6.62	6.15	
60 cm	June 23	0.006*	5.47a	5.07	4.83a	
	July 13	0.305	4.72	4.64	4.36	
top 70 cm	June 23	0.359	16.82	16.39	16.00	
	July 13	0.216	15.76	15.81	14.78	
Cluster						
			Lower	Mid	Upper	
20 cm	June 23	0.395	6.36	6.41	6.69	
	July 13	0.754	6.57	6.58	6.35	
60 cm	June 23	0.007*	5.39a	5.03	4.83a	
	July 13	0.152	4.66	4.71	4.29	
top 70 cm	June 23	0.887	16.35	16.31	16.55	
	July 13	0.463	15.64	15.74	14.97	

Table 20. ANOVA summary for region soil water content means at Phillips 2. Within rows, asterisk in p-value column highlights significance at 0.05 level, and region mean values followed by the same letter are different at the 5% significance level.

Depth	Date	P-value	Region means (cm)			
			Flow			
			Divergent	Convergent	Planar	Depression
20 cm	June 7	0.317	7.81	7.58	7.63	7.55
	June 22	0.015*	6.62ab	6.03a	6.25	6.06b
	July 19	0.002*	4.95ab	3.70a	4.26	3.85b
60 cm	June 7	0.913	5.02	5.08	5.09	5.11
	June 22	0.244	4.72	4.99	4.92	4.84
	July 19	0.832	3.96	3.94	3.76	3.88
top 70 cm	June 7	0.810	18.14	17.99	18.26	18.01
	June 22	0.553	16.19	15.84	16.32	16.10
	July 19	0.125	12.65	11.19	11.74	11.50
Soil-Landscape						
Depth	Date	P-value				
			Lower	Mid	Upper	
20 cm	June 7	0.364	7.71	7.58	7.82	
	June 22	0.123	6.11	6.23	6.59	
	July 19	0.084	3.83	4.25	4.81	
60 cm	June 7	0.470	5.09	5.12	4.92	
	June 22	0.063	5.05	4.93	4.61	
	July 19	0.531	4.10	3.91	3.75	
top 70 cm	June 7	0.715	18.30	18.01	18.05	
	June 22	0.969	16.13	16.03	16.03	
	July 19	0.814	11.61	11.75	12.17	
Cluster						
Depth	Date	P-value				
			Lower	Mid	Upper	
20 cm	June 7	0.011*	7.59	7.42a	7.91a	
	June 22	0.001*	6.01a	5.99b	6.69ab	
	July 19	0.004*	3.66a	4.02b	4.89ab	
60 cm	June 7	0.748	5.08	5.12	4.99	
	June 22	0.066	5.07	4.96	4.68	
	July 19	0.566	4.09	3.93	3.79	
top 70 cm	June 7	0.690	18.09	17.91	18.23	
	June 22	0.822	15.96	15.93	16.19	
	July 19	0.482	11.40	11.55	12.31	

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