Terrain analysis in support of precision farming
by Damian Jeremiah Spangrud

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Earth Sciences
Montana State University

Abstract:
Precision farming refers to the practice of "Farming Soils Not Fields". This concept means that a farm field is not thought of as a homogenous unit but as series of separate management units based on soil attributes. The delineation of these management units requires precise knowledge of the soil across the field, to gain this knowledge GPS point sampling and soil interpretation have been used. This study has two aims: (1) to quantify the relationship between sampling methods and the resultant surface; and (2) to identify relationships between measured soil attributes and selected terrain and image attributes.

GPS point data were obtained for 6,284 locations across a 20 ha farm field in southwestern Montana. These data were sampled using stratified random areal and linear sampling techniques. Elevation surfaces were then interpreted and terrain attribute surfaces derived from these samples using ANUDEM and TAPES-G. These surfaces were then compared against each other graphically and statistically. A series of maps and tables show that the stratified random areal samples produced very good results (low RMSE and Moran's I) with much fewer sample points than the linear samples.

Three soil attributes (percent organic matter (OM), depth of mollic epipedon, and pH) were modeled across the same farm field using remotely sensed imagery and derived terrain surfaces. Two spectral band ratios explained 64% of the variation in OM. Three terrain attributes (Wetness index, slope gradient, and plan curvature) explained 48% of the same variation. A combination of the imagery and terrain data explained 70% of the variance in OM using two spectral band ratios, specific catchment area, and wetness index at the 66 sampling sites. Wetness index, slope gradient, and plan curvature combined to explain 48% of the variation in mollic epipedon thickness. Elevation and wetness index combined to explain just 13% of pH.

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TABLE OF CONTENTS

TABLE OF CONTENTS-Continued

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES-Continued

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CHAPTER 1

INTRODUCTION

Precision farming refers to the practice of "Farming Soils Not Fields" (Carr et al., 1991). This concept means that a farm field is not thought of as a homogenous unit but as a series of separate management units based on soil attributes. Each mapped unit can then be managed independently of the others. Precision farming is an "old" idea which has become feasible again notwithstanding the large farm consolidations of the past fifty years. Prior to this recent period, farms were generally small enough for soil variability to be managed according to a farmer's "working knowledge" of how specific crops responded to specific soil environments across the field. Today's farms are too large to implement variable management based on "working knowledge" (Schueller et al., 1992). There can be large variations in the land resources within fields which result in crop yield variations across fields when fertilizers and pesticides are applied at a constant rate. Robert et al. (1990), Buchholz (1991), Carr et al. (1991), Wibawa (1991), and others have demonstrated the potential for using global positioning system technology (GPS) and variable rate technology (VRT) to manage for soil variability on the large farms that now dominate North American agriculture.

Soils and their variability are traditionally determined from existing USDA natural

Resource Conservation Service (NRCS) (formally the Soil Conservation Service (SCS)) soil maps; however, these maps are not produced with the locational accuracy required for variable rate applications (such as precision farming) and they do not show the full extent of the soil variability within a mapped soil (Mausbach et al., 1993). Soil scientists have proposed the use of pedo-transfer functions and geostatistics to develop soil attribute surfaces across and within mapped soil areas (e.g., Webster, 1977; Odeh et al. 1991; Burrough, 1993). Such systems use soil attribute information as the primary determinants of the resulting soil surfaces. Others have proposed using terrain attributes in conjunction with soil attributes to achieve the same end result (e.g., Klingebiel et al., 1987; Odeh et al., 1991; Moore et al., 1993a, 1993b). The terrain analysis approach requires digital elevation models (DEMs) from which terrain attributes are computed. The most widely available DEMs (1:250,000 and 1:24,000 scales) suffer from the same scale problems as current soil maps, although GPS receivers can provide rapid and relatively inexpensive data acquisition for the creation of larger scale DEMs (Tyler, 1993).

Precision farming uses VRT to alter application rates across the field, so that application rate matches the land resource base in that area of the field. Areas of the field which are traditionally over-applied with single application rates will receive decreased inputs which better match crop needs and minimize contamination of water resources. Areas which were under-applied with single application rates will have application rates increased to better address the needs of that area. VRT technology helps in improve the crop return per dollar spent on production. This matching of application rates and needs is the principal objective of precision farming.

The implementation of precision farming requires specific information about the soil and terrain attributes across the field and at the current location of the applicator. Derived terrain attributes can be used to help identify soil attribute variability beyond that of traditional SCS soil maps, and thus increase the level of accuracy of variable rate fertilizer and pesticide applications (Moore et al., 1993a, 1993b). Knowing the location of the applicator, by using a GPS receiver, takes much of the guesswork in the location of the applicator out of the "working knowledge" concept. When pre-existing field information is combined with locational data, the "working knowledge" concept is now quantified and repeatable.

Precision farming makes use of some of the leading technology of the day, but to what end? Macy Farms in Illinois have used VRT on 809.4 ha (2023 acres) since 1991 and reduced their total costs by $33.77 per hectare (Macy, 1993). Robert et al. (1990) and Carr et al. (1991) conducted multiple plot tests to evaluate the benefits of precision farming. Their results varied across the plots, but the overall profits and yields did not decrease with the new precision farming techniques. There may be additional benefits that should be considered, such as reduced water quality impacts and reduced environmental degradation, when the economic benefits do not match the additional costs of implementation of precision farming.

Precision farming faces many challenges in the future and there are a number of important questions that still have to be answered. The technology required to practice precision farming is evolving rapidly. VRT is advancing quickly as the agricultural community discovers the potential economic benefits of such a system and GPS technology is advancing at an astonishing rate as receivers which used to be vehicle- mounted and very complex can now be carried in the palm of your hand and purchased cheaply from numerous vendors. One of the most important questions, yet to be answered, has to do with the division of fields into management units. Soils will help contribute to these decisions but in what manner and what other components are be to considered are some of the important research issues that still need to be addressed.

The following chapters address two research questions related to precision farming. As GPS data is now being used to create DEMs and delineate management units, it is important to evaluate the effects that the location and pattern of GPS data can have on the resultant terrain attributes. These attributes (elevation, specific catchment area, and slope) may represent important parameters for characterizing soil-landscapes. Soil scientists have proposed numerous methods for defining terrain and soil-landscape interactions ranging from geostatistical to classic statistical techniques. These interactions are very sensitive to the modeling assumptions and interpolation schemes used to create attribute data and further work is needed to characterize these relationships. This study, therefore, addresses two sets of issues: (1) the sensitivity of the terrain attributes computed from DEMs to the number and pattern of input GPS data, and (2) the contribution of these terrain attributes and remotely sensed imagery in the prediction of soil properties throughout the field. The effect which alterations to the number and pattern of input GPS data have on the resultant DEM are explored using several sampling strategies. The soil-landscape modeling is accomplished through the use of statistical and geographical analysis of predicted values and their associated errors.

CHAPTER 2

SENSITIVITY OF COMPUTED TERRAIN ATTRIBUTES TO NUMBER AND PATTERN OF GPS-DERIVED ELEVATION DATA

Introduction

The development of digital elevation models during the past decade has encouraged research into soil attribute prediction using many complex and quantifiable soil-landform relationships. Obtaining DEMs at the appropriate scale is difficult. DEMs are available for most of the continental United States at a scale of 1:24,000 (30 meter resolution) and the entire continental United States at a scale of 1:250,000 (3 arc second resolution). Soil maps are currently produced at scales of 1:12,000, 1:15,840, 1:20,000, and 1:24,000 with a minimum mapping unit of 0.8 to 4 ha (2 to 10 acres) (Mausbach et al., 1993). DEMs at soil map scales or larger are needed for soil-terrain modeling to help improve soil attribute prediction. The use of GPS technology in conjunction with surface interpolation algorithms has been proposed as a relatively inexpensive and quick method of obtaining larger scale (higher resolution) DEMs. The effect which the number and pattern of GPS points used in this interpolation has on the resultant DEM and landscape attributes is the focus of this chapter.

GPS technology was initially developed for the United States military in the late 1970s to assist with the locating and positioning of strategic forces. Currently there are 24 GPS satellites in orbit and their orbits are configured so at least three of the satellites are visible to a receiver at any given time. The process of obtaining locational data from a GPS relies on the triangulation of at least three points (satellites). The data received from each of these satellites is validated against the others to correct for any instrumental errors. A stationary receiver used in conjunction with a mobile receiver provides the most accurate measurements, as the fixed receiver provides an additional measurement of satellite data error. GPS satellites are U.S. Department of Defense owned and operated, and certain bands (P and Y) are scrambled to limit civilian accuracy to the tens of meters level for security reasons (Tyler, 1993). However, many manufacturers have developed ways around this "problem" and they continue to obtain sub-meter accuracy using a combination of the non-encrypted signals and real time error correction.

The GPS data can be interpolated from irregular spot heights to a regularly spaced elevation surface using several different interpolation algorithms. There are many grid interpolation algorithms in use today and these range from simple nearest-neighbor calculations to complex thin-plate spline algorithms. The most commonly used algorithms are those which attempt to minimize the variance across the surface and eliminate pits which may result from coarse surface interpolation (with the assumption pits are rare in nature and occur mainly in areas of recent glaciation or karst topography). Four major types of interpolation algorithms have been proposed: (1) local interpolation methods, (2) moving averages, (3) kriging and (4) partial thin-plate (or Laplacian) smoothing splines (Moore and

Hutchinson, 1991; Hutchinson and Gessler, 1994).

Local interpolation techniques apply simple fitted functions across small overlapping subsets of the entire dataset. The resultant values from this technique are quite sensitive to the spacing of the input data points, especially in cases of irregular data sets, and may result in the generation of numerous spurious pits in the data. Much of this sensitivity is due to the rigidness and local area focus of the functions. The functions can become quite complex and indeterminate when applied to more complex datasets and they cannot be easily adapted to the smoothing of noisy data (Hutchinson, 1989; Moore and Hutchinson, 1991).

Moving averages are often used for surface interpolation. The method is simplistic in nature in that the value at a given location is assumed to be a distance weighted average of surrounding data values. The distance weighting function uses a defined search radius to locate the values for this weighting. Data sets with sparse or irregular data used with this technique have the problem that the search radius may not include the required data for an accurate interpolation. The smoothing of data values becomes a concern in areas of sparse data when the search radius is defined as a very large region (Moore and Hutchinson, 1991).

Kriging uses a modification of the weighted-moving average, with the weights now computed to minimize the variance across the surface. This method assumes positive spatial autocorrelation between data. The variance used in kriging is a function of the semivariogram and the separation of the data points. Semi-variograms are plots of the total variance across the surface against distance from any given location on the surface. A function is fitted to this computed semivariogram that, in the best case scenario, defines the best fit curve to the semivariogram to minimize the interpolated variance. The elevation for the interpolated locations is computed as a result of the moving average using the fitted semi-variogram function as the weighting factor (Isaaks and Srivastava, 1989; Cressie, 1991; Moore and Hutchinson, 1991). The selection and definition of a optimal semi-variogram function and associated parameters by the user may be difficult because real world data seldom conform to simple functions, and kriging's sensitivity to anomalous data may cause additional complications.

Partial thin plate (Laplacian) splines are formally related to kriging but do not require the computation or the imposition of semi-variograms. Smoothing parameters are used which determine the trade-off between data fidelity and smoothing. The smoothing parameters are computed for each location by minimizing the generalized cross validation (GCV). The GCV is a measure of the predictive error of the fitted function. It is calculated by systematically removing each point used in fitting the initial function and refitting the function and measuring the change in the predicted value. These parameters allow for the data to be interpolated while eliminating anomalous data. Partial thin plate splines have excellent functionality in their automatic computation of the smoothing parameters and the model fitting. Kriging and partial thin plate splines compare well when the appropriate semi-variograms are used in the kriging process (Cressie, 1991; Moore and Hutchinson, 1991). The main disadvantage of splines is their complexity and the need for elaborate computer programs to generate the functions.

The surfaces (DEMs) which result from these interpolation methods provide the basis for the calculation of topographically important attributes. Dikau (1989) summarized the landform attributes which can be computed from DEMs, and proposed a method for dividing landscapes into relief units based on slope, plan curvature, and profile curvature attributes. Odeh et al. (1991) added upslope distance and upslope area to Dikau's list and found that these accounted for the largest amount of soil variability within their study area. Moore et al. (1991) defined these primary terrain attributes and their significance (Table 1) and Moore et al. (1993a, 1993b) related soil variability to these primary attributes as well as several secondary terrain attributes (wetness index, stream power index, and transport capacity index).

Materials and Methods

Study Area

The study area is located on a farm in the Gallatin Valley of southwest Montana. Data were collected over a 20.23 ha (40 acre) portion of a field owned by Bill Wright and located near the community of Springhill, Montana (T1N R6E Sec 8; Figure 1). The Wright farm is located at the base of the Bridger Mountains (2,700-2,950 m) which run to the north and east of the farm. The site itself has a general southerly aspect, moderate relief (43 m) and an average elevation of approximately 1,509 m. A small intermittent stream runs through the field in a south-south-westerly direction (Figure 2). The soils in the field are complexes of fine-loamy, mixed mineralogy Pachic and Udic Haploborolls and Argiborolls. The field has been farmed for about 50 years with a grain-fallow rotation.

Table 1. Primary topographic attributes that can be computed by terrain analysis from DEM data.(adapted from Moore et al., 1991, 1993d)

Attribute	Definition	Significance
Altitude	Elevation	-Climate, vegetation, potential energy
Upslope height	Mean height of upslope area	-Potential energy
Aspect	Slope azimuth	-Solar insolation, evapotranspiration, flora and fauna distribution and abundance
Slope	Gradient	-Overland and subsurface flow velocity and runoff rate, precipitation, vegetation, geomorphology, soil water content, land capability class
Upslope slope	Mean slope of upslope area	-Runoff velocity
Dispersal slope	Mean slope of dispersal area	-Rate of soil drainage
Catchment slope	Average slope over catchment	-Time of concentration
Upslope area	Catchment area above a short length of contour	-Runoff volume, steady state runoff rate
Dispersal area	Area downslope from a short length of contour	-Soil drainage rate
Catchment area	Area draining to a outlet	-Runoff volume
Specific catchment area	Upslope area per unit width of contour	-Runoff volume, steady-state runoff rate, soil characteristics, soil water content, geomorphology
Flow path length	Maximum distance of water flow to a point in the catchment	-Erosion rates, sediment yield, time of concentration
Upslope length	Mean length of flow paths to a point in the catchment	-Flow acceleration, erosion rates
Dispersal length	Distance from a point in the catchment to the outlet	-Impedance of soil drainage
Catchment length	Distance from the highest point to the outlet	-Overland flow attenuation
Profile curvature	Slope profile curvature	-Flow acceleration, erosion/ and deposition rate, geomorphology
Plan Curvature	Contour curvature	-Converging/diverging flow, soil water content, soil characteristics