



LIBRARY
Michigan State
University

This is to certify that the

dissertation entitled

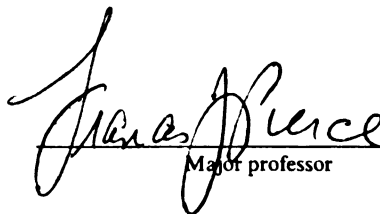
THE POTENTIAL FOR SITE-SPECIFIC MANAGEMENT
OF SOIL AND CORN YIELD VARIABILITY INDUCED
BY TILLAGE

presented by

JOSE CORA

has been accepted towards fulfillment
of the requirements for

PhD degree in CROP & SOIL science


Major professor

Date December 12, 1997

PLACE IN RETURN BOX to remove this checkout from your record.
 TO AVOID FINES return on or before date due.
 MAY BE RECALLED with earlier due date if requested.

DATE DUE	DATE DUE	DATE DUE
SEP 06 2005 11 26 05		
MAY 27 2006		
05 31 10		

THE POTENTIAL FOR SITE-SPECIFIC MANAGEMENT OF SOIL AND CORN
YIELD VARIABILITY INDUCED BY TILLAGE

By

Jose Eduardo Cora

A DISSERTATION

Submitted to
Michigan State University
In partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Crop and Soil Sciences

1997

ha field in central Michigan relative to site-specific management.

ABSTRACT

THE POTENTIAL FOR SITE-SPECIFIC MANAGEMENT OF SOIL AND CORN YIELD VARIABILITY INDUCED BY TILLAGE

By

JOSE EDUARDO CORA

Site-specific management (SSM) for agriculture is a recent concept in soil and crop management that involves the management of the localized conditions within a field. Success in SSM depends on how accurately farmers can delineate areas within fields which require similarly manage inputs. A required first step in the development of SSM strategies is the accurate assessment of the spatial variability of factors, both natural and use-dependent, which regulate the soil-plant-atmosphere system. Therefore, accurate knowledge of variability in soils and landscapes and understanding its relationship to variability of crop yield and/or quality is essential to SSM. This study examines three specific objectives relative to understanding the variability in soils and crops within a field. First, this study assesses the value of soil survey in delineating site-specific management zones by examining the quality of soil map units within an existing soil survey in terms of map unit purity and assessing the magnitude and nature of the spatial variability in soil physical properties as expressed by different sampling designs. Second, this study examines how corn yield varies spatially, how tillage alters soil properties and corn yield, and the extent to which variation in soil properties relate to variability in corn yield. Third, this study evaluates the potential for proven crop simulation models to account for spatial variability in corn yield within a field. A field study was initiated in 1995 to quantify how tillage affected the spatial variability in soils and corn within 3.72

ha field in central Michigan relative to its potential for site-specific management.

Variability was assessed by applying different sampling schemes and measuring soil profile characteristics, soil physical properties and carbon contents of the surface horizon, soil water content and water table depth over time, and productivity of corn over two growing seasons. The soils within the experimental area were quite variable and did not correspond well to the soil map units given in the county soil survey maps. The current soil survey for this field is not accurate and of little value to SSM. The 30.5 m grid described the average condition well but did not accurately describe the spatial variability in soil physical properties. An intensive geostatistical sampling design produced very good estimates of the semivariogram and indicated a strong spatial dependence of all soil physical and soil texture properties measured. Such detailed measurements are too costly for SSM and these results support the development of sensors for increasing the sampling intensity needed for assessing variability. Tillage altered soil physical properties and soil water availability both in their magnitude and spatial structure and altered the spatial variability of corn grain yield differently each year. Soil properties and soil water measurements were of little value in explaining corn grain yields using stepwise regression techniques. However, simulation of the variability in corn yield using the CERES-maize crop simulation model correlated well to measured yields for 1995 but failed to account for water flux from the water table that appeared to regulate corn yields in 1996. There is a potential for crop models to simulate the spatial and temporal variability in yields. Overall, the potential for SSM in this field may be limited by a lack of correspondence between the spatial variability in soils and the temporal nature of variability in corn yield observed during the two years of this study.

I thank my colleagues **ACKNOWLEDGEMENTS** sciences at UNESP-

Jaboticabal, SP, Brazil for their support. A special thanks goes to Celia Bueno for taking

care of I would like to thank my major advisor, Dr. Francis Pierce, for his enthusiastic support, encouragement, and constant friendship throughout the four years that I studied under his guidance. Dr. Pierce always managed to find enough room in his busy schedule in the preparation of this manuscript.

This work benefited greatly from the vision and advice of my committee members: Dr. Alvin Smucker, Dr. Delbert Mokma, and Dr. George Merva. I wish to thank Dr. Ritchie for teaching and helping me understand crop simulation models. I also wish to thank Dr Renate Snider for helping me on the difficult task of writing.

I would like to express my gratitude to CNPq (National Council for Scientific and Technological development, Brazil) and the Universidade Estadual Paulista (UNESP), whose financial support made possible the completion of my degree.

I would like to acknowledge Michigan State University for providing me with the opportunity to participate in the doctoral program offered by the Department of Crop and Soil Science.

A special thanks goes to Tom Mueller for his friendship and for patiently spending innumerable hours teaching me computer skills, which saved me long hours of frustration. My appreciation also goes to Cal Bricker and William Bauer, who gave their benevolent help to conduct the experiment. I thank Brian Long for his technical assistance in the field work. John Anibal is gratefully acknowledged for allowing me to use his farm. I would like to thank Bruno Basso and Brian Baer for their precious technical expertise in simulation crop models and friendship.

I thank my colleagues from the Department of Soil Sciences at UNESP-Jaboticabal, SP, Brazil for their support. A special thanks goes to Celia Bueno for taking care of my personal business. I also thanks the members from the Brazilian Community Association at Michigan State University, specially Moacir Dias Junior, Jose Lima, Djail Santos, Carlos Paglis, for their friendship. A special thanks goes to Luis Roberto Guilherme for his unquestionable friendship. Thanks also go to Ricardo, Clarice,

Ricardinho and Gabriela for providing a home-like atmosphere during this long period.

Special thanks goes to my wife, Ana Luiza, and my daughter, Ana Clara who have always supported and encouraged me to complete this degree and to whom I am grateful for their love and understanding.

Finally I would like to thank my parents Nelson and Doracy for their love and support.

CHAPTER 2 EFFECT OF SOIL PHYSICAL AND TILLAGE SYSTEMS ON CORN GRAIN YIELD.

INTRODUCTION.....	51
MATERIALS AND METHODS.....	53
RESULTS AND DISCUSSIONS.....	60
Tillage Effects on Soil Properties.....	60
Tillage Impacts on Corn Yield.....	66
Influence of Soil Properties on Corn Grain Yield.....	74
CONCLUSIONS.....	76

CHAPTER 3 SIMULATION OF WITHIN FIELD VARIABILITY OF CORN YIELD WITH CERES-MAIZE MODEL.

INTRODUCTION.....	78
MATERIALS AND METHODS.....	80
RESULTS AND DISCUSSIONS.....	84
Model Calibration.....	84
Simulation of Spatial Variability.....	85
CONCLUSIONS.....	96
REFERENCES.....	97

LIST OF TABLES.....	viii
LIST OF FIGURES.....	x
INTRODUCTION.....	1
CHAPTER 1 APPLICABILITY OF SOIL SURVEY AND SOIL PROPERTIES MAPS FOR SITE-SPECIFIC MANAGEMENT.	
INTRODUCTION.....	7
MATERIALS AND METHODS.....	10
Site Description.....	10
Statistical Analysis.....	17
RESULTS AND DISCUSSIONS.....	17
Map Unit Purity.....	17
Spatial Analysis of Soil Physical Properties.....	29
Spatial Analysis for the Regular Grid.....	29
Variation in Surface Soil Properties.....	40
Variation in Soil Profile Properties.....	42
Effect of Scale on Estimation of Spatial Variability in Surface Soil Properties.....	44
CONCLUSIONS.....	50
CHAPTER 2 EFFECT OF SOIL PHYSICAL AND TILLAGE SYSTEMS ON CORN GRAIN YIELD.	
INTRODUCTION.....	51
MATERIALS AND METHODS.....	53
RESULTS AND DISCUSSIONS.....	60
Tillage Effects on Soil Properties.....	60
Tillage Impacts on Corn Yield.....	66
Influence of Soil Properties on Corn Grain Yield.....	74
CONCLUSIONS.....	76
CHAPTER 3 SIMULATION OF WITHIN FIELD VARIABILITY OF CORN YIELD WITH CERES-MAIZE MODEL.	
INTRODUCTION.....	78
MATERIALS AND METHODS.....	80
RESULTS AND DISCUSSIONS.....	84
Model Calibration.....	84
Simulation of Spatial Variability.....	85
CONCLUSIONS.....	96
REFERENCES.....	97

SUMMARY AND CONCLUSIONS.....105

Table 1.1 Map unit descriptions, area within the experimental site, and population of grid samples falling within map unit for the experimental field in Durand, Michigan.....12

Table 1.2. Description of variables with the respective symbols used in the study.....16

Table 1.3. Descriptive statistics and parameters for variogram models of variables obtained from undisturbed soil profile cores (5 cm i.d. by 1 m) within the 30.5 m regular grid (N=55).....30

Table 1.4. Descriptive statistics and parameters for variogram models of variables obtained from soil cores within 30.5 m regular grid (N=55).....31

Table 1.5. Descriptive statistics and parameters for variogram models of variables obtained from soil cores (7.6 by 7.6 cm) within the geostatistical grid (N=162).....45

Table 1.6. Descriptive statistics and parameters for variogram models of soil textural analysis of the Ap horizon for the 30.5 m regular grid (N=55) and for the geostatistical grid (N=419).....48

Table 2.1. Description of variables with the respective symbols used in the stepwise regressions.....58

Table 2.2. Descriptive statistics and variogram model parameters total carbon (TC) and aggregate stability (AS) for both tillage systems after two growing seasons (1996).....60

Table 2.3. Results of paired *t* statistic test on means of selected soil properties for different tillage systems after two growing seasons.....61

Table 2.4. Descriptive statistics and variogram models parameters of variables obtained from soil cores (7.6 by 7.6 cm) within the field geostatistical grid (n=162) for both tillage systems.....64

Table 2.5. Descriptive statistics and variogram model parameters of corn grain yield for both tillage systems in 1995 and 1996.....67

Figure 2.6. Descriptive statistics and variograms models parameters of grain moisture (GrM), plant population (PP), and stover yield (SB) for both tillage systems in 1995 and 1996.....73

Table 2.7. Results of stepwise regression of no-tillage corn grain yield and soil properties for two years.....74

Table 2.8. Results of stepwise regression between no-till and chisel plow corn grain yield and soil properties for 1995.....	75
---	----

LIST OF TABLES

Table 1.1 Map unit descriptions, area within the experimental site, and population of grid samples falling within map unit for the experimental field in Durand, Michigan.....	12
Table 1.2. Description of variables with the respective symbols used in the study.....	16
Table 1.3. Descriptive statistics and parameters for variogram models of variables obtained from undisturbed soil profile cores (5 cm i.d. by 1 m) within the 30.5 m regular grid (N=55).....	30
Table 1.4. Descriptive statistics and parameters for variogram models of variables obtained from soil cores within 30.5 m regular grid (N=55).....	31
Table 1.5. Descriptive statistics and parameters for variogram models of variables obtained from soil cores (7.6 by 7.6 cm) within the geostatistical grid (N=162).....	45
Table 1.6. Descriptive statistics and parameters for variogram models of soil textural analysis of the Ap horizon for the 30.5 m regular grid (N=55) and for the geostatistical grid (N=419).....	48
Table 2.1. Description of variables with the respective symbols used in the stepwise regressions.....	58
Table 2.2. Descriptive statistics and variogram model parameters total carbon (TC) and aggregate stability (AS) for both tillage systems after two growing seasons (1996).....	60
Table 2.3. Results of paired <i>t</i> statistic test on means of selected soil properties for different tillage systems after two growing seasons.....	61
Table 2.4. Descriptive statistics and variogram models parameters of variables obtained from soil cores (7.6 by 7.6 cm) within the field geostatistical grid (n=162) for both tillage systems.....	64
Table 2.5. Descriptive statistics and variogram model parameters of corn grain yield for both tillage systems in 1995 and 1996.....	67
Figure 2.6. Descriptive statistics and variograms models parameters of grain moisture (GrM), plant population (PP), and stover yield (SB) for both tillage systems in 1995 and 1996.....	73
Table 2.7. Results of stepwise regression of no-tillage corn grain yield and soil properties for two years.....	74

Table 2.8. Results of stepwise regression of the difference between no-till and chisel plow corn grain yield and soil properties for 1995.....	75
Figure 1.1. The Order two soil survey map (2:20000 scale; Threlkeld and Feenstra, 1974)	
Table 3.1. Soil characteristics of the profile 15 used in the calibration of CERES-Maize model.....	82

Figure 1.2. Location of the 30.5 m regular (A), geospatial analysis (N=162) (B), and geospatial analysis (N=419) (C) grids relative to the map units from the Order two soil survey. Refer to Table 1.1 for map units descriptions.....	14
Figure 1.3. Location of the grid soil profile samples relative to the units from the Order two soil survey. Refer to Table 1.1 for map units descriptions.....	18
Figure 1.4. Representative soil profile of the Breckenridge sandy loam 0 to 2% (Bt) as given in the Soil Survey of Shiawassee County, MI (Threlkeld and Feenstra, 1974) and the grid profiles falling within the map unit. Refer to Table 1.1 for map units descriptions....	19
Figure 1.5. Representative soil profile of the Conover loam 0 to 2% (Cta) as given in the Soil Survey of Shiawassee County, MI (Threlkeld and Feenstra, 1974) and the grid profiles falling within the map unit. Refer to Table 1.1 for map units descriptions.....	20
Figure 1.6. Representative soil profile of the Metamora loam 2 to 6% (MaB) as given in the Soil Survey of Shiawassee County, MI (Threlkeld and Feenstra, 1974) and the grid profiles falling within the map unit. Refer to Table 1.1 for map units descriptions.....	21
Figure 1.7. Representative soil profile of the Macomb loam 0 to 2% (MaA) as given in the Soil Survey of Shiawassee County, MI (Threlkeld and Feenstra, 1974) and the grid profiles falling within the map unit. Refer to Table 1.1 for map units descriptions.....	22
Figure 1.8. Representative soil profile of the Wasepi sandy loam 0 to 2% (WeA) as given in the Soil Survey of Shiawassee County, MI (Threlkeld and Feenstra, 1974) and the grid profiles falling within the map unit. Table 1.1 for map units descriptions.....	23
Figure 1.9. Interpolated maps of clay (A), silt (B), and sand (C) contents (%) of the Ap horizon for the 30.5 m grid. Refer to Table 1.1 for map units descriptions.....	25
Figure 1.10. Interpolated maps of clay content (%) of the Bt horizon (A), thickness of the Bt horizon (cm) (B), and depth of the Bt horizon (cm) (C) for the 30.5 m regular grid. Refer to Table 1.1 for map units descriptions.....	26
Figure 1.11. Interpolated maps of clay (A), silt (B), and sand (C) content (%) of the C horizon for the 30.5 m regular grid. Refer to Table 1.1 for map units descriptions.....	27

Figure 1.12. Interpolated maps of volumetric water content (%) at -6 kPa (A), -33 kPa (B), and -100 kPa (C) for the 30.5 m regular grid. Refer to Table 1.1 for map units descriptions.....11

Figure 1.1. The Order two soil survey map (2:20000 scale; Threlkeld and Feenstra, 1974) (A) and a high resolution Digital Elevation Model (m) for the experimental field (B).....11

Figure 1.2. Location of the 30.5 m regular (A), geospatial analysis (N=162) (B), and geospatial analysis (N=419) (C) grids relative to the map units from the Order two soil survey. Refer to Table 1.1 for map units descriptions.....14

Figure 1.3. Location of the grid soil profile samples relative to the units from the Order two soil survey. Refer to Table 1.1 for map units descriptions.....18

Figure 1.4. Representative soil profile of the Breckenridge sandy loam 0 to 2% (Bt) as given in the Soil Survey of Shiawassee County, MI (Threlkeld and Feenstra, 1974) and the grid profiles falling within the map unit. Refer to Table 1.1 for map units descriptions.....19

Figure 1.5. Representative soil profile of the Conover loam 0 to 2% (Cta) as given in the Soil Survey of Shiawassee County, MI (Threlkeld and Feenstra, 1974) and the grid profiles falling within the map unit. Refer to Table 1.1 for map units descriptions.....20

Figure 1.6. Representative soil profile of the Metamora loam 2 to 6% (MsB) as given in the Soil Survey of Shiawassee County, MI (Threlkeld and Feenstra, 1974) and the grid profiles falling within the map unit. Refer to Table 1.1 for map units descriptions.....21

Figure 1.7. Representative soil profile of the Macomb loam 0 to 2% (MaA) as given in the Soil Survey of Shiawassee County, MI (Threlkeld and Feenstra, 1974) and the grid profiles falling within the map unit. Refer to Table 1.1 for map units descriptions.....22

Figure 1.8. Representative soil profile of the Wasepi sandy loam 0 to 2% (WeA) as given in the Soil Survey of Shiawassee County, MI (Threlkeld and Feenstra, 1974) and the grid profiles falling within the map unit. Refer to Table 1.1 for map units descriptions.....23

Figure 1.9. Interpolated maps of clay (A), silt (B), and sand (C) contents (%) of the Ap horizon for the 30.5 m grid. Refer to Table 1.1 for map units descriptions.....25

Figure 1.10. Interpolated maps of clay content (%) of the Bt horizon (A), thickness of the Bt horizon (cm) (B), and depth of the Bt horizon (cm) (C) for the 30.5 m regular grid. Refer to Table 1.1 for map units descriptions.....26

Figure 1.11. Interpolated maps of clay (A), silt (B), and sand (C) content (%) of the C horizon for the 30.5 m regular grid. Refer to Table 1.1 for map units descriptions.....27

Figure 2.2. Percent difference (NT-CP) in profile volumetric water content at different depths and on different dates.....45

Figure 1.12. Interpolated maps of gravimetric water content (%) at -6 kPa (A), -33 kPa (B), and -100 kPa (C) for the 30.5 m regular grid. Refer to Table 1.1 for map units description.....	32
Figure 1.13. Interpolated maps of volumetric water content (%) at -6 kPa (A), -33 kPa (B), and -100 kPa (C) for the 30.5 m regular grid. Refer to Table 1.1 for map units description.....	33
Figure 1.14. Interpolated maps of air filled porosity (%) at -6 kPa (A), -33 kPa (B), and -100 kPa (C) for the 30.5 m regular grid. Refer to Table 1.1 for map units description.....	34
Figure 1.15. Interpolated maps of gravimetric water content (%) at -1500 kPa (A), volumetric available water (%) (B), and gravimetric available water (%) (C) of the Ap horizon for the 30.5 m regular grid. Refer to Table 1.1 for map units description.....	35
Figure 1.16. Interpolated maps of Thickness of the Ap horizon (cm) (A), and Total carbon (%) in the top 5 cm (B), for the 30.5 m regular grid. Refer to Table 1.1 for map units description.....	36
Figure 1.17. Interpolated maps of profile clay content up to 1 m (%) (A), profile clay + silt content up to 1 m (%) (B), and profile available water (%) (C) for the 30.5 m regular grid. Refer to Table 1.1 for map units description	37
Figure 1.18. Interpolated maps of maximum (A) and minimum (B) water table depth (m) for the 30.5 m regular grid in 1995. Refer to Table 1.1 for map units description.....	38
Figure 1.19. Interpolated maps of bulk density (g/cm^3) (A) and total porosity (%) (B) on the surface 7.6 cm for the 30.5 m regular grid. Refer to Table 1.1 for map units description.....	39
Figure 1.20. Volumetric water content at -33 kPa on the surface 7.6 cm for the 30.5 m grid scale (A) and the geospatial scale (B). Refer to Table 1.1 for map units description.....	46
Figure 1.21. Interpolated map of clay (A), silt (B), and sand (C) contents (%) for the geospatial grid (N=419).....	47
Figure 2.1. Location of the grid soil profile samples relative to the map units from the Order two soil survey (A) and detail of the tillage strips (B). Refer to Table 1.1 for map units description. Refer to Table 1.1 for map units description.....	55
Figure 2.2. Percent difference (NT-CP) in profile volumetric water content at different depths and on different dates.....	65

Figure 2.3. Interpolated maps of corn grain yield (kg /ha) for no-tillage (A), chisel plow (B), the difference between no-tillage and chisel plow by subjecting the difference to geostatistical analysis (C), and by subtracting (B) from (A) (D) for 1995.....68

Figure 2.4. Interpolated maps of corn grain yield (kg/ha) for no-tillage (A), chisel plow (B), the difference between no-tillage and chisel plow by subjecting the difference to geostatistical analysis (C), and by subtracting (B) from (A) (D) for 1996.....69

Figure 2.5. Interpolated maps of average of the two years of corn grain yield (kg/ha) for no-tillage (A), chisel plow (B), the difference between no-tillage and chisel plow by subjecting the difference to geostatistical analysis (C), and by subtracting (B) from (A) (D).....70

Figure 3.1 Location of the grid soil profile samples relative to the units from the Order two soil survey. Refer to Table 1.1 for map units descriptions.....81

Figure 3.2. Plot of measured and simulated corn grain yield for 1995.....86

Figure 3.3. Frequency distribution, mean, standard deviation (STD), and coefficient of variation (CV) for measured and simulated corn grain yield for 1995.....87

Figure 3.4. Measured (A), simulated (B), and difference between measured and simulated (C) of corn grain yield (kg/ha) for 1995.....88

Figure 3.5. Precipitation recorded at the experimental area from April 1st to October 31st, 1996.....9

Figure 3.6. Maximum water table depth (m) for the experimental site in 1996.....91

Figure 3.7. Volumetric soil water contents (%) at drainage upper limit and lower limit for the grid point 15 and volumetric soil water content in different dates.....92

Figure 3.8. Frequency distribution, mean, standard deviation (STD), and coefficient of variation (CV) for measured and simulated corn grain yield for 1996.....93

Figure 3.9. Plot of measured and simulated corn grain yield for 1996.....94

Figure 3.10. Measured (A), simulated (B), and difference between measured and simulated (C) of corn grain yield (kg/ha) for 1996.....95

INTRODUCTION

Site-specific management (SSM) for agriculture is a recent concept in soil and crop management that involves knowledge of the localized conditions within a field to be managed (Pierce et al., 1997). This new management concept offers farmers opportunities to increase crop production, optimize resource use, and reduce the potential undesirable effects of agriculture on environmental quality (Robert, 1993). Since the aim of SSM is to assess variability within fields and manage for that variability, knowledge of soil variability within a field is a required first step in the development of SSM strategies.

Variability of soil properties results in spatially varying crop yields. One challenge in site-specific management is to determine which major factors are responsible for variations in crop yield. According to Mulla and Schepers (1997), some of the more important factors include spatial patterns in pest infestations, plant available water, soil drainage, crop rooting depth, nutrient availability, soil texture, organic matter content and pH. Soil survey-mapping units and nutrient maps have been used in SSM to assess the soil variability within fields. When currently available soil survey information is used, however, the relationship between soil mapping units is not always strong (Pierce et al., 1995). Soil maps are usually drawn at scales from 1:12000 to 1:24000, which probably mask important sources of variability in site-specific management operations. Soil mapping units often contain inclusions that are important and standard soil survey maps

may not provide the fine-scale resolution required for site-specific management (Robert, 1993; Moore et al., 1993; Mausbach et al., 1993; Pierce et al., 1995). The emphasis in SSM has been on fertilizer management, although correlation between nutrient and yield maps is not always strong (Pierce et al., 1995; Everett and Pierce, 1996). However, plant available water, soil physical and morphological properties, and landscape attributes may be more important than soil fertility in explaining crop yield variability. The importance of texture (Han et al., 1996; Khakural et al., 1996), soil moisture (Jaynes et al., 1995) and landscape attributes (Khakural et al., 1996; Lindstrom et al., 1995), for the development of soil management zones in SSM is beginning to be recognized.

Studies have shown that soil properties frequently exhibit spatial dependence, i.e., samples collected close to one another are often more similar in value than widely spaced samples (Trangmar et al., 1985). Mallants et al. (1996) found spatial structure for water retention data in a multi-layered soil profile. In recent years, there have been important advances in geostatistical methods for the detection and characterization of spatial dependence of soil properties. The process involves estimating the semivariogram that describes the dependence among samples as a function of direction and separation distance, and fitting the appropriate model to the semivariogram (Issaks and Srivastava, 1989). A variogram is basically a plot of dissimilarity (semi-variance) between samples against distance between samples (see, for example, Issaks and Srivastava, 1989). The semi-variance ideally increases with distance between sample location, to a more or less constant value (the sill or total semi-variance) at a given separation distance, called the range of the spatial dependence (Trangmar et al., 1985). Samples separated by distances

closer than the range are spatially related. Those separated by distances greater than the range are not spatially related. The semi-variance, when the distance of sample separation tends to zero, is called the nugget variance or nugget effect (Webster, 1985). It gives an indication of variability at scales less than the data spacing and/or of measurement error. The sampling design is important for accurate estimation of the shape of the semivariogram. Each distance class in the semivariogram computation must be represented by a sufficient number of pairs of data points (Wollenhaupt et al., 1997). A low number of available data pairs will result in abrupt changes in the variogram over small lag differences (Entz and Chang, 1991) and too wide a distance between samples will affect the shape of the variogram near the origin. Therefore, collecting some samples at smaller spacing is recommended (Wollenhaupt et al., 1997). However, recommendations for sampling designs are not unanimous: Journel and Huijbregts (1978) suggested at least 30 to 50 pairs as a minimum for calculation of each distance class of the variogram, while Webster and Oliver (1990) suggested at least 100 pairs.

Soil variability can occur naturally as a result of complex geological and pedological processes or by anthropogenical processes. Identical land units from a pedological point of view can act quite differently when subjected to different managements. The major agricultural management tool affecting soil properties is tillage (Hubbard et al., 1994). Tillage affects soil air and water relationships. It also affects the biological characteristics of the soil including litter layers and macroinvertebrate populations, and affects chemical processes through their effects on biologic, temperature and water content (Hubbard et al., 1994). Finally, tillage affects runoff volume and consequently erosion. The spatial variability of structure-related soil properties may be

affected by tillage systems (Bouma and Finke, 1993). In a field scale study after a soil leveling, Finke et al. (1992) identified a disturbed soil layer in which the thickness showed a clear spatial structure reflected by the original surface topography. Tillage systems and their associated changes in soil and plant environment are components of agricultural production that might benefit from site-specific management, but that has been generally ignored in the site-specific activities. For example, soil water flow would be modified. When dealing with site-specific management, variability is dealt with in terms of space and time (Verhagen and Bouma, 1997). The way to assess such variability is to make direct observations or measurements of variability for a period of time on elements of importance for site-specific management, such as crop growth and soil water and soil nutrient contents during the year. However, future developments of soil conditions could not be taken into account when only actual conditions are characterized. Furthermore, to make observations and to take measurements within fields every year are time consuming and costly. Input data and require much less calculation (Addiscott and Wagonet, 1985).

Consequently, An attractive alternative to measurement of crop growth and examining alternative agricultural management practices for crop production is simulation modeling to predict crop growth. Crop growth simulation models are increasingly used to support field research, extension, and teaching (Addiscott, 1993). The number of costly, multi-treatment, time-consuming field trials can be substantially reduced by crop simulation as crop models can quantify the magnitude and variability in response to treatments (Ritchie et al., 1989; Jones and Ritchie, 1991; Hanks and Ritchie, 1991). del for several purposes.

Basically, there are two distinct types of crop models: one is essentially practical, and combines a few rules of thumb to predict the behavior of crops. The other is

seemingly scientific in spirit, and seek to represent the biological and physiological processes thought to occur in plants and their environments (Passioura, 1996).

These two approaches correspond to what Addiscott and Wagenet (1985) termed functional and mechanistic in their analysis of leaching models.

Mechanistic models seek to describe the most fundamental mechanisms of the processes that are involved as currently understood. For example, soil water flow would be modeled using Darcy's Law, and solute transport would involve mass flow and diffusion-dispersion (Addiscott and Wagenet 1985). Because of the large amount of input information and the uncertainty of some assumptions, mechanistic models are usually not used by those other than their developers (Hanks and Ritchie, 1991).

Functional models, on the other hand, represent the same processes but aims to provide a general description of the whole process (Gaunt et al., 1997). These types of models may be able to express a process as accurately as mechanistic models, although they use less input data and require much less calculation (Addiscott and Wagenet, 1985).

Consequently, others users besides the developers can utilize them without much difficulty. The best functional models might be thought of as containing rational empiricism to express rather complex relationships (Hanks and Ritchie, 1991). The CERES family of crop models is predominantly functional rather than mechanistic (Ritchie et al., 1985), and they are built with the minimum data set concept (Nix, 1983).

This consists of information on weather, soil, crop genetic and management. The CERES models were developed to provide users with an operational model for several purposes: assistance with farm decision making, risk analysis for strategic planning, within-year

management decisions, large area yield forecasting, policy analysis, and definition of research needs (Hanks and Ritchie, 1991).

Intuitively, crop models should have considerable value in evaluating site-specific management but have found limited use (Van Uffelen et al., 1997). These limited applications appear to be caused by the lack of knowledge about within-field variability of soil properties essential for predicting crop yield.

Currently, the strength of SSM is the availability of technologies to enhance spatial data collection and control crop production inputs site-specifically; the weakness is the lack of understanding of the variability within fields and the agronomic knowledge to manage it. This study has three specific objectives relative to understanding the variability in soils and crops within a field. First, this study assesses the value of a 2nd order soil survey in delineating site-specific management zones by examining the quality of soil map units within an existing soil survey in terms of map unit purity and assessing the magnitude and nature of the spatial variability in soil physical properties as expressed by different sampling designs. Second, this study examines how corn yield varies spatially, how tillage alters soil properties and corn yield, and the extent to which variation in soil properties relate to variability in corn yield. Third, this study evaluates the potential for proven crop simulation models to account for spatial variability in corn yield within a field.

(Hladik and Schepers, 1997), are accounted for in soil surveys. However, the relationship between soil map unit delineations in current soil surveys and the variation in soil properties (Robert et al., 1993), soil fertility tests (Pierce and Warner, 1994; Pierce et al., 1995; McGraw and Hamb, 1995), and crop yield (Everett and Pierce, 1996) have been

CHAPTER 1

Applicability of Soil Surveys and Soil Property Maps for Site-Specific Management

INTRODUCTION

Site-specific management (SSM) for agriculture is based on the notion that matching inputs to localized conditions within a field will increase crop productivity, optimize resource use, and minimize the potential undesirable effects of agriculture on environmental quality (Robert, 1993). A required first step in the development of SSM strategies is the accurate assessment of the spatial variability of the factors which regulate the soil-plant-atmosphere system that ultimately control crop yield and the environmental impacts of production agriculture. Ultimately, it is important to understand how the spatial variability of these factors relates to the spatial variability in crop yield and environmental quality within and between years. Yule et al. (1996) also pointed out that Soil surveys represent an extensive knowledge set describing the spatial distribution of soil and landscape properties important for land use and were considered early on as a basis for SSM (Larson and Robert, 1991). Some of the more important yield determining factors of importance to SSM, including plant available water, soil drainage, crop rooting depth, nutrient availability, soil texture, organic matter content and pH (Mulla and Schepers, 1997), are accounted for in soil surveys. However, the relationship between soil map unit delineations in current soil surveys and the variation in soil properties (Robert et al., 1993), soil fertility tests (Pierce and Warncke, 1994; Pierce et al., 1995; McGraw and Hemb, 1995), and crop yield (Everett and Pierce, 1996) have been

reported to be poor and their relevance to SSM questioned (Robert, 1993). Some lack of correlation would be expected, given the composition of a given map unit and the fact that different factors may impact yields within a given year. Soil mapping units by necessity of design can contain a range of variability and include multiple soils and inclusions within the delineation (Moore et al., 1993). The extent of map unit impurities and the degree to which they impact the relationship between crop yield and soil surveys depends on many factors, particularly the complexity of soils associated with nature of the soil forming factors within the survey area and the scale of the survey (Sadler and Russel, 1997; Mulla and Schepers, 1997). Beckett and Webster (1971), for example, found that most within-field variability was already present within an area of one hectare. As some studies have suggested, standard soil survey maps may not provide the fine-scale resolution required for site-specific management, where 1:6000 or smaller scale maps may be needed to adequately define field variability (Robert, 1993; Moore et al., 1993; Mausbach et al., 1993; Pierce et al., 1995). Yule et al. (1996) also pointed out that conventional soil survey techniques used to describe soil series do not adequately identify variation in soil physical and chemical parameters required for SSM and that high-quality soil maps are necessary. Depending on the situation, the spatial variation observed in crop yields or nutrient availability may have little to do with the inherent soil properties that form the basis for map unit composition, particularly when the conditions within a field were manmade.

While the emphasis in recent years has been on variable rate fertilizer management, the correlation between nutrient availability as determined by standard soil testing procedures and crop yield is not always strong (Hergert et al., 1997; Everett and

Pierce, 1996; Pierce et al., 1995; Swayer, 1994). The factors most important to SSM as described by Mulla and Shepers (1997) relate more to water availability and rooting conditions than soil fertility. Therefore, soil physical and morphological properties (Han et al., 1996; Jaynes et al., 1995; Khakural et al., 1996) and landscape attributes (Khakural et al., 1996; Lindstrom et al., 1995) may be more important than soil fertility in explaining crop yield variability and may be more useful in delineating site-specific management zones.

Intensive sampling and interpolation schemes have been advanced as a means of creating management maps for use in SSM (Wollanhaupt et al., 1997) because soil properties frequently exhibit spatial dependence, i.e., samples collected close to one another are often more similar in value than widely spaced samples (Trangmar et al., 1985). Using geostatistical procedures, Mallants et al. (1996) concluded that most hydraulic parameters, including water retention, at different profile layers fit semivariograms that could be described by means of spherical models, with a spatial range from 4 to 7 m. Variograms for bulk density have ranges reported to vary from 18 to 56 m (Reinert, 1990; Boyer et al., 1996; Chung et al., 1995) and can differ between horizons of a given profile (35 m for a plowpan and 51 m for the A1 horizon, Poier and Richter, 1992). Other soil physical characteristics reported to exhibit spatial dependence include saturated hydraulic conductivity (range varied from 10.2 and 13.8 m, Reinert, 1990); sand (range = 40 m), silt (range = 78 m), clay (range = 43m) (Boyer et al., 1996); organic carbon content (range varied from 47 to 56 m, Poier and Richter, 1992; Boyer et al., 1996); and penetrometer resistance and organic matter with ranges of 14 and 13.4 m, respectively (Chung et al., 1995). While geostatistics and other spatial analysis

techniques have proven useful in quantifying within field variation of soil properties, the question remains as to how successful sampling and interpolation techniques can be used to delineate site-specific management zones that correlate to crop yield and predict environmental quality impacts of SSM.

Studies have shown a lack of correlation between crop yields and both soil survey maps and nutrient availability maps created from grid sampling data (Pierce et al., 1995; Everett and Pierce, 1996). Other factors are suspect to impact crop yields more than nutrient availability in the fields examined, particularly those related to water availability. This study assessed the value of soil survey map units and soil property maps in delineating management zones for SSM by examining the quality of map units within an existing soil survey in terms of map unit purity and assessing the magnitude and nature of the spatial variability in soil physical properties as expressed by different sampling designs.

MATERIALS AND METHODS

Site Description

This study was conducted in 1995 and 1996 in a 3.72 ha section of a larger field located 6 km south of Durand, Michigan ($47^{\circ} 47' 30''\text{N}$, $83^{\circ} 52' 30''\text{W}$). The field had been managed in a corn-soybean rotation under no-tillage for more than 10 yr. The Order 2 soil survey map (1:20000 scale; Threlkeld and Feenstra, 1974) and a high resolution Digital Elevation Model (DEM; Thomas Mueller, personal communication, 1997) for the field are illustrated in Figure 1.1.

soil survey map (1:20000 scale; Threlkeld and Feenstra, 1974) (A) and a high resolution Digital Elevation Model (m) for the experimental field (B).

Table 1.1 Map unit descriptions, area within the experimental site, and population of grid samples falling within map unit for the experimental field in Dundas, Michigan.

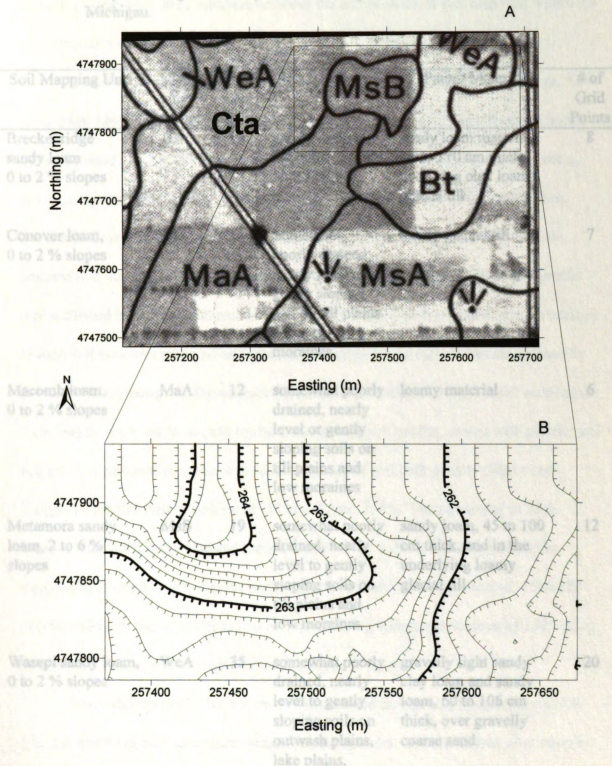


Figure 1.1. The Order two soil survey map (1:20000 scale: Threlkeld and Feenstra, 1974) (A) and a high resolution Digital Elevation Model (m) for the experimental field (B).

Table 1.1 Map unit descriptions, area within the experimental site, and population of grid samples falling within map unit for the experimental field in Durnod, Michigan.

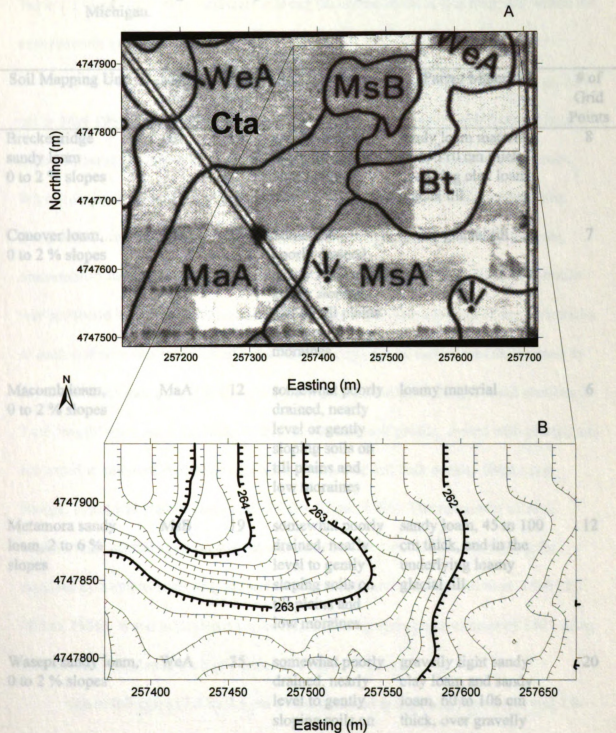


Figure 1.1. The Order two soil survey map (1:20000 scale: Threlkeld and Feenstra, (1974) (A) and a high resolution Digital Elevation Model (m) for the experimental field (B).

Table 1.1 Map unit descriptions, area within the experimental site, and population of grid samples falling within map unit for the experimental field in Durand, Michigan.

Soil Mapping Unit	Map Unit Symbol	Map Area (%)	Soil Landforms	Parent Material	# of Grid Points
Breckenridge sandy loam 0 to 2 % slopes	Bt	19	poorly drained, nearly level soils on till plains	sandy loam material, 45 to 110 cm thick, overlying clay loam glacial till	8
Conover loam, 0 to 2 % slopes	CtA	15	Somewhat poorly drained, nearly level to gently sloping soil on till plains and low moraines	loamy glacial till	7
Macomb loam, 0 to 2 % slopes	MaA	12	somewhat poorly drained, nearly level or gently sloping soils on till plains and low moraines	loamy material	6
Metamora sandy loam, 2 to 6 % slopes	MsB	19	somewhat poorly drained, nearly level to gently sloping soils on till plains and low moraines	sandy loam, 45 to 100 cm thick, and in the underlying loamy glacial till	12
Wasepi sandy loam, 0 to 2 % slopes	WeA	35	somewhat poorly drained, nearly level to gently sloping soils on outwash plains, lake plains, stream terraces, and glacial drainage-ways	gravelly light sandy clay loam and sandy loam, 60 to 106 cm thick, over gravelly coarse sand	20

The landforms descriptions (Threlkeld and Feenstra, 1974) for each map unit are given in Table 1.1 along with other information about the composition of that map unit within the experimental site.

A 30.5 m regular grid was imposed on the experimental site (122 by 305 m, 3.72 ha) in May 1995 (Figure 1.2a). Intact soil profile cores (5 cm i.d.) were obtained from each grid point to a depth of 1 m away from the wheel tracks using a hydraulic probe. When compression on the soil profile samples was suspected, the entire sample was discarded. Cores were placed in PVC pipes that were split to accommodate the core, reassembled, taped and capped to protect them during storage at 4°C. Each soil profile was sectioned by soil horizon and its thickness recorded. The top 5 cm of the Ap horizon of each soil core was removed and ground, and total organic carbon was determined by dry combustion using a CHN analyzer (Carlo Erba Instruments, Italy). Small sections (5-7 cm length) were cut from each horizon within each soil profile, coated with plastic, and subjected to standard procedures for determination of soil bulk density (Blake and Hartge, 1986) and water retention at -33 kPa (Klute, 1986). The remainder of each horizon was carefully ground and the soil analyzed for particle size analysis by the standard hydrometer method (Gee and Bauder, 1986) and water retention at -1500 kPa (Klute, 1986). Water table depth was measured during spring and summer of 1995 using piezometers installed at each grid point to a depth of 1.5 m.

Intact soil cores (7.6 by 7.6 cm) were obtained in triplicate from 0-7.6 and 7.6-15.2 cm depths at each grid point using a double-cylinder, hammer-driven core sampler (Blake and Hartge, 1986).

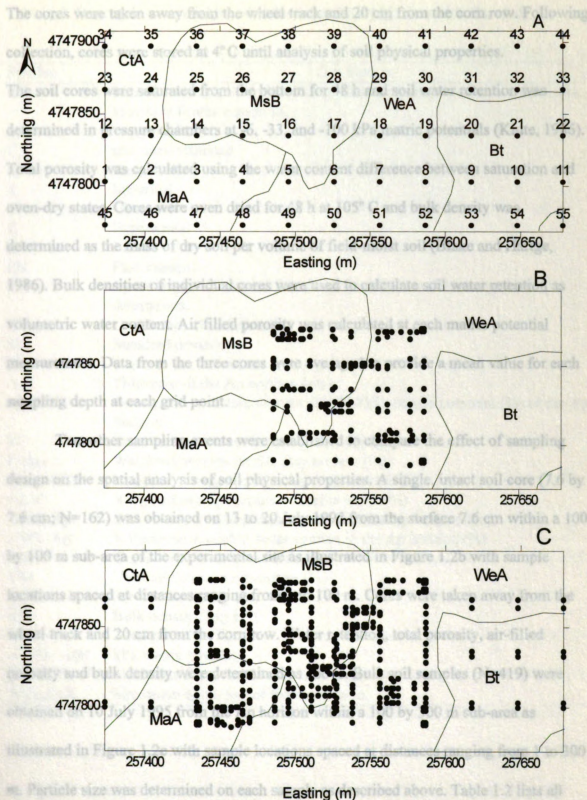


Figure 1.2. Location of the 30.5 m regular (A), geospatial analysis (N=162) (B), and geospatial analysis (N=419) (C) grids relative to the map units from the Order two soil survey. Refer to Table 1.1 for map unit descriptions.

The soil cores were saturated from the bottom for 48 h and soil water retention was determined in pressure chambers at -6, -33, and -100 kPa matric potentials (Klute, 1986). Total porosity was calculated using the water content difference between saturation and oven-dry states. Cores were oven dried for 48 h at 105° C and bulk density was determined as the mass of dry soil per volume of field-moist soil (Blake and Hartge, 1986). Bulk densities of individual cores were used to calculate soil water retention as volumetric water content. Air filled porosity was calculated at each matric potential measurement. Data from the three cores were averaged to provide a mean value for each sampling depth at each grid point.

Two other sampling events were established to compare the effect of sampling design on the spatial analysis of soil physical properties. A single, intact soil core (7.6 by 7.6 cm; N=162) was obtained on 13 to 20 July 1995 from the surface 7.6 cm within a 100 by 100 m sub-area of the experimental site as illustrated in Figure 1.2b with sample locations spaced at distances ranging from 1 to 100 m. Cores were taken away from the wheel track and 20 cm from the corn row. Water retention, total porosity, air-filled porosity and bulk density were determined as above. Bulk soil samples (N=419) were obtained on 10 July 1995 from the Ap horizon within a 100 by 300 m sub-area as illustrated in Figure 1.2c with sample locations spaced at distances ranging from 1 to 300 m. Particle size was determined on each sample as described above. Table 1.2 lists all variables with the respective symbols used in this study.

Table 1.2. Description of variables with the respective symbols used in the study.

Geostatistical analyses were performed using Variowin 2.2 software (Pannatier, 1996).

Symbol	Description
IGF (%)	Indicative Goodness of Fit. IGF is a number without units; a value close to zero indicates a good fit.
C_0	nugget effect
C_s	structural variance
R	Range (m)
S	Spherical
G	Gaussian
E	Exponential
L	Linear
PN	Pure nugget
a	a pure nugget effect was found and therefore no sill or range could be determined.
CV (%)	Coefficient of variation (%)
SD	Standard deviation
Bt	Depth to the Bt horizon (cm);
Ap	Thickness of the Ap horizon (cm);
Ap-1500	Gravimetric moisture content at -1500 kPa matric potential (%) of the Ap horizon
TC	Total carbon content in the top 5 cm (g kg^{-1})
P-clay	Weighted average profile clay content (%)
P-clay+silt	Weighted average profile clay + silt content (%)
PAW	Weighted average profile available water (%)
AWG-Ap	Gravimetric available water content in the Ap horizon (%)
AWV-Ap	Volumetric available water content in the Ap horizon (%)
GM	Gravimetric moisture content (%)
VM	Volumetric moisture content (%)
AFP	Air filled porosity (%)
BD	Bulk density (Mg m^{-3})
TP	Total porosity (%)
-6, -33, -100	kPa matric potential.
WT-MIN	Minimum depth (m) of the water table.
WT-MAX	Maximum depth (m) of the water table.

Statistical Analysis

Geostatistical analyses were performed using Variowin 2.2 software (Pannatier, 1996). Variograms were derived by plotting the semivariance of the soil data as functions of vector distance. Each parameter was subjected to semivariance analysis using isotropic and anisotropic models (linear, spherical, exponential, and gaussian) for defining semivariograms. The models were then used along with kriging techniques to develop maps showing spatial patterns in variability of selected soil properties (Issaks and Srivastava, 1989). Descriptive statistics and correlation were calculated using SAS (SAS, 1990).

RESULTS AND DISCUSSION

Map Unit Purity

The first phase of this analysis was to examine the variation within map units by comparing soil profiles obtained on a 30.5 m grid with map unit descriptions in the published soil survey. The map in Figure 1.3 provides the location of the grid soil profile samples relative to the map units from the Order 2 soil survey, with each profile numbered for reference. For each map unit, Figures 1.4-1.8 compare the horizons and soil textures of the representative soil profile as given in the soil survey of Shiawassee County (Threlkeld and Feenstra, 1974) with the grid profiles falling within the map unit in the experimental area. The characteristics of the Ap horizon, the Bt horizon, and the C horizon of each grid profile were compared to the corresponding horizons of the representative profile of that series.

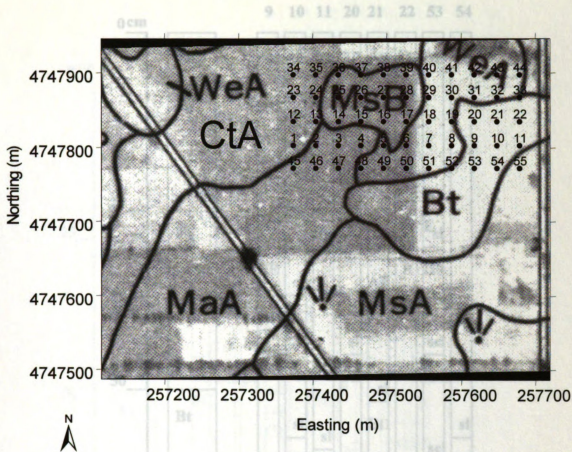


Figure 1.3. Location of the grid soil profile samples relative to the map units from the Order two soil survey. Refer to Table 1.1 for map units descriptions.

Figure 1.4. Representative soil profile of the Breckenridge sandy loam 0 to 2% (Bt) as given in the Soil Survey of Shiawassee County, MI (Threlkeld and Peeterson, 1974) and the grid profiles falling within the map unit. Refer to Table 1.1 for map units descriptions.

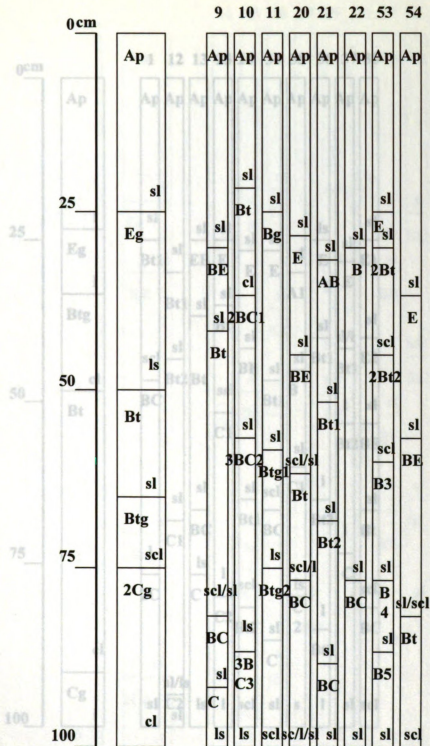


Figure 1.5. Representative soil profile of the Conover loam 0 to 2% (C1a) as given in the Soil Survey of Shiawassee County, MI (Threlkeld and Feenstra, 1974).

Figure 1.4. Representative soil profile of the Breckenridge sandy loam 0 to 2% (Bt) as given in the Soil Survey of Shiawassee County, MI (Threlkeld and Feenstra, 1974) and the grid profiles falling within the map unit. Refer to Table 1.1 for map units descriptions.

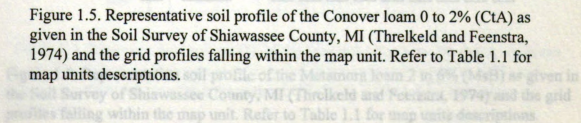


Figure 1.5. Representative soil profile of the Conover loam 0 to 2% (CtA) as given in the Soil Survey of Shiawassee County, MI (Threlkeld and Feenstra, 1974) and the grid profiles falling within the map unit. Refer to Table 1.1 for map units descriptions.

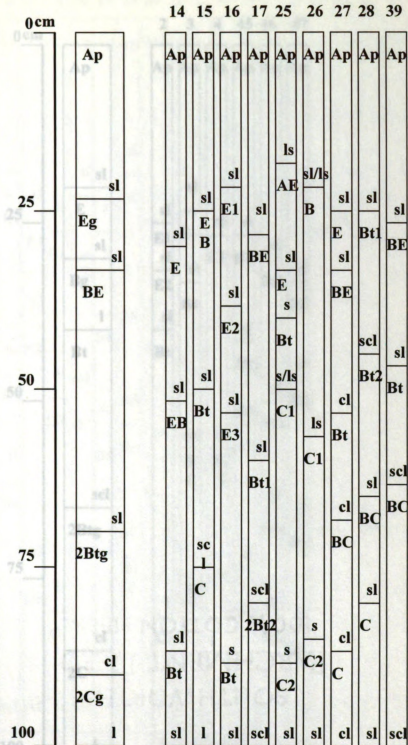


Figure 1.6. Representative soil profile of the Metamora loam 2 to 6% (MsB) as given in the Soil Survey of Shiawassee County, MI (Threlkeld and Feenstra, 1974) and the grid profiles falling within the map unit. Refer to Table 1.1 for map units descriptions.

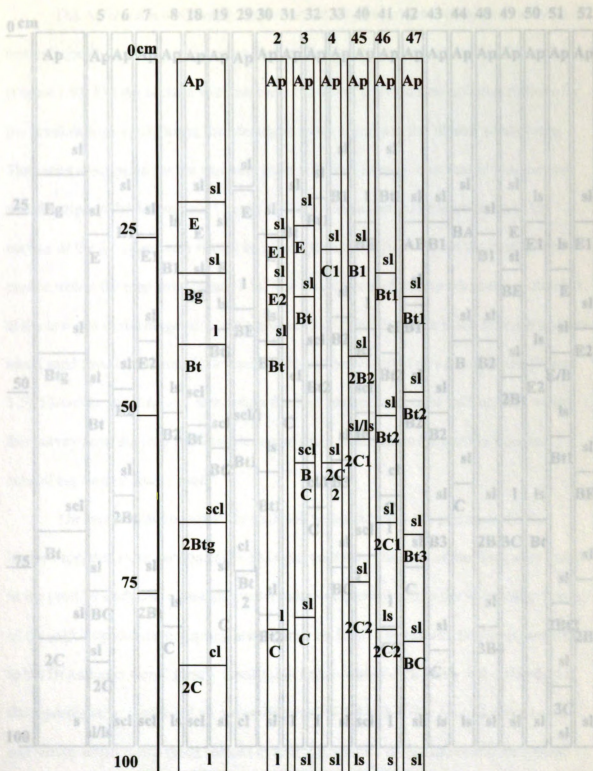


Figure 1.7. Representative soil profile of the Macomb loam 0 to 2% (MaA) as given in the Soil Survey of Shiawassee County, MI (Threlkeld and Feenstra, 1974) and the grid profiles falling within the map unit. Refer to Table 1.1 for map units descriptions.

0 cm	5	6	7	8	18	19	29	30	31	32	33	40	41	42	43	44	48	49	50	51	52
	Ap	Ap	Ap	Ap	Ap	Ap	Ap	Ap	Ap	Ap	Ap	Ap	Ap	Ap	Ap	Ap	Ap	Ap	Ap	Ap	Ap
	sl																				
25	Eg	sl		sl	ls	E	sl	E	sl	Bt1	B1	l	Bt1	sl	sl	sl	sl	sl	ls		sl
	E	E1		E1	B1	E	E	E	Bt	Bt1		BE		AB	B1	BA	B1	E	E1	ls	E1
	sl			sl	BE	ls	l	ls	ls	sl	sl	l	cl	B1		sl	sl	BE	BE	E	sl
50	Btg	sl		E2	ls	scl	Bt1	BE	BE	cl	Bt2	sl	Bt2	sl	sl	B	B2	sl	E/B	ls	E2
	Bt	E2		B2	Bt	scl	Bt1	ls	C	sl	BC	sl	cl	B2	B2	sl	sl	2Bt	ls	sl	
	sl	2Bt			Bt2	Bt1	Bt1	Bt1	Bt1	cl	B3	cl	C	sl	C	sl	sl	l	ls	BE	
75	Bt	sl		sl	sl	cl	cl	cl	cl	C	sl	sl	C	sl	sl	B3	2B3C	Bt	sl	sl	
	sl	BC		2Bt	ls	C	Bt2	Bt2	Bt2	BC	C	l	C	sl	sl	sl	sl	2Bt	2Bt	2Bt	
	2C	sl		C								C2					3B4		sl	sl	
	2C															C					
100	s	sl/ls	scl	scl	ls	scl	sl	cl	sl	l	l	sl	scl	l	sl	ls	ls	sl	sl	3C	sl

Figure 1.8. Representative soil profile of the Wasepi sandy loam 0 to 2% (WeA) as given in the Soil Survey of Shiawassee County, MI (Threlkeld and Feenstra, 1974) and the grid profiles falling within the map unit. Refer to Table 1.1 for map units descriptions.

The Ap horizon of the entire experimental area was characterized as a sandy loam texture regardless of map unit, with a few profiles having textures of loam or loamy sand (Figure 1.9). The Ap horizon was generally consistent with the map unit descriptions for the Breckenridge sandy loam, the Metamora sandy loam, and the Wasepi sandy loam. The series description for the Macomb loam indicates a sandy loam texture but the map unit description for Shiawassee County indicates the surface to be loam texture. The surface of the Conover loam should be a loam texture but this was not the case for any profile within the map unit (Figure 1.5). The clay content of the Ap horizon is within but at the low end of the range for a loam texture (8 to 27%), but there is too little silt and too much sand (maximum sand for a loam is 52%) to be classified as a loam texture (Figure 1.5). However, the map unit description for the Conover loam does indicate that within this survey area, the map unit includes some small areas where the surface layer and subsoil are sand or loamy sand.

The representative profile for each soil series indicates the presence of a Bt horizon and that some portion of the Bt is gleyed. Few evidences of mottling were found in the profiles analyzed, although a water table was present within the soil profile at many of the grid locations during spring and summer of 1995. The texture, thickness, and depth to the Bt horizons varied greatly among grid points within each series and differed from the representative profiles of all series (Figures 1.4-1.8 and 1.10). Areas defined by the soil survey as till plains (soils formed in loamy glacial till materials) contained typical outwash parent material, i.e., profiles 35 and 13 (Conover loam), 16, 25, and 26 (Metamora sandy loam), 45 and 46 (Macomb loam) (Figures 1.5, 1.6 and 1.7).

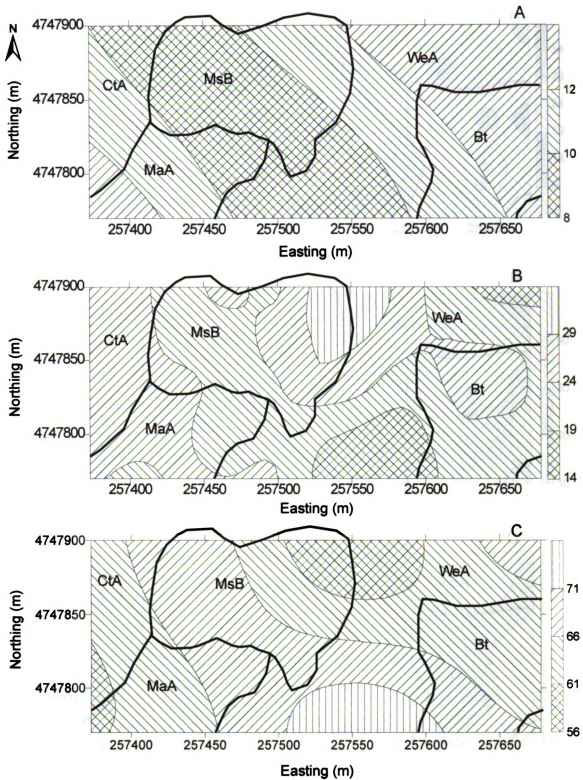


Figure 1.9. Interpolated maps of clay (A), silt (B), and sand (C) contents (%) of the Ap horizon for the 30.5 m grid. Refer to Table 1.1 for map units descriptions.

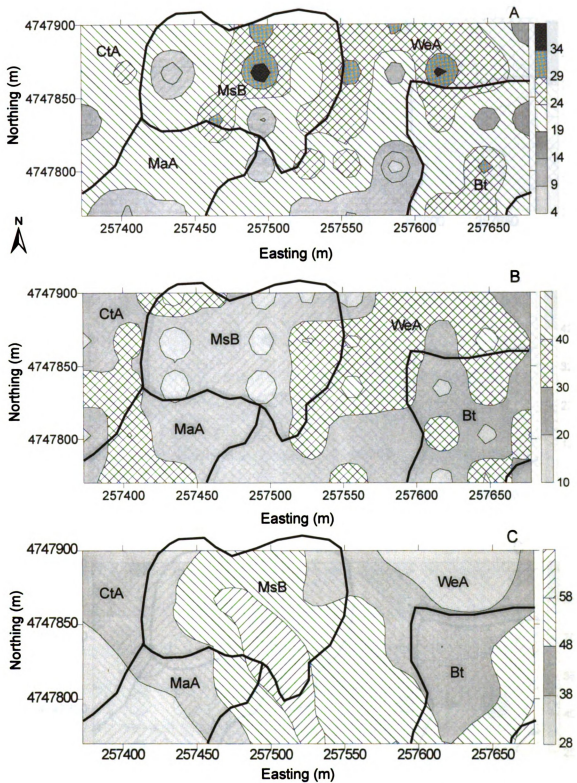


Figure 1.10. Interpolated maps of clay content (%) of the Bt horizon (A), thickness of the Bt horizon (cm) (B), and depth to the Bt horizon (cm) (C) for the 30.5 m regular grid. Refer to Table 1.1 for map unit descriptions.

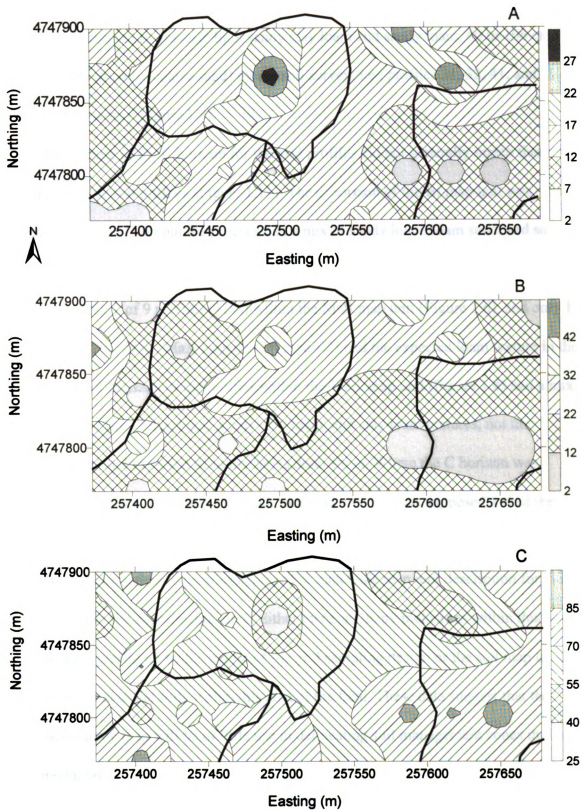


Figure 1.11. Interpolated maps of clay (A), silt (B), and sand (C) content (%) of the C horizon for the 30.5 m grid. Refer to Table 1.1 for map units descriptions.

In addition, typical till materials were present within areas described as outwash parent material (soils formed in gravelly light sandy clay loam and sandy loam, 60 to 106 cm thick, over fine gravelly coarse sand) by the soil survey, i.e., profiles 31, 32, 41, and 29 (Wasepi sandy loam) (Figure 1.8).

The texture of the C horizon for the grid profiles did not generally match that of the representative soil profiles (Figure 1.11). The C horizon of the Bt map unit was supposed to be clay loam but the profiles had a mix of sandy loam, loam sand, and sandy clay loam textures (Figure 1.4). Only 2 of 10 profiles (20%) within the CtA map unit (Figure 1.5), only 1 of 9 profiles (11%) within the MsB map unit (Figure 1.6), and only 1 of 6 profiles (17%) of the MaA map unit (Figure 1.7) had the expected loam texture in the C horizon. The C horizon of the profiles within the WeA map unit (Figure 1.8) had a mix of sandy loam, loamy sand, loam, sandy clay loam, and clay loam textures, not the gravelly coarse sand expected from the series description. Where the C horizon was supposed to be a loam, there was too much sand and where it was supposed a sand the soil had more clay and silt (Figure 1.11).

None of the grid soil profiles appeared to match the map unit description for the soil series within the experimental area. Either there are many inclusions within this area and these were picked up by the nature of the grid sampling design or the soil map units do not correspond to the soils within this area of the field. These data suggest that the current soil survey map will be of little use in delineating soil management zones in this experimental area.

Spatial Analysis of Soil Physical Properties

The second approach to establishing soil management zones for SSM was to analyze the spatial dependence of soil physical properties within this experimental area. The interest here was whether the soil profile and surface core data from the 30.5 m regular grid would provide accurate maps of soil physical properties that could delineate useful soil management zones within the experimental area. Also how sampling soil more intensively with more complex sampling designs improved the estimation of the spatial dependence of selected soil physical properties was tested.

Spatial Analysis for the Regular Grid

The data for each 30.5 m grid soil profile were parameterized to provide new quantitative variables for analysis as given in Table 1.3. These profile variables and the soil properties measured on the intact soil cores obtained from each grid point were subjected to geostatistical analysis (Tables 1.3 and 1.4). Maps for these variables interpolated using the calculated semivariograms are given in Figures 1.12-1.19 with overlays of the soil survey map units provided for reference.

Table 1.3. Descriptive statistics and parameters for variogram models of variables obtained from undisturbed soil profile cores (5 cm i.d. by 1 m) within the 30.5 m regular grid (N=55). [‡]

Variable	Mean	SD	range	CV (%)	C _o	C _s	C _o /(C _o + C _s) (%)	R (m)	Model	IGF
Bt	47.0	16.6	23-90	35	210.00	150	58	170	S	6.2e-03
AWG-Ap	4	2	1-10	49	4.752	a			PN	7.3e-03
AWV-Ap	7	3	1-16	47	10.34	a			PN	9.2e-03
Ap-1500	10	2	6-16	22	2.183	3.431	39	110.0	S	6.5e-03
Ap	26.7	3.2	18-38	12	9.400	a			PN	3.5e-02
TC	1.29	0.36	0.8-2.33	28	0.067	0.0004	99	1.0	L	8.8e-03
P-clay	15	4	6-25	31	21	a			PN	2.9e-02
P-clay+silt	36	10	16-58	29	110	a			PN	2.0e-02
PAW	15	4	9-26	29	9.349	10.199	42	110.5	S	2.9e-02
WT-MAX	1.30	0.16	0.94-1.68	12	0.009	0.023	30	217.5	S	8.6e-03
WT-MIN	1.14	0.26	0.30-1.52	23	0.034	0.044	44	195.0	S	6.6e-03

[‡] Descriptions of symbols are presented in Table 1.2.

Table 1.4. Descriptive statistics and parameters for variogram models of variables obtained from soil cores within 30.5 m regular grid (N=55). [‡]

Variable	Mean	SD	range	CV (%)	C _o	C _s	C _o /(C _o + C _s) (%)	R (m)	Model	IGF
Depth 0 to 7.6 cm										
BD	1.52	0.07	1.32-1.67	5	0.005	a		a	PN	2.5e-03
TP	36	2	32-41	6	4.232	a		a	PN	1.2e-02
GM-6	16	3	11-23	18	7.52	a		a	PN	5.0e-03
GM-33	15	2	11-21	17	5.44	a		a	PN	2.8e-03
GM-100	14	3	10-21	18	6.006	a		a	PN	5.0e-03
VM-6	24	4	18-33	16	12.959	2.880	82	118.8	S	1.5e-02
VM-33	22	3	17-30	15	7.439	4.199	64	91.2	G	6.2e-03
VM-100	21	3	16-30	16	6.48	4.919	57	129.6	S	5.8e-03
AFP-6	32	11	6-52	34	68.4	56.400	55	81.6	S	1.0e-02
AFP-33	37	9	19-55	24	29.967	52.650	36	74.4	S	5.7e-03
AFP-100	40	9	23-57	21	28.467	46.717	38	79.2	S	5.1e-03
Depth 7.6 to 15.2 cm										
BD	1.64	0.06	1.48-1.76	4	0.003	0.0008	81	58.8	S	1.8e-02
TP	35	2	32-40	6	4.80	a		a	PN	1.3e-02
GM-6	15	2	11-20	17	4.992	1.8560	73	93.1	S	3.9e-03
GM-33	13	2	10-19	17	3.432	1.7670	66	97.6	S	1.3e-03
GM-100	13	2	9-18	17	3.016	2.1320	59	89.6	S	1.2e-03
VM-6	24	4	18-33	16	8.26	6.4400	56	95.0	S	1.1e-03
VM-33	22	3	17-31	15	5.759	5.7580	50	104.0	S	5.0e-04
VM-100	21	3	16-31	16	4.509	6.4890	41	99.2	S	9.7e-04
AFP-6	31	9	10-49	29	45.044	48.445	48	104.0	S	2.1e-03
AFP-33	38	8	22-54	21	28.975	35.907	45	110.4	S	2.2e-04
AFP-100	41	8	24-55	19	30.00	33	48	124.8	S	8.9e-04

[‡] Descriptions of symbols are presented in Table 1.2.

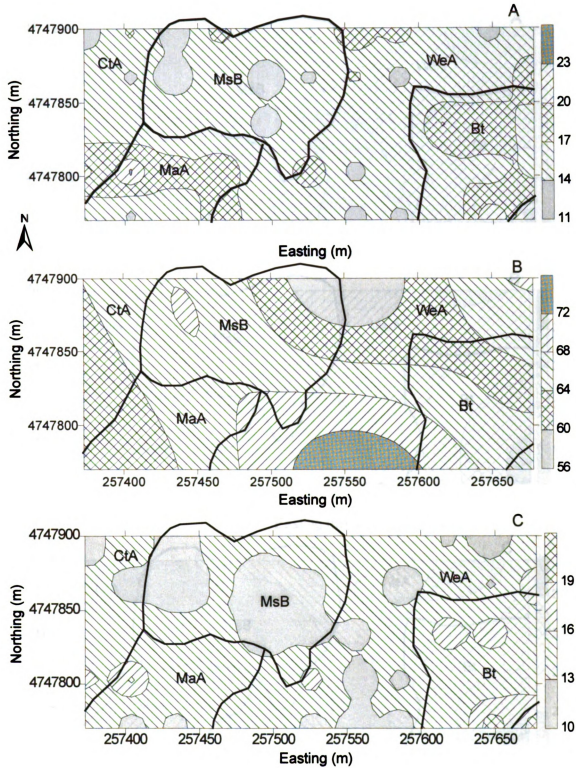


Figure 1.12. Interpolated maps of gravimetric water content (%) at -6 kPa (A), -33 kPa (B), and -100 kPa (C) on surface 7.6 cm for the 30.5 m regular grid. Refer to Table 1.1 for map unit descriptions.

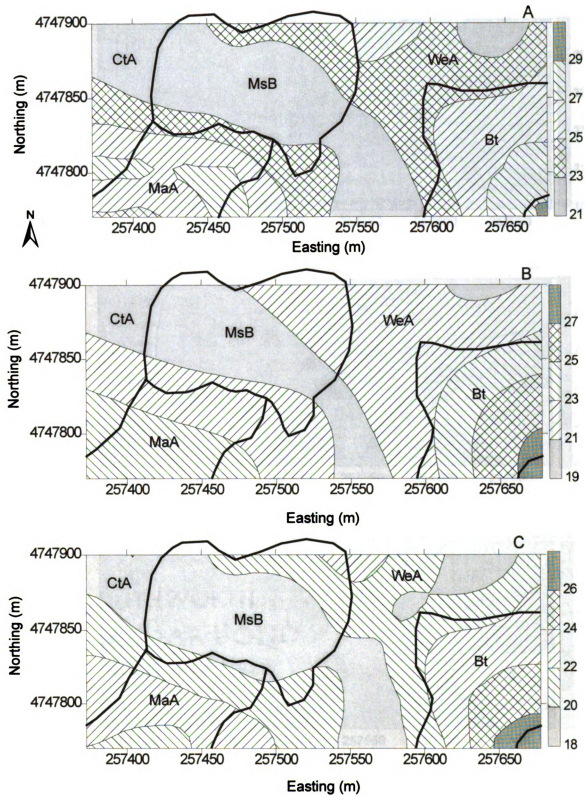


Figure 1.13. Interpolated maps of volumetric water content (%) at -6 kPa (A), -33 kPa (B), and -100 kPa (C) on surface 7.6 cm for the 30.5 m regular grid. Refer to table 1.1 for map unit descriptions.

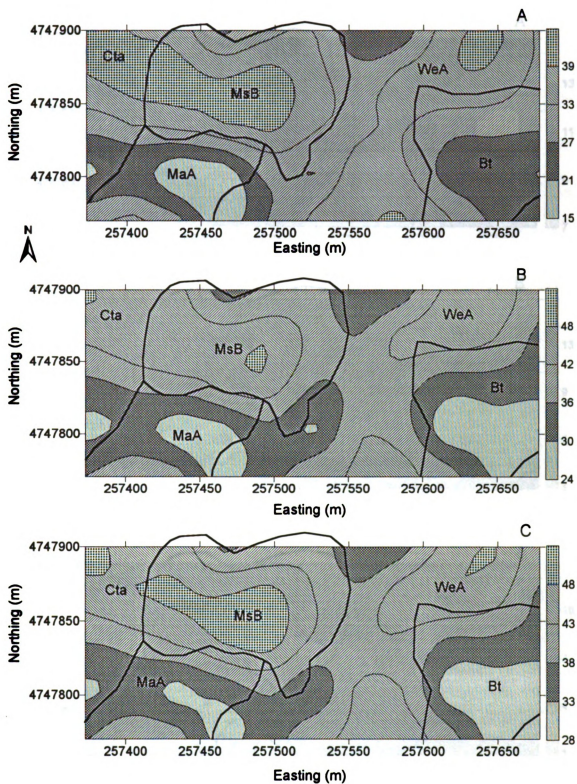


Figure 1.14. Interpolated maps of air filled porosity at -6 kPa (A), -33 kPa (B), and -100 kPa (C) for the 30.5 m regular grid. Refer to Table 1.1 for map unit descriptions.

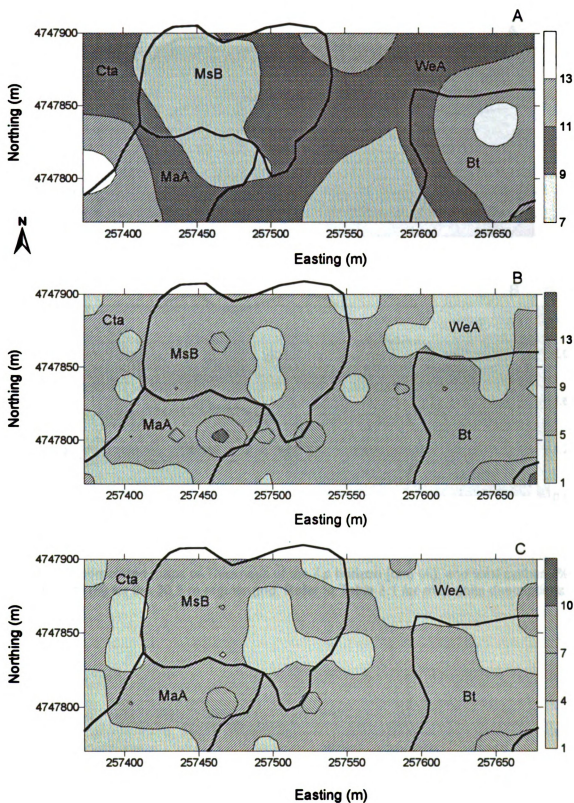


Figure 1.15. Interpolated maps of gravimetric water content (%) at -1500 kPa (A), volumetric available water (%) (B), and gravimetric available water (%) (C) of the Ap horizon for the 30.5 m regular grid. Refer to Table 1.1 for map units descriptions.

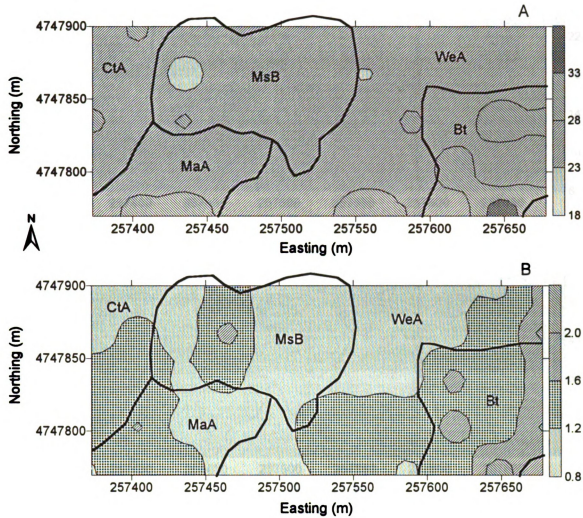


Figure 1.16. Interpolated maps of Thickness of the Ap horizon (cm) (A), and total carbon (%) in the top 5 cm (B) for the 30.5 m regular grid. Refer to Table 1.1 for map units descriptions.

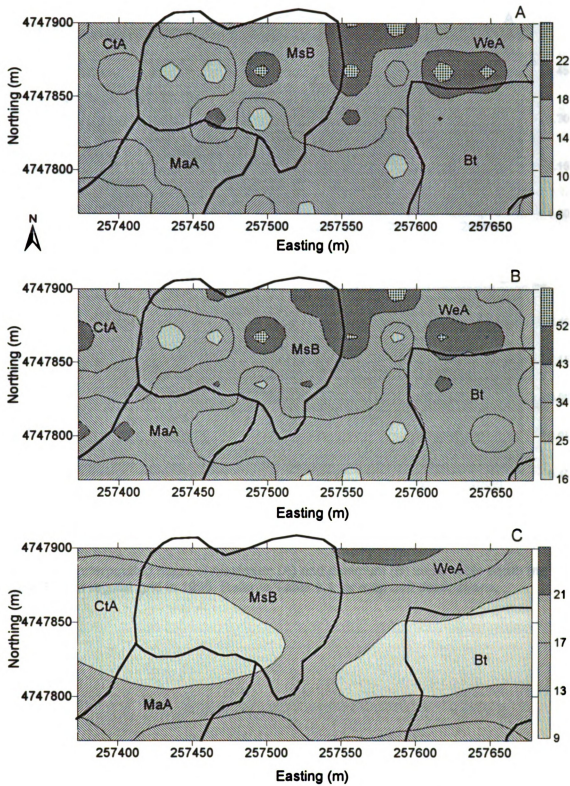


Figure 1.17. Interpolated maps of profile clay content up to 1 m (%) (A), profile clay + silt content up to 1 m (%) (B), and profile available water (%) (C) for the 30.5 m regular grid. Refer to Table 1.1 for map unit descriptions.

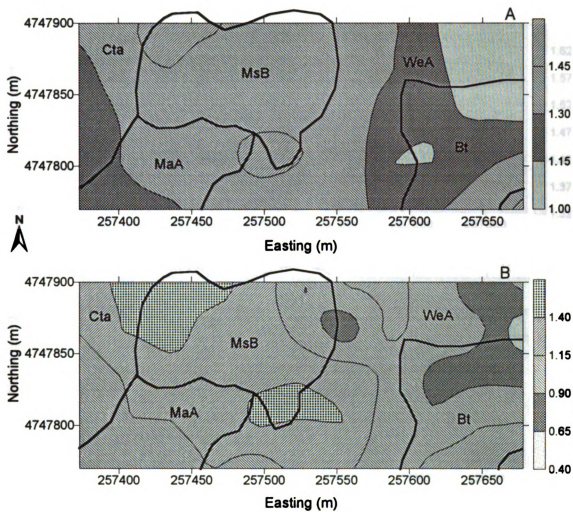


Figure 1.18. Interpolated maps of maximum (A) and minimum (B) water table depth (m) for the 30.5 m regular grid in 1995. Refer to Table 1.1 for map unit descriptions.

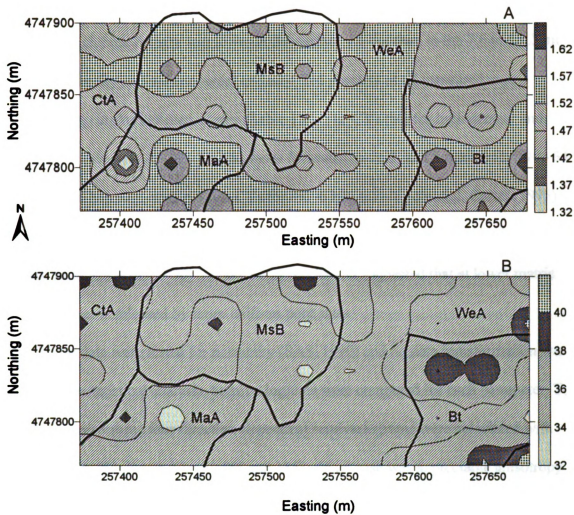


Figure 1.19. Interpolated maps of bulk density (g/cm³) (A) and total porosity (%) (B) on surface 7.6 cm for the 30.5 m regular grid. Refer to Table 1.1 for map units descriptions.

Variation in Surface Soil Properties

Although bulk density was lower in the surface 7.6 cm than in the 7.6 to 15.2 cm depth, total porosity and water content and air-filled porosity at all measured matric potentials were similar between depths (Table 1.4). The CVs (%) for bulk density and total porosity were very low, in the mid-teens for water content, and ranged from 19 to 34 % for air-filled porosity, with highest CVs for the -6 kPa matric potential. Carter (1995) also reported low CVs (< 10 %) for soil bulk density and high variability at high matric potential. Mallants et al. (1996) found similar results and suggested that at lower matric potentials, water is released by more uniform pore sizes

These data were tested for normality (SAS, 1990) and no data transformation was needed for geostatistical analysis. Semivariograms were computed for each parameter. To examine for anisotropy, four direction-dependent semivariograms were calculated with lags grouped in 45° classes (0°, 45°, 90° and 135°). In no case was appreciable anisotropy evident; thus we assumed variograms to be isotropic and used omni-directional variograms (90° angular tolerance, i.e., direction independent) for the remainder of the analysis. In order to achieve acceptable precision and to smooth the structure of the variograms, maximum lag spacing equal to grid spacing, and lag tolerance equal to half the lag spacing were chosen (Issaks and Srivastava, 1989). All variograms were estimated using a minimum total of 1485 sample pairs, and a minimum of 214 sample pairs for each lag distance.

Parameters of omni-directional semivariograms were determined based on the best-fitted model for soil properties at both soil depths. Indicative Goodness of Fit (IGF), a calculation performed by the program used for the spatial data analysis (Variowin 2.2,

Pannatier, 1996), was used to quantify the traditional visual fit. The IGF is a number without units: a value close to zero indicates a good fit. Since it is a standardized measure of fit, its value is comparable from one modeling session to another, allowing a numerical check how well each model fits the experimental measures (Pannatier, 1996).

Total porosity at both depths and bulk density and gravimetric moisture for all matrix potentials for the surface 7.6 cm showed no spatial dependence as the semivariograms exhibited pure nugget effect (Table 1.4). Most other semivariograms were best described by the spherical model, except for a fit of the gaussian model for the volumetric moisture content at -33 kPa in the surface 7.6 cm. Except for a range of 59 m for the bulk density of the 7.6 to 15.2 cm layer, the range for most parameters centered on 100 ± 25 m. Increasing the detail of sampling can reveal spatial structure in the apparently random effects of the pure nugget variances (Burrough, 1983 cited by Trangmar et al., 1985) and this principle will be addressed later.

The ratio of the nugget effect to the sill (total semi-variance) enables classification and comparison among soil properties (Trangmar et al., 1985). This ratio was used to define distinct classes of spatial dependence for the soil variables as follows: if the ratio was $\leq 25\%$, the variable was considered strongly spatially dependent; if the ratio was between 25 and 75%, the variable was considered moderately spatially dependent; and if the ratio was $> 75\%$, the variable was considered weakly spatially dependent (Chien et al., 1997; Cambardella et al., 1994). Moderate spatial dependence was found for most variables, except for volumetric moisture at -6 kPa at 0 to 7.6 cm depth and for bulk density at 7.6 to 15.2 cm, which were weakly spatially dependent. Patterns of moderate spatial dependency for soil properties were also found in studies by Cambardella et al.

(1994) and Chien et al. (1997). Both intrinsic factors of soil formation, and extrinsic factors, such as soil management practices, may control spatial variability of soil properties. Usually, strong spatial dependence can be attributed to intrinsic and weak spatial dependence to extrinsic factors (Cambardella et al., 1994). In general, combination of both, results in soil parameters exhibiting moderate spatial dependence (Cambardella et al., 1994).

Variation in Soil Profile Properties

Table 1.3 lists the descriptive statistics and the results of the geostatistical analysis for water table depth measurements and for general physical properties obtained from undisturbed soil profile cores sampled at each grid point to a depth of 1 m. In general, these parameters showed a higher C.V. in comparison with the data previously discussed (Table 1.4). No spatial dependence was observed for gravimetric and volumetric available soil water content of the Ap horizon, thickness of the Ap horizon, and profile clay and clay + silt content. The semivariograms were best described by the spherical model for the Ap horizon gravimetric water soil content at -1500 kPa, maximum and minimum water table depth, depth of the Bt horizon, and profile available soil water. A linear model was found to best fit the experimental data for total carbon content in the top 5 cm. This implies that the model is linear and does not reach a sill (Issaks and Srivastava, 1989). The range of spatial correlation varied from 110 m for the Ap horizon gravimetric soil water content at -1500 kPa to 217.5 m for maximum water table depth. The ratio of nugget variance to total semi-variance was 39 to 58%, indicating moderate spatial dependence.

Analysis of soil variability using semi-variograms has aided identification of soil mapping units and placement of mapping unit boundaries (Webster, 1985). Trangmar et al. (1985) presented several examples where semi-variance analysis was used to quantify spatial dependence of soil genetic processes and soil-forming factors such as rainfall, parent material composition and deposition. At our site, no spatial dependence was found for thickness of the Ap horizon and profile clay and clay + silt content, parameters that are traditionally used for defining the boundaries of soil map units. Lack of spatial dependence, also, indicates that the area may contain considerable inclusions that are important sources of variability and would not be shown in soil survey maps.

Kriging techniques were used to make contour maps of all soil parameters. Kriging is a local estimation technique which provides the best linear unbiased estimation of variables at unsampled locations using the structural properties of semi-variogram and the initial set of data values (Trangmar et al, 1985). For those variables that exhibited no spatial variability, the inverse distance squared was used as interpolation method. The information shown in contour maps is useful to gain a better understanding of the spatial distribution of soil properties and to visualize and define different management zones in a given area.

Figures 1.12 to 1.19 show the soil map units overlaid by the interpolated soil property maps generated from the 30.5 m regular grid, in order to determine the extent of alignment between the two maps. Not a single soil property aligned with soil map units (Figures 1.12 to 1.19), which confirms that the soil map units did not reflect the soil variability present within this particular field. However, the maps generated

geostatistically showed quite well that the experimental area displayed a sandier Ap horizon in its central western part and a clayey Ap horizon in its eastern part. In general, clayey areas coincided with a relatively higher water table (Figure 1.18), lower elevation (Figure 1.1b), higher volumetric water content (Figure 1.13), shallower Bt horizon (Figure 1.10c), and higher total carbon in the top 5 cm (Figure 1.16b). These observations suggest that the spatial coincidence of these properties could form the basis for defining management zones.

Effect of Scale on Estimation of Spatial Variability in Surface Soil Properties

Soil physical properties measured from intact soil cores obtained from the 0 to 7.6 cm depth were similar for the 30.5 m grid (N=55) and the geospatial grid (N=162), although air-filled porosity values were higher and less variable (lower CVs) for the more intensive sample values (Tables 1.4 and 1.5). The semivariogram for the geospatial grid values for bulk density, total porosity, and the measured gravimetric water contents showed strong spatial dependence in these soil properties that was not evident in the semivariograms for the 30.5 m grid values. The semivariograms for volumetric water contents and air-filled porosity for the geospatial grid values showed lower nugget effect (C_0) and structural (C_s) variances, lower ratios of the nugget effect to the sill, and smaller ranges than those derived from the 30.5m grid values. The best fit model of the semivariograms were primarily exponential for the geospatial grid and spherical for the 30.5 m grid. While descriptive statistics for the two sampling schemes are very similar, the spatial distribution of the soil physical properties predicted by the kriging the semivariograms will be quite different as evidenced by maps for the volumetric water

contents at -33 kPa matric potential (VM-33) obtained for the two grid scales in Figure

1.20. The interpretations relative to site-specific management based on these maps would be quite different.

Table 1.5. Descriptive statistics and parameters for variogram models of variables obtained from soil cores (7.6 by 7.6 cm) within the geostatistical grid (N=162).[‡]

Variable	Mean	SD	range	CV (%)	C ₀	C ₁	C ₀ /(C ₀ + C ₁) (%)	R (m)	Model	IGF
BD	1.52	0.08	1.30-1.67	5	0.003	0.0032	50	17.9	S	1.6e-03
TP	36	2	31-44	7	2.006	4.189	32	13.3	S	4.9e-03
GM-6	14	2	2-20	15	2.927	2.543	54	68.6	S	1.1e-03
GM-33	13	2	9-19	14	0.296	4.0	7	46.2	E	5.6e-03
GM-100	12	2	9-18	15	0.828	3.276	20	45.5	S	1.3e-02
VM-6	22	3	3-28	14	5.369	4.732	53	66.5	S	2.4e-02
VM-33	20	2	14-27	13	0.462	7.5	6	58.8	E	8.9e-03
VM-100	19	2	13-26	14	0.395	7.5	5	53.2	E	8.8e-03
AFP-6	39	8	21-89	21	41.89	23.43	64	9.0	S	3.8e-02
AFP-33	44	7	27-62	16	11.128	46.106	19	43.4	E	5.4e-03
AFP-100	46	7	29-64	16	12.72	46.106	22	47.6	E	5.0e-03

[‡] Descriptions of symbols are presented in Table 1.2.

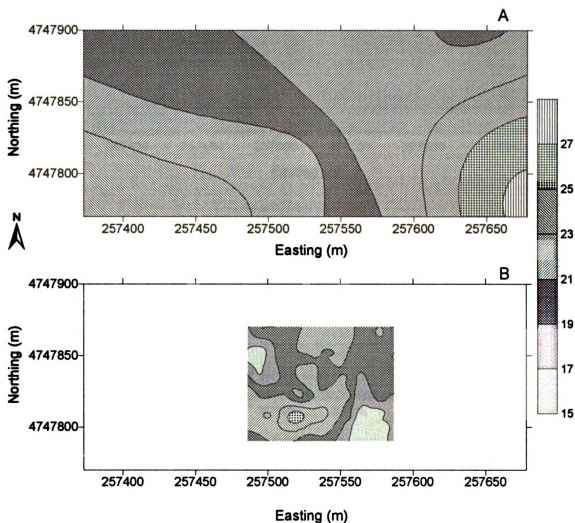


Figure 1.20. Volumetric water content (%) at -33 kPa on surface 7.6 cm for the 30.5 m grid scale (A) and the geospatial scale (B). Refer to Table 1.1 for map unit descriptions.

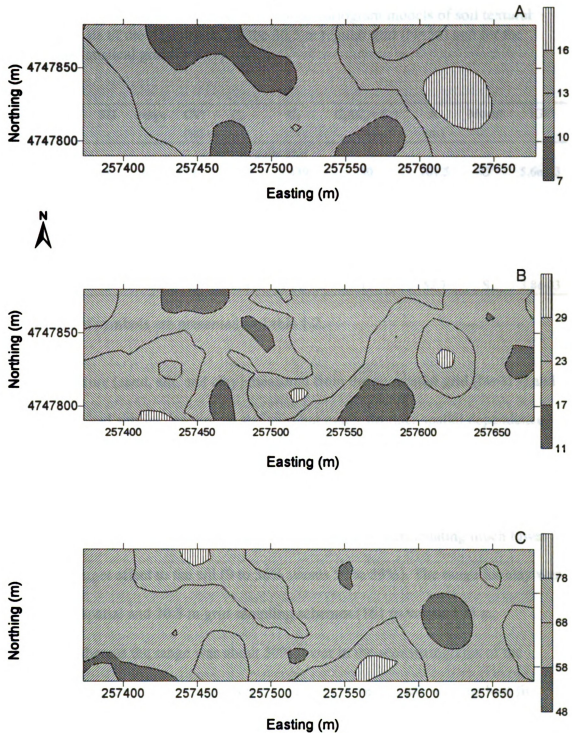


Figure 1.21. Interpolated map of clay (A), silt (B), and sand (C) contents (%) on surface 18 cm for the geopatiel grid (N=419).

Table 1.6. Descriptive statistics and parameters for variogram models of soil textural analysis of the Ap horizon for the 30.5 m regular grid (N=55) and for the geostatistical grid (N=419).

Variable (%)	Mean	SD	range	CV (%)	C _o	C _s	C _o /(C _o + C _s) (%)	R (m)	Model	IGF
Regular grid										
Clay	11	3	6-18	26	5.524	5.439	50	161.5	G	5.6e-03
Sand	65	7	45-79	11	36.18	26.456	58	98.9	G	1.6e-02
Silt	23	6	12-38	24	13.437	22.079	38	103.4	S	9.2e-03
Geostatistical grid										
Clay	11	3	6-27	24	3.477	6.033	36	175	S	1.9e-02
Sand	67	7	45-82	10	4.4	43.12	9	52.7	S	1.0e-02
Silt	22	5	5-38	23	3.778	24.57	13	52.7	S	3.8e-03

‡ Descriptions of symbols are presented in Table 1.2.

Soil texture (sand, silt, and clay) measured from the geospatial grid (N=419) and the 30.5 m grid had similar descriptive statistics but much stronger spatial dependence was detected in the geospatial grid values (Table 1.6). The nugget (C_o) variances were lower in the semivariograms determined from the geospatial grid than those determined from the 30.5 m grid but the structural (C_s) variances were higher, creating much lower ratios of the nugget effect to the sill (9 to 36% versus 50 to 58%). The range for clay was similar for geospatial and 30.5 m grid sampling schemes (161 m versus 175 m, respectively) whereas the range was about 50% lower in the semivariograms of the geospatial grid for sand (52.7 versus 98.9 m) and silt (53 versus 103 m). The best fit model was spherical for all textures in the semivariogram from the geospatial grid and gaussian for clay and sand for the semivariogram from the 30.5 m grid. Kriging the semivariograms produced quite different soil texture maps for the experimental area (Figure 1.9 and 1.21) The 30.5 m grid soil texture map showed less variability or a

smoother contour map, mainly for clay and sand content, where the best fit model was gaussian (Figure 1.9a and 1.9c). Similar patterns in those maps were not very well defined if compared to the geospatial grid. Although the silt content map for the geospatial grid (Figure 1.21b) showed more variability, it is possible to visualize similar patterns in the central eastern part, compared to the silt content map for the 30.5 m grid (Figure 1.9b). In general, similar patterns when present, were very poor defined for all texture maps.

When soils were sampled in detail using geostatistical designs, soil texture and soil physical properties exhibited strong spatial dependence allowing for precise soil property maps for the experimental area. The 30.5 m grid proved inadequate in detail and/or sample spacing for estimating the semivariogram for the measured soil physical properties and would not be a suitable sampling scheme for creating accurate soil property maps. The cost of soil sampling and analysis preclude these detailed studies on the farm. However, sensor technologies may allow mapping soil physical properties at the required intensity or allow direct mapping of soil management zones from sensor readings (Sudduth et al., 1997). The coarse grid sampling schemes, however, provide good estimates of descriptive statistics for soil physical properties and may be quite useful in directed sampling schemes for estimating average properties of predetermined site-specific management zones.

Semi-variance analysis and kriging interpolation techniques demonstrated that there were similarities in patterns for some of the soil parameters. This suggests that areas exhibiting similar patterns could be defined as different management zones. However, because the spatial variability of soil physical properties is strongly influenced by the

scale of the investigation, it remains to be seen whether or not these results will be useful for extrapolating spatial information obtained at the field scale to the watershed or regional scale. The results showed that sampling efficiency is a function of spatial dependence of the variable of interest. As the distance of spatial correlation increases, fewer observation sites are needed without significant information loss. However, before a particular sampling design scheme is selected, one would have to consider cost effectiveness of the available scheme, as well as practical considerations such as time constraints, site accessibility, cost of the laboratory analyses for each sample, among others site specific issues.

CONCLUSION

The soils within the experimental area were quite variable and did not correspond well to the soil map units given in the county soil survey maps. The soil survey for this field is not accurate and of little value to SSM. The 30.5 grid was descriptive but did not accurately describe the spatial variability in soil physical properties. The intensive geostatistical sampling designs produced very good estimates of the semivariogram and indicated a strong spatial dependence of all soil physical and soil texture properties measured. The cost of intensive soil sampling, even at the 30.5 m grid spacing, are cost prohibitive to any practical application in SSM. This fact points to sensors of soil properties as needed to make assessment of soil physical condition reasonable and efficient.

CHAPTER 2

Spatial Variability in Soil Physical Properties and Corn Yield Induced by Tillage

INTRODUCTION

The major focus of site-specific management (SSM) or precision farming has been nutrient management; however, variability in crop yield has not generally corresponded to variation in nutrient availability or to the variable rate application of fertilizers (Everett and Pierce, 1996). Water availability to plants is a major factor-regulating crop yields but is often not been a major consideration in SSM for agriculture, in part because water availability is weather dependent and is difficult and/or expensive to measure in space and time. Within a given climate, the availability of water can be related to soil physical and hydraulic properties, water table, and landscape effects, which vary spatially and temporally.

Studies on crop yield variability have cited higher yields in lower landscape positions where soil water availability was higher (Spomer and Piest, 1982; Stone et al. 1985; Hanna et al., 1982). In southeastern Washington, higher yields in lower landscape positions, such as on interfluvies and toeslopes, were attributed to differences in surface soil thickness (Ciha, 1984). Combinations of soil properties and landscape geometry can account for yield variability. Khakural et al. (1996) found that depth to free CaCO_3 , surface available P, available K, relative elevation, and slope gradient explained 65% of the variability in corn yield while depth to free CaCO_3 , surface available P, relative

elevation, slope gradient, and profile curvature explained 78% of the variability in soybean yield. Few examples exist, however, where soil physical and hydraulic properties have been used to explain crop yield variability.

Tillage is a major agricultural input affecting soil physical, chemical and biological properties with impacts primarily at or near the soil surface (Blevins, et al., 1983; Hill, and Meza-Montalvo, 1990; Seta et al., 1993; Kitur et al., 1993; Hubbard et al., 1994; Richardson and King, 1995). Management activities like plowing and leveling are known to influence the spatial variability of structure-related soil properties (Bouma and Finke, 1993). Finke et al. (1992), for example, found that the thickness of a disturbed soil displayed a spatial structure that reflected the surface topography before the leveling took place. Hydraulic properties of the surface soil layer affect water through their effects on infiltration, evaporation, soil water storage, and conductivity of water to and away from the soil surface. Tillage and associated crop residue management also affect runoff and erosion, further confounding these processes (Seta et al., 1993; Richardson and King, 1995). The extent to which tillage and crop residue management alter the spatial variation in soil properties and subsequently crop yield are of interest in SSM because tillage type and intensity and the timing of tillage could be altered site-specifically (Voorhees et al., 1993).

Site-specific tillage may be desirable since soils vary with regard to optimal tillage needs for crop production and for conservation of soil and water (Voorhees et al., 1993) and many different soil and conservation needs can be present within a fields. The practicality of site-specific tillage will vary by location and tillage type. For example, in rolling landscapes, where many soils are in close association ranging from upland to

depressional in nature, it may be not practicable to till the soils as separated entities although the intensity of tillage could be varied. When soil series are more distinct, then individually designed tillage systems can be developed for specific soil series or landscape position (Voorhees et al., 1993). Khakural et al. (1992) measured soil properties across two discrete but closely associated landscape positions and found that the improvement in soil properties on an upland soil with conservation tillage outweighed the effects of these same high residue tillage on a depressional soil. Managing tillage operations according to spatially varying soil characteristics has the challenge of trying to satisfy multiple, and often opposing objectives, e.g., soil conditions best for plant growth may not be best for erosion concern or pollution impact.

Because water availability is so important to crop yield and because tillage impacts important soil properties and processes that regulate water availability either directly or indirectly, research on managing tillage operations according to spatially varying soil characteristics remains an important need. This study assesses the co-spatial variability of soil physical properties and corn yield under long-term no-tillage and how tillage affects those spatial relationships for a glacially derived landscape in central Michigan.

MATERIAL AND METHODS

A field study was conducted in 1995 and 1996 in a 3.72 ha section of a larger field located 6 km south of Durand, Michigan (47° 47' 30"N, 83° 52' 30"W). The field had been managed in a corn-soybean rotation under no-tillage for more than 10 years. Paired strips 4.57 m wide and 305 m long were established across the experimental area in April

1995 to evaluate tillage effects on the spatial variability of soil properties and corn grain yield. Chisel plowing was assigned randomly to a strip within each of 10 replicated pairs (Figure 2.1) creating a randomized complete block experimental design with 10 replications. Chisel plowing followed by one pass of a field cultivator was performed in the spring on 3 May, 1995 and 6 May, 1996. In both years, corn was planted on 8 May at 66000 plants ha⁻¹ (hybrid Pioneer brand 3733). In 1995, no starter fertilizer was applied, while in 1996 consisted of 94 L ha⁻¹ of 10-34-00 (N-P-K). Nitrogen fertilizer applications consisted of 145.6 kg N ha⁻¹ on 3 July, 1995 and 150 kg N ha⁻¹ on 27 July, 1996. Weed control followed standard recommendations for the pre-emergence applications for this area for corn.

Corn grain yields for both tillage systems were obtained every 15 m along the length of each strip from the center two rows of the 6-row plots. Plant populations at harvest were measured at the same area. At each 30.5 m grid point where soil profiles had been described (Figure 1.3, Chapter 1), 10 consecutive plants within 15 m section of two corn rows centered on grid intersection were harvested and oven-dried to determine stover yield.

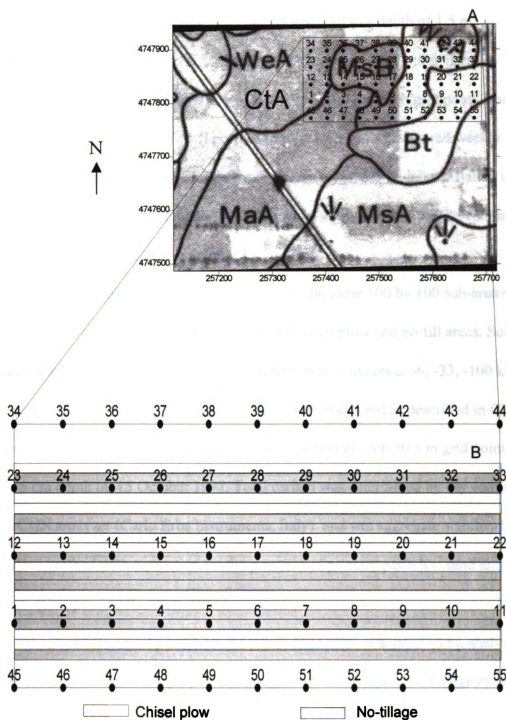


Figure 2.1. Location of the grid soil profile samples relative to the map units from the Order two soil survey (A) and detail of the tillage strips (B). Refer to Table 1.1 for map unit descriptions.

At the 30.5 m regular grid locations, water table depth was measured weekly throughout the growing season using piezometers installed to a depth of 1.5 m. Volumetric soil water content in the surface 18 cm was measured by time domain reflectometry (TDR) in both tillage systems in the proximity of each grid point. Soil profile volumetric water content (soil profile storage water) was monitored weekly at every other 30.5 m grid point by neutron probe access tubes, 1.5 m deep, installed in both tillage systems. Water table depth, surface volumetric soil water, and profile volumetric water content were always measured on the same day.

Undisturbed soil cores were obtained within the same 100 by 100 sub-area of the experimental site as described in Chapter 1 for the chisel plow and no-till areas. Soil hydraulic properties (volumetric soil water content; pore volumes at -6, -33, -100 kPa matric potential, total porosity; and bulk density) were measured as described in Chapter 1. Soil samples were obtained from each tillage treatment at each 30.5 m grid point from the 0 to 5 cm depth on 15 October 1997. Total carbon was determined by dry combustion using a CHN analyzer (Carlo Erba Instruments, Italy). and wet aggregate stability by the single sieve method with correction for the presence of primary particles: sand and coarse fragments (Kemper and Rosenau, 1986).

Tillage effects on crop yield for the whole field were evaluated using analysis of variance for a randomized complete block design with 10 replications. Tillage means for crop yield were tested using LSD at 0.05 probability level. A t-test for paired samples was used to test the effect of tillage on total carbon, aggregate stability, average seasonal volumetric water content, average seasonal profile water content obtained at each grid point.

Geostatistical analyses were performed as described in Chapter 1 for soil and plant variables for both tillage systems. Geostatistical methods were used to measure and model the spatial correlation for soil parameters and corn yields for both tillage systems. Variograms were derived by plotting the semivariance of the soil and plant data as a function of vector distance. Each parameter was subjected to semivariance analysis using isotropic and anisotropic models (linear, spherical, exponential, and gaussian) for defining semivariograms. The models were then used along with kriging techniques to develop maps showing spatial patterns in variability of selected soil properties, corn yield and plant variables (Issaks and Srivastava, 1989). Descriptive statistics and correlation were calculated using SAS (SAS, 1990).

Stepwise regression analysis was used to model the effects of soil physical properties on corn yield. The variables and respective symbols used in the regression analysis are listed in the Table 2.1.

Table 2.1. Description of variables with the respective symbols used in the stepwise regressions.

Symbol	Description
AFP6	Air filled porosity (%) at -6 kPa matric potential as described in Chapter 1.
AFP33	Air filled porosity (%) at -33 kPa matric potential as described in Chapter 1.
AFP100	Air filled porosity (%) at -100 kPa matric potential as described in Chapter 1.
Ap	Thickness of the Ap horizon (cm);
Ap-1500	Gravimetric moisture content at -1500 kPa matric potential (%) of the Ap horizon
Ap-clay	Clay content of the Ap horizon (%)
Ap-silt	Silt content of the Ap horizon (%)
Ap sand	Sand content of the Ap horizon (%)
BD	Bulk density (Mg m^{-3})
Bt	Depth to the Bt horizon (cm);
G6	Gravimetric water content (%) at -6 kPa matric potential as described in Chapter 1.
G33	Gravimetric water content (%) at -33 kPa matric potential as described in Chapter 1.
G100	Gravimetric water content (%) at -100 kPa matric potential as described in Chapter 1.
PAW	Weighted average profile available water (%)
P-clay	Weighted average profile clay content (%)
P-clay+silt	Weighted average profile clay + silt content (%)
POP	Plant population (plants ha^{-1})
TC	Total carbon content in the top 5 cm (%)
TP	Total porosity (%)
V6	Volumetric water content (%) at -6 kPa matric potential as described in Chapter 1.
V33	Volumetric water content (%) at -33 kPa matric potential as described in Chapter 1.
V100	Volumetric water content (%) at -100 kPa matric potential as described in Chapter 1.
VWC-tasseling	Volumetric water content (%) at the top 18 cm measured by TDR during the corn tasseling period.
VWC-silking	Volumetric water content (%) at the top 18 cm measured by TDR during the corn silking period
VWC-AVE	Average volumetric water content (%) at the top 18 cm measured by TDR during the growing season.

Table 2.1 (cont'd)

VWC-MAX	Maximum volumetric water content (%) at the top 18 cm measured by TDR during the growing season.
VWC-MIN	Minimum volumetric water content (%) at the top 18 cm measured by TDR during the growing season.
WT-MIN	Minimum depth (m) of the water table during the growing season.
WT-MAX	Maximum depth (m) of the water table during the growing season.
WT-AVE	Average depth (m) of the water table during the growing season
WT-tasseling	Water table depth (m) during the corn tasseling period.
WT-silking	Water table depth (m) during the corn tasseling period

RESULTS AND DISCUSSION

Three important aspects of this research are addressed in sequence as follows: (i) how tillage, after more than a decade of no-tillage management, altered soil physical properties spatially; (ii) how corn yield varied spatially over a two year period under different tillage management; and (iii) the extent to which soil physical properties, water table, and soil water content during the growing season explain the spatial variability in corn yield for the two years of this study; and whether these differences related in any way to differences in corn yield in the two tillage systems.

Tillage Effects on Soil Properties

The surface 5 cm of soil in the chisel plowed areas had, on the average, 22% lower total carbon (TC) (11.9 g kg^{-1}) than soil managed under no-tillage (15.2 g kg^{-1}) (Table 2.2). The t-test was significant for differences in TC due to tillage (Table 2.3).

Table 2.2. Descriptive statistics and variogram model parameters of total carbon (TC) and aggregate stability (AS) on surface 5 cm for both tillage systems after two growing seasons (1996).[‡]

Tillage	Variable	Mean	range	CV (%)	C_o	C_s	$C_o/(C_o + C_s)$ (%)	R (m)	M [†]	IGF
TC (g kg^{-1})										
NT	TC	15.2	7.7-27.9	29	43.196	128.396	34	104	S	4.2e-02
CP	TC	11.9	7.0-20.5	32	45.6	133.196	34	102	S	4.2e-02
AS (%)										
NT	AS	82.8	47.1-97.4	11	363.97	1019.14	36	102	S	4.1e-02
CP	AS	72.5	44.3-95.3	20	191.67	773.852	25	87	S	3.2e-02

[†] M = Model

[‡] Descriptions of symbols are presented in Table 1.2.

Table 2.3. Results of paired *t* statistic test on means of selected soil properties for different tillage systems after two growing seasons (1996).

	TC	AS.	VWC	PWC [†]
Mean	3.3	10.3	0.026	0.014
STD error	0.04	2.29	0.002	0.0079
LO 95% CI	2.6	5.62	0.021	-0.0025
UP 95% CI	4.2	14.98	0.030	0.314
T	8.33	4.48	12.36	1.83
P	0.0000	0.0001	0.0000	0.0892

[†] Number of observations N=15.

TC = Total carbon (g kg⁻¹);

AS = Aggregate stability (%);

VWC = volumetric water content (m³ m⁻³) at the top 18 cm measured by TDR.

PWC = average profile volumetric water content (m³ m⁻³) up to 1 m depth measured by neutron probe.

LO 95% CI = lower 95% confidence interval.

UP 95% CI = upper 95% confidence interval.

STD error = standard error.

T = test statistic *t*

P = p-value. Small p-value means that the mean of the difference is not zero. The p-value is for a two tailed test.

The spatial dependence of TC was moderately strong for both tillage systems and so was the difference in TC between tillage systems (Table 2.2). These differences in TC may result from carbon losses due to tillage as indicated in other tillage studies (Elliott et al., 1994; Gupta et al., 1994; Guillermo et al., 1997) but may also reflect a movement of carbon accumulated in the surface of no-till being moved to a lower depth with tillage. This would be consistent with reports on the effect of tillage the positioning of carbon within the soil (Pierce et al., 1994; Staricka et al., 1991).

Average aggregate stability (AS) in the chisel plow soil (72.5%) was 10% lower than the no-till soil (82.8%) (Table 2.2). For a small percent of the sample grid points, AS was higher in the chisel plow than in the corresponding no-till soil.

This may reflect small-scale variability in AS that would not be accounted for in the sampling scheme since tillage locations were not exact. In any event, the t-test was significant for differences in AS due to tillage (Table 2.3). The spatial dependence of AS was moderately strong for both tillage systems but the difference in AS between tillage systems was weak, largely due to the occasions where the difference between tillage systems reversed direction (Table 2.2). Tillage, as would be expected, generally reduced aggregate stability and is consistent with other studies (Guillermo et al., 1997; Caron et al., 1996).

Tillage, as expected, altered the soil physical properties determined on intact soil cores (Table 2.4). While average values for the soil properties for each tillage system was within one standard deviation of the means, tillage eliminated (pure nugget effect of the semivariogram) or reduced (higher nugget effect to total variance ratio) the spatial dependence of soil physical properties established under long-term no-tillage.

Table 2.4. Descriptive statistics and variogram models parameters of variables obtained from soil cores (7.6 by 7.6 cm) within the field geostatistical grid (n=162) for both tillage systems.[‡]

Variable	Mean	SD	range	CV (%)	C _o	C _s	C _o /(C _o + C _s) (%)	R (m)	Model	IGF
No-till										
BD	1.52	0.08	1.30-1.67	5	0.003	0.003	50	17.9	S	1.6e-03
TP	36	2	31-44	7	2.006	4.189	32	13.3	S	4.9e-03
GM-6	14	2	2-20	15	2.927	2.543	54	68.6	S	1.1e-03
GM-33	13	2	9-19	14	0.296	4.000	7	46.2	E	5.6e-03
GM-100	12	2	9-18	15	0.828	3.276	20	45.5	S	1.3e-02
VM-6	22	3	3-28	14	5.369	4.732	53	66.5	S	2.4e-02
VM-33	20	2	14-27	13	0.462	7.500	6	58.8	E	8.9e-03
VM-100	19	2	13-26	14	0.395	7.500	5	53.2	E	8.8e-03
AFP-6	39	8	21-89	21	41.89	23.43	64	9.0	S	3.8e-02
AFP-33	44	7	27-62	16	11.13	46.11	19	43.4	E	5.4e-03
AFP-100	46	7	29-64	16	12.72	46.11	22	47.6	E	5.0e-03
Chisel plow										
BD	1.41	0.10	1.21-1.64	7	0.010	a		a	PN	3.3e-03
TP	39	3	32-47	7	7.395	1.652	82	56.6	S	5.4e-03
GM-6	15	2	10-21	14	2.385	2.789	46	52.4	G	9.5e-03
GM-33	13	2	10-18	14	0.998	3.293	23	60.7	S	8.3e-03
GM-100	13	2	9-17	14	0.917	3.161	22	57.3	S	1.3e-02
VM-6	21	3	15-30	13	4.514	3.996	53	54.5	G	3.5e-03
VM-33	19	2	13-25	13	2.664	5.004	35	66.9	S	5.3e-03
VM-100	18	2	13-24	14	2.751	4.671	36	62.8	S	5.3e-03
AFP-6	46	8	24-61	17	61.44	a		a	PN	1.2e-02
AFP-33	51	7	26-66	15	44.65	17.98	71	69	S	2.8e-03
AFP-100	53	7	28-69	14	42.75	17.67	71	69	S	3.7e-03

[‡] Descriptions of symbols are presented in Table 1.2.

Differences in spatial structure between tillage systems would indicate that the differences between tillage systems were spatially dependent.

On the average, soil water retention, both gravimetric and volumetric, was not greatly affected by tillage and for the most part both tillage systems had similar spatial dependence. There was a change in the best fit model for the semivariogram for soil water retention and air filled porosity, and an increase in the ratio of nugget to total variance and range for most matric potentials. Changes due to tillage in these properties similar in magnitude were reported for the Capac Loam soil (fine-loamy, mixed, mesic Aeric Ochraqualf) in Michigan (Pierce et al., 1994). The CVs were < 10 % for bulk density and total porosity and between 13 and 21% for the other soil properties.

The volumetric water content (VWC) in the surface 18 cm for the growing season averaged 0.026 m m^{-3} (Table 2.3) lower in chisel plow than in no-tillage as has been reported elsewhere (Hubbard et al., 1994; Griffith et al., 1986; Waddell and Weil, 1996; Azooz et al., 1996).

Soil profile water content measured with a neutron probe on the average over the growing season showed no significant differences over the 1 m depth between tillage systems. The upper 75 cm portion of the soil profile, however, did show tillage effects, with higher volumetric water contents in no- till (Figure 2.2).

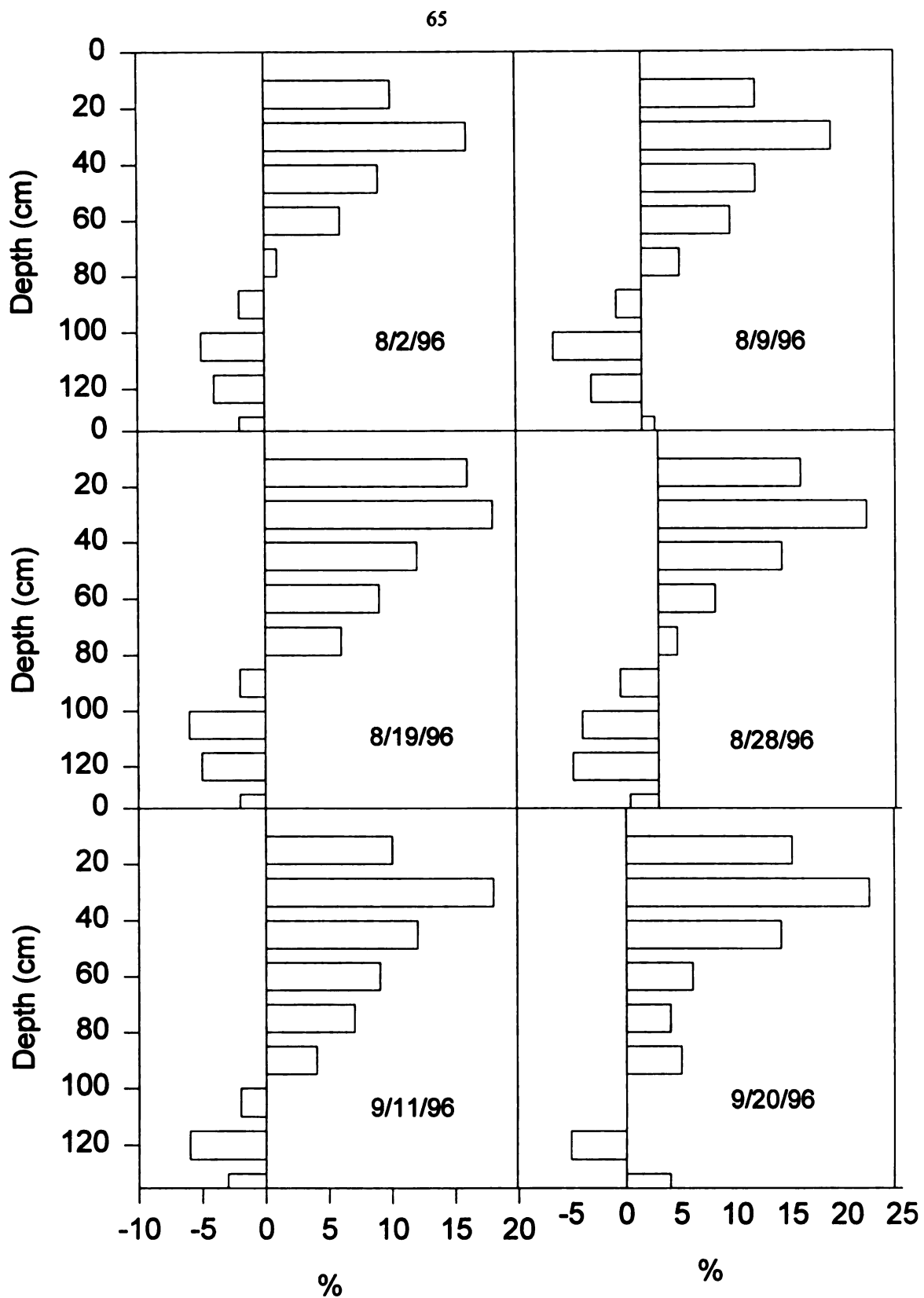


Figure 2.2. Percent difference (NT-CP) in profile volumetric water content at different depths and on different dates.

Tillage Impacts on Corn Yield

Average corn grain yields were similar for 1995 and 1996 (8477 and 8869, respectively) but the standard deviation, range, and CV were higher in 1996 (Table 2.5). Corn grain yield in the chisel plow treatment averaged 298 kg ha⁻¹ higher than no-till in 1995 (LSD = 228 kg ha⁻¹) but average yields were not different in 1996. Starter fertilizer was not applied in 1995 and given the potential for starter fertilizer benefits in chisel plow, this may be a factor in this observation. On a field average, chisel plowing had a small yield advantage in 1995 and 1996; however, given costs of energy and equipment and changes in soil quality, the difference may not be economical.

Of interest here was whether the spatial dependence of corn grain yield would change if the soil were plowed and under what condition corn grain yield would be different under different tillage management. Corn grain yields varied spatially each year, more so in 1996 than in 1995, and varied differently with tillage (Figure 2.3 and 2.4). Corn grain yields were spatially dependent in both years but yields in 1996 exhibited moderate to strong spatial dependence while spatial dependence of yield was weak in 1995, as evidenced by lower nugget effect to total variance ratios, ($C_o/(C_o + C_s)$); Table 2.5). The structural variance (C_s) was 6 to 13 times higher in 1996 than in 1995. Nugget effect (C_o) were similar between years within a tillage system but were higher in no-till than chisel plow both years. The two year average corn grain yield for each tillage system showed slightly higher average yield for chisel plow (8803 versus 8542 kg ha⁻¹ for no-till) but similar variances and very similar spatial dependence for the two tillage systems (Table 2.5).

Table 2.5. Descriptive statistics and variogram model parameters of corn yield for both tillage systems in 1995 and 1996.[‡]

Year	Mean kg ha ⁻¹	SD	range Kg ha ⁻¹	CV (%)	C ₀	C _s	C ₀ /(C ₀ + C _s) (%)	R (m)	M	IGF
No-till (NT)										
1995	8328	706.4	5826-9832	8	385000	100000	79	57.8	G	3.6e-03
1996	8757	1007	2653-10535	11	384963	582963	40	81.6	E	1.5e-03
Average	8542	687.5	4584-9833	8	168000	264000	39	59.4	E	4.4e-03
Chisel plow (CP)										
1995	8626	542.4	6258-10096	6	228000	57000	80	49.3	S	1.3e-03
1996	8980	1078	2019-10799	12	264000	756000	26	56.1	E	5.3e-03
Average	8803	652.7	5007-10077	7	124700	258000	32	59.5	E	4.8e-03
Difference NT-CP										
1995	-298	715.2	-2320-1956		387566	112183	77	62.9	G	4.2e-03
1996	-223	886	-3299-2590		655700	71100	90	170	S	5.7e-03
Average	-261	594	-2346-1383		280740	53952	84	163	S	5.2e-03

[‡] Descriptions of symbols are presented in Table 1.2.

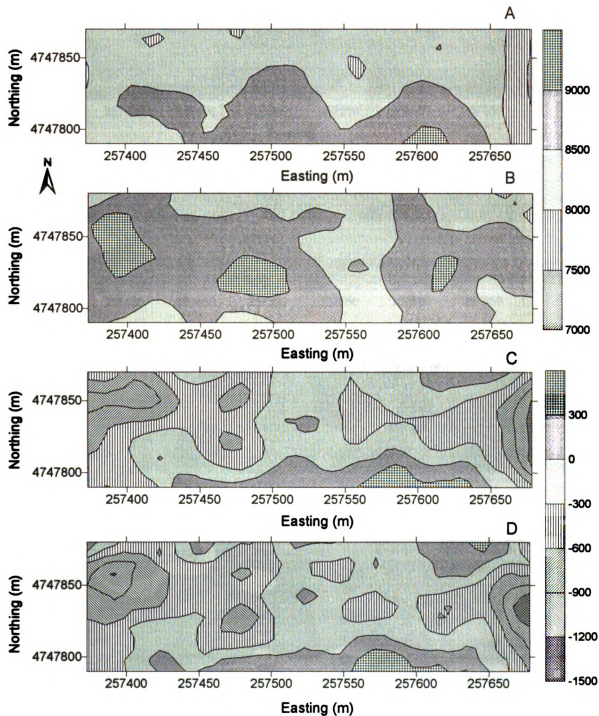


Figure 2.3. Interpolated maps of corn grain yield (kg ha/ha) for no-tillage (A), chisel plow (B), the difference between no-tillage and chisel plow by subjecting the difference to geostatistical analysis (C), and by subtracting (B) from (A) (D) for 1995.

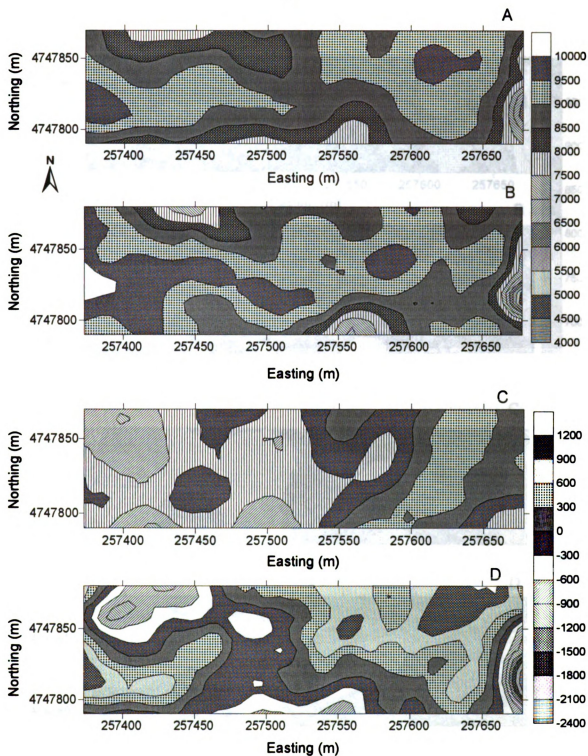


Figure 2.4. Interpolated maps of corn grain yield (kg/ha) for no-tillage (A), chisel plow (B), the difference between no-tillage and chisel plow by geostatistical analysis (C), and by subtracting (B) from (A) (D) for 1996.

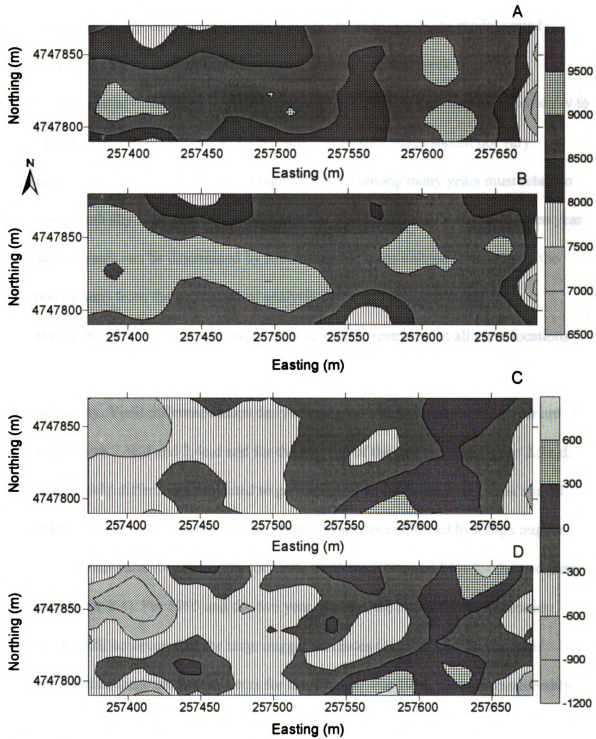


Figure 2.5. Interpolated maps of average of the two years of corn grain yield (kg/ha) for no-tillage (A), chisel plow (B), the difference between no-tillage and chisel plow by subjecting the difference to geostatistical analysis (C), and by subtracting (B) from (A) (D).

Where spatial dependence is moderate to strong, the exponential model fit the semivariogram for grain yield (1996 and two year average) while the model varied between tillage systems in 1995 where spatial dependence was weak.

The spatial differences in yield between tillage systems provides an opportunity to identify site-specific tillage zones. To be useful, difference maps should not vary substantially between years, or the average difference among many years must relate to some economically manageable zone delineation. Yield difference maps for a given year or multiple years can be determined by subtracting the maps created from kriging the semivariograms from the geostatistical analysis of the two tillage systems or by calculating the yield difference between the two tillage treatments at all yield locations and subjecting the difference to geostatistical analysis as was done for the tillage yields independently. Yield difference maps derived using both techniques for each year are given in Figure 2.3c,d and 2.4c,d and for the average of the two years in Figure 2.5 c,d. Calculated yield differences subjected to geostatistical analysis exhibited weak spatial dependence in both years and for the two year average, as evidenced by a high nugget variance to total variance ratio (77% for 1995, 90 % for 1996, and 84% for the two year average; Table 2.4). For 1995 and the two year average, the two difference maps are similar. Recall, however, that the large nugget variances for 1995 and the two year average indicate large prediction errors for these maps. For 1996, there is considerably more variability expressed in the subtracted map (Figure 2.4d) than the kriged difference map (Figure 2.4c). Since the subtracted map was generated from maps with high spatial dependence whereas the spatial dependence of the difference was weak, the subtracted map may be a more realistic representation of the real difference between the tillage

systems. In any case, the extent to which the average map delineates economically viable management zones is uncertain. Lamb et al. (1997) found a weak relationship among years between relative yield and location in a 1.8 ha field during 5 years of study in Minnesota. Therefore, it may take many years of yield map data to delineate management zones within a field.

Corn grain moisture at harvest was similar for both tillage systems for 1995 and 1996 and variability was low (CVs ranged from 3 to 6 %; Table 2.6). Grain moisture exhibited strong spatial dependence in no-till and moderate spatial dependence in chisel plow in both (low to moderate nugget to total variance ratios; Table 2.6). The best fit models to semivariograms were spherical for no-tillage and gaussian for chisel plow. The range was higher in 1995 than in 1996 and slightly higher for no-till than chisel plow. Plant populations averaged near the target population of 66,000 plants ha⁻¹, with slightly higher values in chisel plow than no-till and higher in 1996 than in 1995 (Table 2.6). Variation in plant population was similar to grain yield (Table 2.6), with CVs ranging from 6 to 11 % and generally moderate to weak spatial dependence, with no spatial dependence found for no-till in 1996. The model fit to the variogram and the range varied within years and tillage systems for plant populations. Stover biomass measured at harvest was quite variable (CVs ranged from 18 to 22%). In 1995, stover was higher in chisel plow than no-till but the reverse was true in 1996. Spatial dependence of stover was moderate to strong, depending on year and tillage system, and the spherical model fit the semivariogram in all cases, with the range varying from 88 to 110 m.

Table 2.6. Descriptive statistics and variogram models parameters of grain moisture (GrM), plant population (PP), and stover yield (SB) for both tillage systems in 1995 and 1996. ‡

Variable	Mean	SD	range	CV (%)	C ₀	C _s	C ₀ /(C ₀ + C _s) (%)	R (m)	Model	IGF
No-tillage - 1995										
GrM	19	0.55	17.1-20.1	3	0.0599	0.3639	14	114	S	8.9e-03
PP	60716	6879	35254-73255	11	2.6e+07	2.6e+07	50	80	G	1.3e-02
SB	3490	636	2463-4906	18	179189	3455786	52	105	S	4.3e-02
No-tillage - 1996										
GrM	19.7	1.15	16-22.5	6	0.1399	1.4881	9	68	S	7.1e-03
PP	63701	6381	25633-79188	10	3.5e+07	a		a		
SB	3999	794	1973-5659	20	1511720	466116	32	100	S	4.1e-02
Chisel plow - 1995										
GrM	19.1	0.49	17.5-20.1	3	0.09	0.2639	34	92	G	5.6e-03
PP	63732	4143	50820-74172	6	1.2e+07	1.9e+07	63	92	G	1.8e-02
SB	4358	950	2941-8373	22	866320	5506470	16	88	S	3.2e-02
Chisel plow - 1996										
GrM	19.8	1.10	16.6-23	6	0.5069	1.3649	37	59	G	8.5e-03
PP	66711	7114	16021-77815	11	3.0e+07	4.2e+07	71	29	S	6.4e-03
SB	3531	700	2578-5365	20	1946340	3595790	54	110	S	4.4e-02

‡ Descriptions of symbols are presented in Table 1.1.

Influence of Soil Properties on Corn Grain Yield

For 1995, using stepwise regression analysis ($P \leq 0.05$), 52 % of the variability in corn yield was explained by a linear combination of volumetric water content in the surface 18 cm at tasseling (VMC-tasseling), at silking (VMC-silking), and the average in the soil surface during the growing season (VWC-average; Table 2.7). The negative coefficient on the VWC-average variable may reflect the negative impacts of excessive water during the wet conditions during the early portion of the growing season in 1995. Positive coefficients for VMC-tasseling and VMC-silking reflect the importance of water during the reproductive period for corn. For 1996, only one significant regression was observed; a simple linear regression of corn yield on clay content of the Ap horizon explained 25 % of the variability in yield. No other linear combinations of soil properties measured in Chapter 1 or water table depths or soil water contents measured during the growing season (regression variables given in Table 2.1) were significant in explaining yield variability in either year.

Table 2.7. Results of stepwise regression of no-tillage corn grain yield and soil properties for two years.

Year	Variables	Coefficient	P-value
1995	Constant	10919.30	0.0000
	VWC-tassiling	221.07	0.0082
	VWC-silking	121.25	0.0444
	VWC-average	-496.67	0.0001
1996	Constant	7489.80	0.0000
	Ap-clay	135.93	0.0029

Others report that yield variability within a given year is controlled by soil properties that affect patterns in plant available water holding capacity or soil drainage and aeration. Mulla et al. (1992) studied spatial patterns in properties affecting winter wheat grain yield. The properties with the highest correlation to variation in yield were soil profile available water content and organic matter. Jaynes et al. (1995) also found that spatial variations in corn yield were correlated with soil properties that affected variations in soil moisture, especially in years that were excessively wet. Thus, a close relationship can be expected between soil properties that affect variations in soil moisture and crop yields. In this study, however, most of the yield variability was not explained by soil physical properties or by water availability as measured by water table depth or water content measurements over the growing season.

Stepwise regression analysis was used to the parameters in Table 2.1 to the differences between corn yields obtained with chisel plowing and no-till. For 1995, 50% of the yield difference between tillage systems was related to a linear combination of VMC-tasseling, VMC-average, and the water table depth at tasseling (WT-tasseling; Table 2.8).

Table 2.8. Results of stepwise regression of the difference between no-till and chisel plow corn grain yield and soil properties for 1995.

Variables	Coefficient	P-value
Constant	5276.45	0.0011
VWC-tasseling	224.63	0.0001
VWC-average	-415.51	0.0106
WT-tasseling	-1674.31	0.0099

From this relationship it appears that no-till was higher yielding than chisel plowing in 1995 when season average surface water contents were lower (lower water contents in the early part of the growing season in 1995) and water at tasseling was more available (the surface water content was higher and the water table was closer to the surface). No other linear combinations of regression variables in Table 2.1 were significant in explaining the variability in corn yield in 1995 and none were significant for 1996.

The general lack of significant relationships between corn yield and the parameters in Table 2.1 is not surprising given the dynamic nature of the factors that regulate crop yield. Crop simulation models were developed to capture the dynamics of crop growth and development. Chapter 3 describes the evaluation of the CERES-maize model (DSSAT version 3, 1994) to account for the spatial variability in corn yield using the data measured in this study.

CONCLUSION

Tillage altered soil physical properties and soil water availability primarily by destroying or reducing the spatial structure developed under no tillage. Tillage also altered the spatial pattern of corn grain yield but was different each year. While chisel plowing produced higher corn yields in 1995 for the field, no-till produced higher yields in some portions of the field in both years. Yield differences between tillage systems varied spatially, with spatial patterns differing each year. Soil properties and water availability measurements were of little value in explaining corn yields in either year using multiple regression techniques. Crop simulation models, however, might be better

suited to this task and should be evaluated as to their ability to predict the spatial variability in crop yield over time.

A considerable effort was made to measure factors that might affect corn grain yields, but a substantial amount of spatial and temporal variability was found. The information from this study suggests that corn grain yield variability can be substantial from year to year and between tillage systems. The lack of grain yield stability on the study area causes some concern for practical applications of this information on site-specific management. Several years worth of yield maps will be needed to define site-specific soil management zones in this experimental area.

CHAPTER 3

Simulation of Within Field Variability of Corn Yield with CERES-Maize

INTRODUCTION

Simulation models are valuable tools for predicting crop yields and examining alternative agricultural management practices for crop production and their potential impacts on the environment. Simulation models are used for both scientific research purposes and to contribute to decision-making processes at experimental and governmental levels (Addiscott, 1993). Intuitively, crop models should have considerable value in evaluating site-specific management (SSM) systems and associated component precision farming practices but have found limited use (Van Uffelen et al., 1997; Han et al., 1995). Sadler and Russell (1997) suggested that limited application appears to be caused by lack of knowledge about within-field variability of soil properties needed for predicting crop yield.

Traditionally, models were developed assuming soil properties to be homogenous (Han et al., 1995). Several modeling attempts have been reported using soil map delineation as a means to express spatial variability patterns, using “representative” soil profiles for each delineation (Kiniry et al., 1997; Pang et al., 1997; Gabrielle and Kengni, 1996). However, the assumption that delineated areas on a second order soil map can serve to adequately represent soil spatial variability is flawed because considerable variation occurs within map units (Beckett and Webster, 1971). Nonetheless, since SSM

aims to maximize crop production through efficient use of managed inputs according to localized variability in soils, pests, and crop condition (Pierce and Sadler, 1997), model inputs should include details on within field variability. If soils in a field exhibit large spatial variability, many different management zones may be identified for SSM. According to Verhagen and Bouma (1997), modeling results can be very useful for evaluating effects of spatial and temporal soil variability on crop yield because they can cover a wide range of conditions that are relevant to agricultural production and environmental quality concerns.

The ability of models to predict yield based on soil variability on a finer spatial scale still needs to be demonstrated in order to strengthen confidence in their usefulness for SSM (Sadler and Russel, 1997). Therefore, results of simulations must be validated with real data, obtained by field measurements on a finer scale and several growing seasons (Verhagen and Bouma, 1997). Interpolation techniques make it possible to extend results of simulations obtained at point locations to large land areas (Finke, 1993). Therefore, simulations over the range of annual weather conditions expected for a given area could be used to delineate areas displaying consistent patterns over time that can be used for SSM.

Both complex mechanistic models and simple functional ones have been used to estimate crop yields. The Decision Support System for Agrotechnology Transfer (DSSAT) integrates several models, which are in the functional class, with standardized input and output (IBSNAT, 1989). The DSSAT maize model (CERES-Maize) has been tested and used in the USA and around the world with promising results. Kiniry et al. (1997) tested the model at one county in each of the nine states in the U.S. (Minnesota,

New York, Iowa, Illinois, Nebraska, Missouri, Kansas, Louisiana, and Texas) and concluded it was appropriate for predicting yield for most counties. Hodges et al. (1987) found that earlier versions of CERES-Maize accurately simulated maize grain yield in the northern U.S. Corn Belt. Researches have adapted the model in Michigan (Algozin et al., 1988), California (Pang et al., 1997), France (Gabrielle and Kengni, 1996), and China (Wu et al., 1989).

While CERES-Maize model has been used successfully in many situations, like most crop simulation models, it has not been tested under conditions where soil spatial variability within a field was taken into account. A successful application of CERES-Maize to known conditions of spatial variability over time would encourage the use of crop simulation models in SSM. This study used the CERES-Maize model to evaluate the potential for proven crop simulation models to account for known soil spatial variability on simulated corn yield within a field.

MATERIAL AND METHODS

The DSSAT version 3 (1994) of the CERES-Maize model was applied to an extensive data set consisting of soil profile properties and corn performance data (1995 and 1996) obtained on a 30.5 m grid positioned in a 3.9 ha area located within a larger field 6 km south of Durand, Michigan as described in Chapters 1 and 2 (Figure 3.1). The model was first calibrated on one site (soil profile #15) chosen because it was nearly level, representative of the soil mapping unit, the water table not present within 1.5 m, and plant populations were similar and close to the target in both years (1995 and 1996).

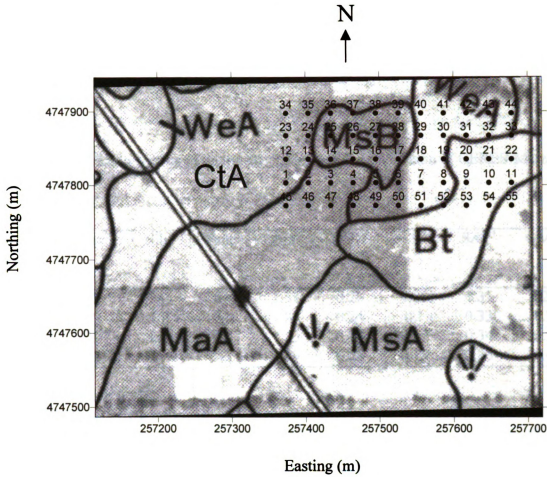


Figure 3.1. Location of the grid soil profile samples relative to the map units from the Order two soil survey. Refer to Table 1.1 for map units descriptions.

Soil profile characteristics of profile 15 as used in the model calibration are given in

Table 3.1. The model was calibrated for 1995 only in order to establish appropriate crop coefficients for the corn hybrid used both years.

Table 3.1. Soil characteristics of the profile 15 used in the calibration of CERES-Maize model.

Horizon depth (cm)	Clay [*]	Silt	Sand	BD [‡]	DUL [†]	LL [‡]	SAT [†]	OM ^{**}
0-25	12	24	64	1.51	0.20	0.05	0.35	1.26
25-49	19	16	64	1.70	0.24	0.1	0.33	0.7
49-75	31	22	48	1.66	0.30	0.17	0.34	0.5
75-100	22	31	46	1.69	0.28	0.15	0.33	0.4

^{*}Clay, silt and sand = (%);

[‡]BD = bulk density (Mg m^{-3});

[‡]LL = lower limit of available soil water ($\text{m}^3 \text{m}^{-3}$);

[†]DUL = drained upper limit of available soil water ($\text{m}^3 \text{m}^{-3}$);

[†]SAT = saturated limit of available soil water ($\text{m}^3 \text{m}^{-3}$)

^{**}OM = organic matter (%).

Input to the model included on-site weather data collected both years, soil data (soil profile properties), soil N balance parameters, crop management data, and genetic parameters and crop coefficients for the corn hybrid used. The minimum set of weather data (daily minimum and maximum temperatures, solar radiation, and rainfall) was collected by a minimum data weather station established at the experimental area. The soil N balance parameters and crop management data were obtained from the characteristics of the site described in Chapter 2. Plant nutrients were not a limitation factor for the present study, and pests (insects, diseases, and weed) were controlled and

posed no limitations to crop growth and yield. The genetic parameters: the thermal time from seed emergence to the end of the juvenile stage (P1), the thermal time from silking to physiological maturity or black layer formation (P5), and the photoperiod sensitivity coefficient (P2) were calibrated with real time periods observed during the growing season. The maximum kernel number per plant parameter (G2) and potential kernel growth rate parameter, (G3) were set as 650 and $9.6 \text{ mg kernel}^{-1} \text{ d}^{-1}$. The values of G2 and G3 were close to those for corn hybrids grown in the northern U.S. Corn Belt.

As described in Chapter 1, other data were obtained at each grid site including water table depth measured weekly throughout the growing season using piezometers installed at each grid point to a depth of 1.5 m, volumetric soil water content in the surface 18 cm measured weekly by time domain reflectometry (TDR), and soil profile volumetric water content (soil profile storage water) monitored weekly at every other 30.5 m grid point by neutron probe access tubes, 1.5 m deep. From these measurements, soil factors needed for model input related to soil water were obtained including: drainage coefficient (SWCON), lower limit of the available soil water (LL), drained upper limit of the available soil water (DUL) or field capacity, potential extractable soil water (PLEXW), and saturated water content (SAT). These parameters were also calculated according empirical equations based on the texture of each horizon (Ritchie 1997, personal communication) and compared to the measured data set. The SCS curve number and soil albedo were determined for each grid point (Ritchie et al., 1990). The initial soil water content for simulation was set to field capacity.

Once the model was calibrated for a grid point 15, it was used to simulate corn yield for all grid points for the two years (1995 and 1996), varying the profile soil data for

each grid point, the weather for each respective year, and using plant populations measured at harvest as model input. The performance of the CERES-Maize model was evaluated by regressing actual corn yields measured for each grid location within the experimental site (Chapter 2) with yields predicted by the model.

RESULTS AND DISCUSSION

Model Calibration

The calibration of the CERES-Maize model on profile 15 required a few changes to the initial model parameters. The drainage rate was set to 0.5 d^{-1} , based on estimates by the procedure of Ritchie and Crum (1989). Soil albedo was set to 0.13 (Ritchie et al., 1990). The SCS runoff curve number was set to 67 (Ritchie et al., 1990). The P1 genetic parameter was set a 200 degrees day, and P5 was set at 680 degrees days to produce a corn growing period consistent with the experimental site. The P2 genetic parameter was set at 0.5 h^{-1} . These input values gave a harvest index (ratio of total biomass to grain yield) close to 0.5, which is expected for corn grain yield when neither nutrients nor water are limiting. Plant population for the grid point 15 was $60000 \text{ plants ha}^{-1}$ for 1995. The model predicted corn grain yield well for the calibration year differing by only -2 % for 1995. These differences were considered reasonable for model performance and the model was considered ready for use in the evaluation of spatial variability.

Simulation of Spatial Variability

Corn grain yields simulated by CERES-Maize corresponded well to measured yields in 1995 (Figure 3.2-3.4). The simulated yields generally fall on the 1:1 line and a simple linear regression of simulated on measured yield accounted for 86% variability (Figure 3.2). There is a tendency of the model to underpredict at yields above 9 000 kg ha⁻¹ (Figure 3.2) and this is made clear in the comparison of frequency diagrams of measured and simulation yields in Figure 3.3.

The average, standard deviation and CV for the measured and simulated data for the whole area (33 profiles) are very similar, with the difference in mean of only 27 kg ha⁻¹ (Figure 3.3). The yield maps interpolated from measured and simulated yields are comparable (Figure 3.4a,b), with maps show similar patterns within the area, i.e., lower yields in the eastern part of the field and higher yields in the central southern part. Differences between yield maps were generally within ± 300 kg ha⁻¹ (Figure 3.4c). The performance of CERES-Maize in predicting the corn yield variability within the experimental area for 1995 is encouraging and is consistent with earlier evaluations of the model (Kiniry et al., 1997).

Simulations for 1996 were performed using the same model coefficients and soil data sets used for 1995 and using the 1996 weather data and 1996 plant population for each grid point. The CERES-Maize model predicted very low grain yields for 1996, with an average of 1167 kg ha⁻¹ and a range of 469 to 1946 kg ha⁻¹, while the measured yields averaged 8928 kg ha⁻¹ and ranged from 7180 to 10 159 kg ha⁻¹. Plant population for 1996 was similar to that for 1995.

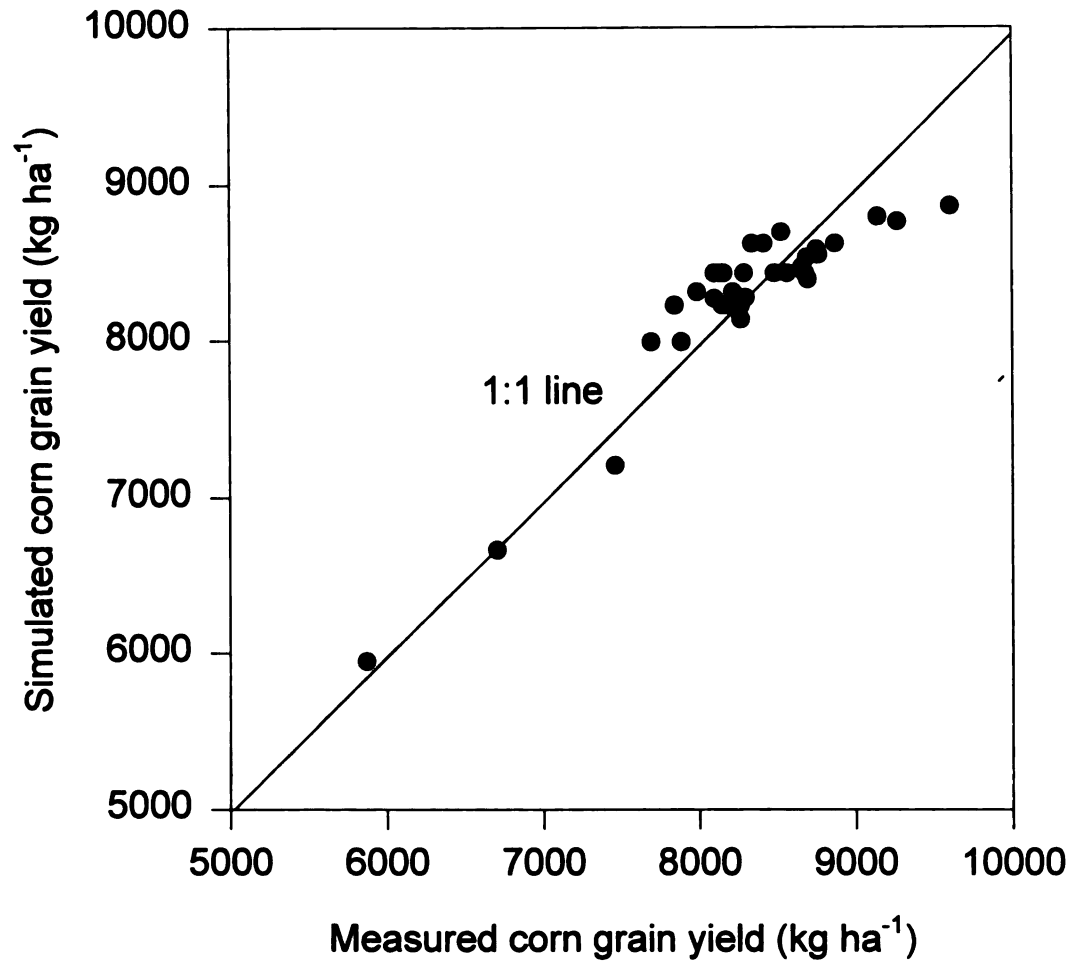


Figure 3.2. Plot of measured and simulated corn grain yield for 1995.

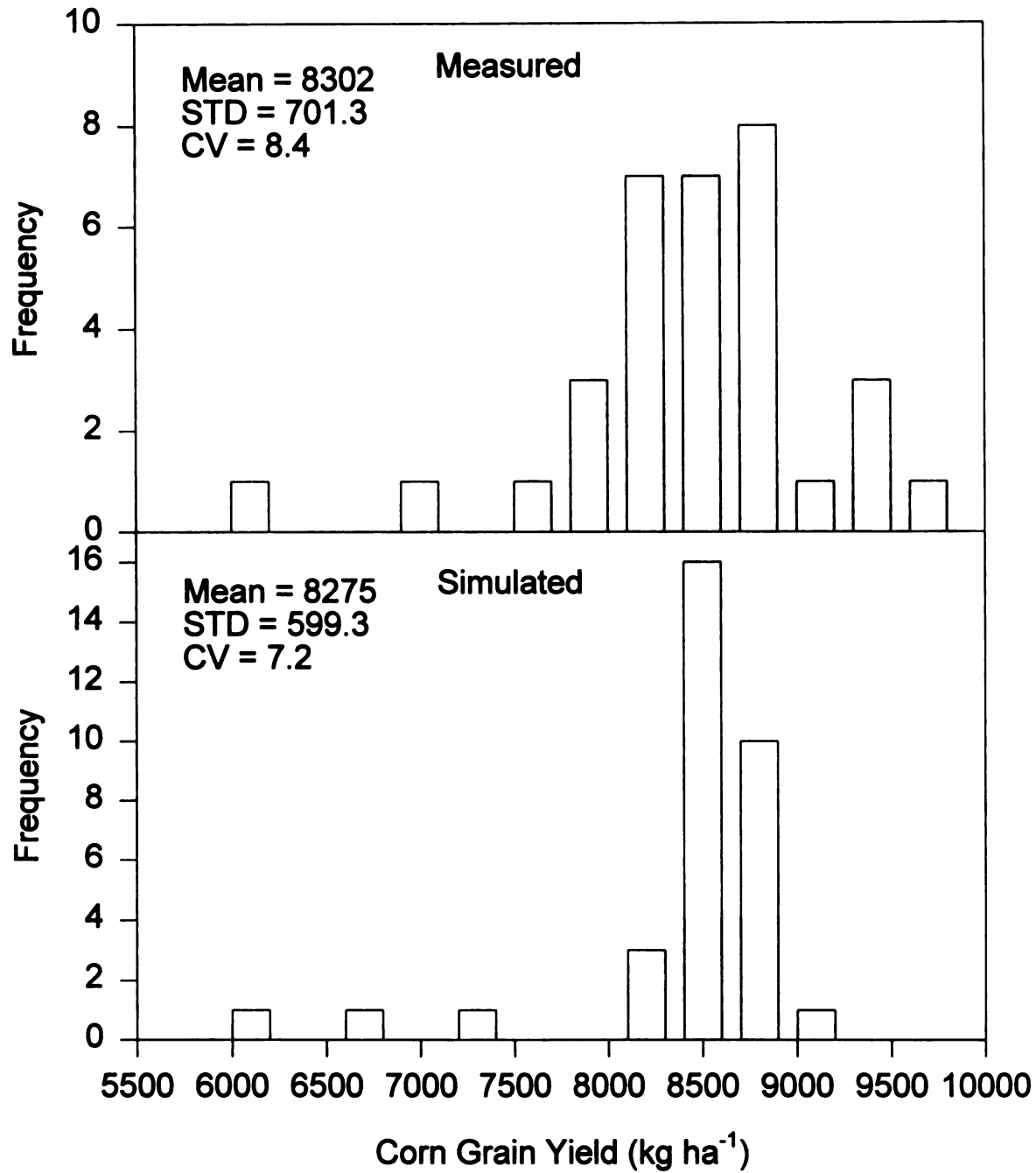


Figure 3.3. Frequency distribution, mean, standard deviation (STD), and coefficient of variation (CV) for measured and simulated corn grain yield for 1995.

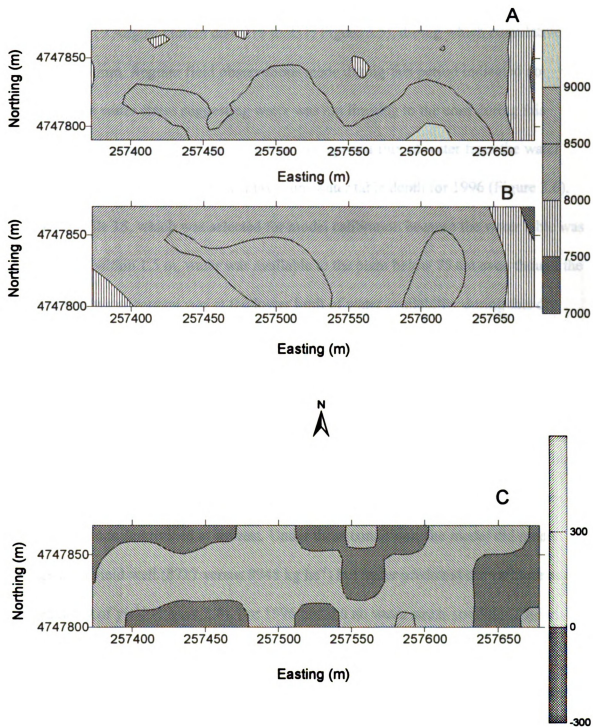


Figure 3.4. Measured (A), simulated (B), and difference between measured and simulated (C) of corn grain yield (kg/ha) for 1995.

The model greatly under predicted grain yields because of a drought during grain fill from 1 to 19 August (Julian date 213 to 231; Figure 3.5), during which cumulative rainfall was 3 mm. Regular field observations made during this period indicated no apparent plant water stress suggesting water was not limiting to the corn during this period. Water was available to the plant from the upward flux of water from the water table as evidenced by the map of the maximum water table depth for 1996 (Figure 3.6). Even for profile 15, which was selected for model calibration because the water table was generally not within 1.5 m, water was available to the plant below 75 cm even though the upper profile water content was at the lower limit of water availability during this dry period (Figure 3.7). The problem for the CERES-Maize model is that it does not account for the presence of a water table and the upward flux of water into the root zone.

Since water did not appear to be limiting in this field in 1996, the simulations were rerun with the model set to eliminate water stress during the growing season. Thus, simulated corn grain yields were determined primarily by weather conditions and the plant populations determined at harvest. Under these conditions, the model did predict the average corn yield well (8717 versus 8948 kg ha⁻¹) but under predicted the variance and the frequency of yield (Figure 3.8). For 1996 under a no water stress condition, the model over predicted yield below 9000 kg ha⁻¹ (above the 1:1 line in Figure 3.9) and under predicted yields above 9000 kg ha⁻¹ (below the 1:1 line in Figure 3.9). The indication of under prediction at higher yields was evident in 1995 as well.

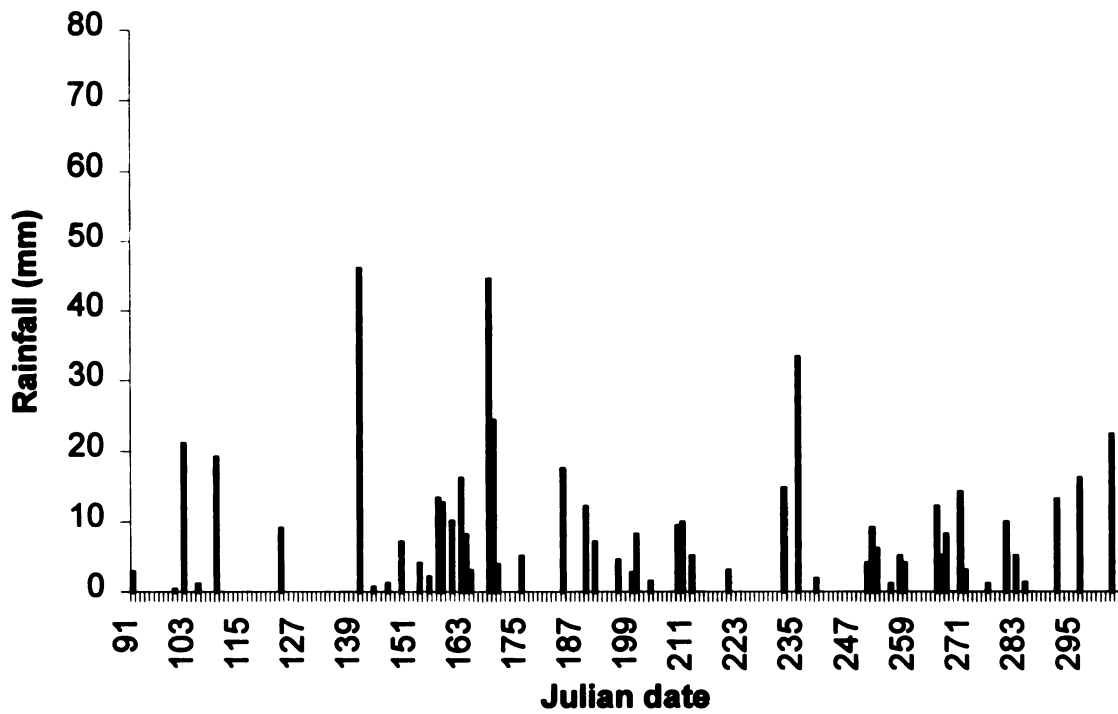


Figure 3.5. Precipitation recorded at the experimental area from April 1st to October 31st, 1996.

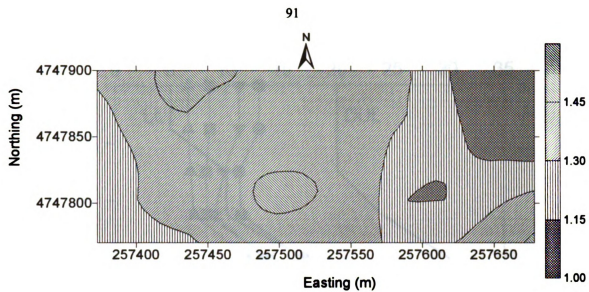


Figure 3.6. Maximum water table depth (m) for the experimental site in 1996.

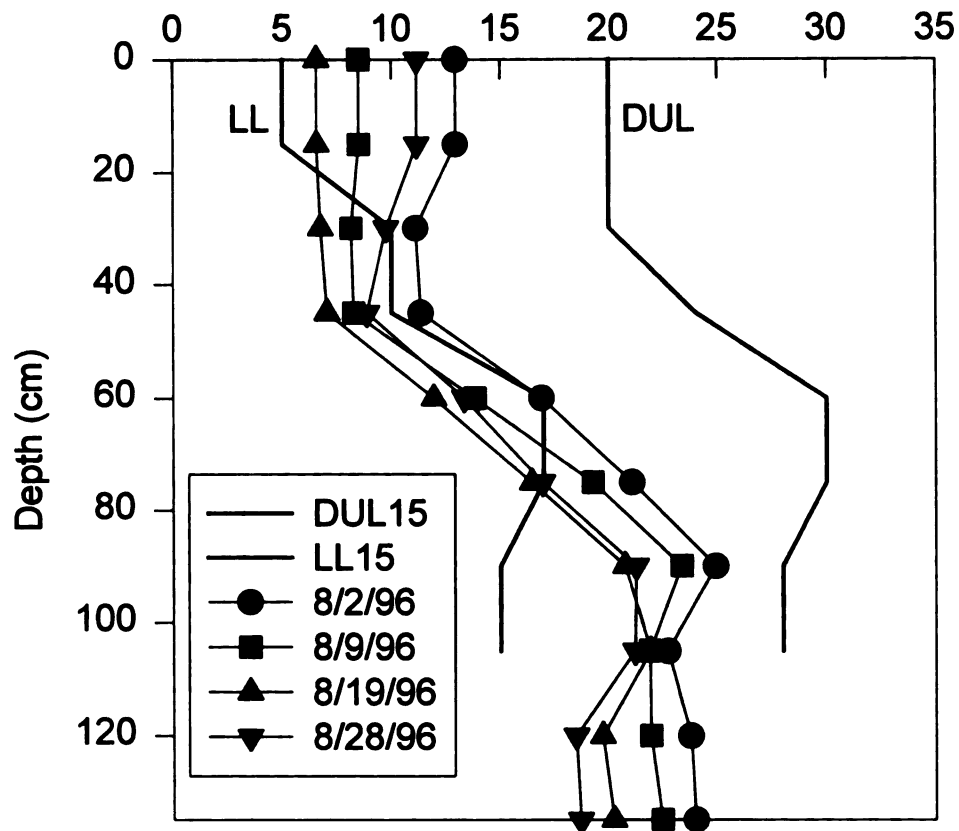


Figure 3.7. Volumetric soil water content (%) at drainage upper limit and lower limit for the grid point 15 and volumetric soil water content in different dates

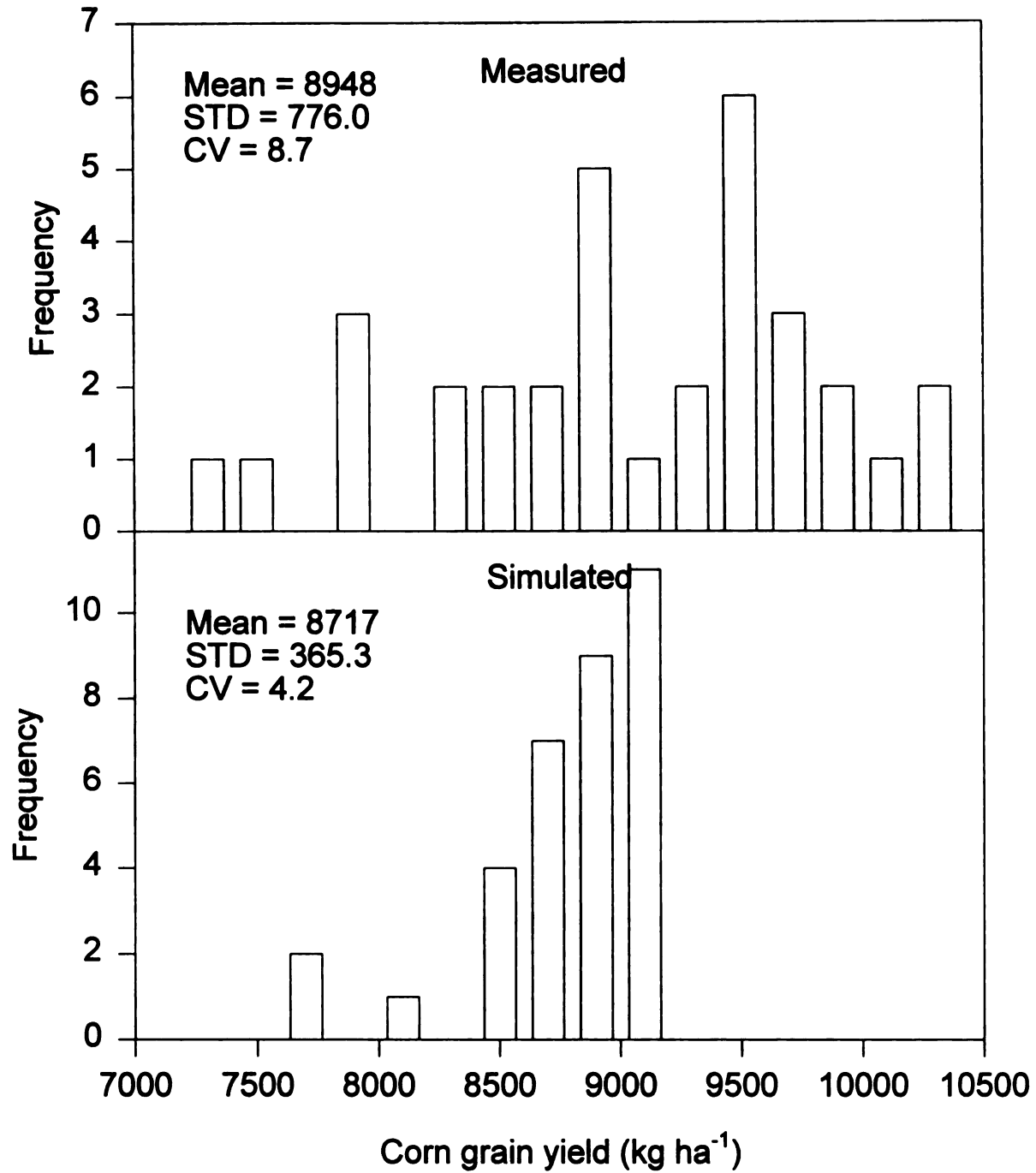


Figure 3.8. Frequency distribution, mean, standard deviation (STD), and coefficient of variation (CV) for measured and simulated corn grain yield for 1996.

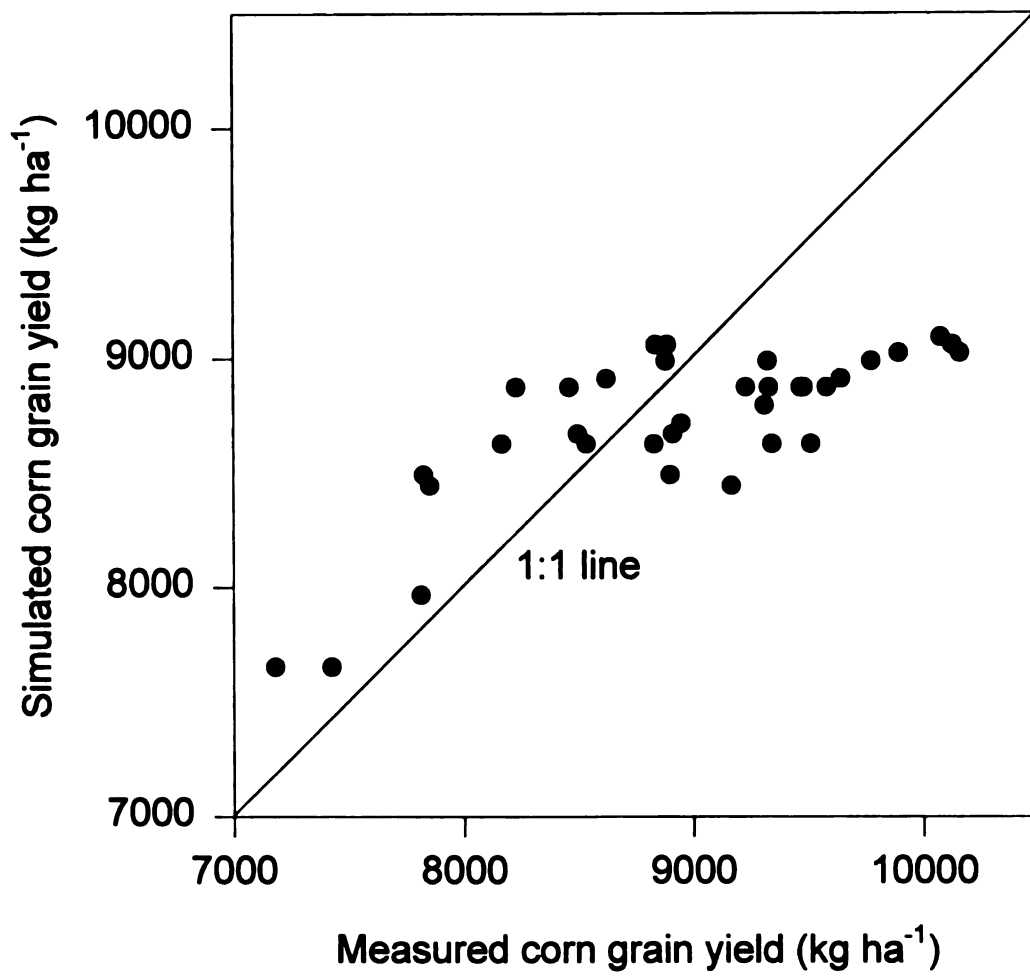


Figure 3.9. Plot of measured and simulated corn grain yield for 1996.

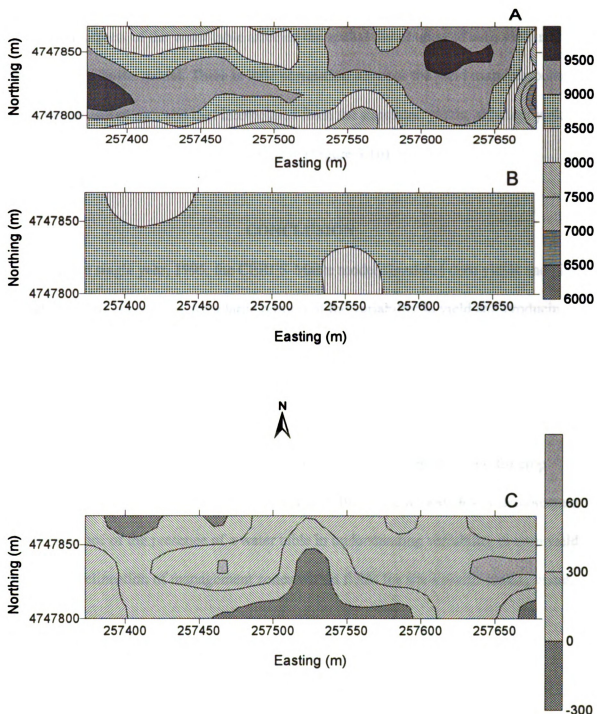


Figure 3.10. Measured (A), simulated (B), and difference between measured and simulated (C) of corn grain yield (kg/ha) for 1996.

For 1996, the results indicate that variation in soil properties in combination with differential effects of the water table affected the spatial distribution of corn yield not accounted for in the model. There is little correlation between the yield map interpolated from the measured data and that interpolated from the simulated yields, although yield differences were generally within 600 kg ha⁻¹ (Figure 3.10).

CONCLUSION

For a single year, 1995, the CERES-Maize model simulated corn yields and yield variability well, accounting for a large portion of the variability in yield and producing a yield map very similar to the measured values. A drought during 1996 showed the importance of water table in supplying water to corn within this field. The CERES-Maize does not account for water table and will need modification for soils where water table contributions are significant to crop yield. These results show the potential for crop models to simulate the spatial and temporal variability in yields and clearly demonstrate the importance of the presence of a water table in understanding variability in crop yield and in the delineation of management zones within fields for site-specific management.

LIST OF REFERENCES

REFERENCES

- Addiscott, T.M. 1993. Simulation modeling and soil behavior. *Geoderma* 60:15-41.
- Addiscott, T.M. and R.J. Wagenet. 1985. Concepts of solute leaching in soils: a review of modelling approaches. *J. Soil Sci.* 36:411-424.
- Algozin, K.A., V.F. Bralts and J.T. Ritchie. 1988. Irrigation strategy selection based on crop yield, water, and energy use relationships: A Michigan example. *J. Soil Water Conserv.* 43:428-431.
- Azooz, R.H., M.A. Arshad, and A.J. Franzluebbers. 1996. Pore size distribution and hydraulic conductivity affected by tillage in northwestern Canada. *Soil Sci. Soc. Am. J.* 60:1197-1201.
- Beckett, P.H.T. and R. Webster. 1971. Soil variability: a review. *Soil and Fertil.* 34:1-15.
- Blake, G.R. and K.H. Hartge. 1986. Bulk density. p.363-375. *In* A. Klute (ed.) *Methods of soil analysis. Part 1.* 2nd ed. Agron. Monogr. 9. ASA, Madison, WI.
- Blevins, R.L., M.S. Smith, and W.W. Frye. 1983. Changes in soil properties after 10 years of no-tillage and conventional tilled corn. *Soil Tillage Res.* 3:135-146.
- Bouma, J. and P.A. Finke. 1993. Origin and Nature of Soil Resource Variability. p.3-13. *In* P.C. Robert et al. (ed) *Procedures of Soil Specific Crop Management: A Workshop on Research and Development Issues.* SSSA Spec. Publ. Soil Sci. Soc. Am., Madison, WI.
- Boyer, D.G., R.J. Wright, C.M. Feldhake, and D. P. Bligh. 1996. Soil spatial variability relationships in a steeply sloping acid soil environment. *Soil Sci.* 161:278-287.
- Cambardella, C.A., T.B. Moorman, J.M. Novak, T.B. Parkin, D.L. Karlen, R.F. Turco, and A.E. Konopka. 1994. Field-scale variability of soil properties in central Iowa soils. *Soil Sci. Soc. Am. J.* 58:1501-1511.
- Caron, J. C.R. Espindola, and D.A. Angers. 1996. Soil structural stability during rapid wetting: Influence of land use on some aggregate properties. *Soil Sci. Soc. Am. J.* 60:901-908.
- Carter, M.R. 1995. Spatial variability of soil porosity under reduced tillage in a Humo-Ferric Podzol. *Can. J. Soil Sci.* 75:149-152.
- Chien, Y., D. Lee, H. Guo, and K. Houn. 1997. Geostatistical analysis of soil properties of mid-west Taiwan soils. *Soil Sci.* 162:291-298.

- Chung, C.K., S. Chong, and E.C. Varsa. 1995. Sampling strategies for fertility on a stoy silt loam soil. *Commun. Soil Sci. Plant Anal.* 26:741-763.
- Ciha, A.J. 1984. Slope position and grain yield of soft white winter wheat. *Agron. J.* 76:193-196.
- Elliott, E.T., I.C. Burke, C.A. Monz, S.D. Frey, K.H. Paustian, H.P. Collins, E.A. Paul, C.V. Cole, R.L. Blevins, W.W. Frye, D.J. Lyon, A.D. Halvorson, D.R. Huggins, R.F. Turco, and M.V. Hickman. 1994. Terrestrial carbon pools: Preliminary data from the Corn Belt and Great Plains regions. p. 179-191. In Doran, et al. (eds.) *Defining soil quality for a sustainable environment*. SSSA Spec. Publ. No 35. Soil Sci Soc. Am., Madison, WI.
- Entz, T. and C. Chang. 1991. Evaluation of soil sampling schemes for geostatistical analyses: A case study for soil bulk density. *Can. J. Soil Sci.* 71:165-176.
- Everett, M.W. and F.J. Pierce. 1996. Variability of corn yield and soil profile nitrates in relation to site-specific management. p. 43-53. *In* P.C. Robert et al. (ed.) *Precision Agriculture*. ASA Misc. Publ. ASA, CSSA, and SSSA, Madison, WI.
- Finke, P.A. 1993. Field scale variability of soil structure and its impact on crop growth and nitrate leaching in the analysis of fertilizing scenarios. *Geoderma* 60:89-107.
- Finke, P.A., J. Bouma, and A. Stein. 1992. Measuring field variability of disturbed soils for simulation purpose. *Soil Sci. Soc. Am. J.* 56:187-192.
- Gabrielle, B. and L. Kengni. 1996. Analysis and field-evaluation of the CERES models' soil components: nitrogen transfer and transformations. *Soil Sci. Soc. Am. J.* 60:142-149.
- Gaunt, J.L., J. Riley, A. Stein, and F.W.T. Penning de Vries. 1997. Requirements for effective modelling strategies. *Agric. Systems* 54:153-168.
- Gee, G.E. and J.W. Bauder. 1986. Particle-size Analysis. p.383-410. *In* A. Klute (ed.) *Methods of soil analysis. Part 1*. 2nd ed. Agron. Monogr. 9. ASA, Madison, WI.
- Griffith, D.R., J.V. Mannering, and J.E. Box. 1986. Soil and moisture management eith reduced tillage, p. 19-55. *In* M.A. Sprague and G.B. Triplett (ed.) *No tillage and surface-tillage agriculture*. Willey, New York.
- Guillermo, A.S., H.E. Echeverria, and E.M. Casanovas. 1997. Crop-pasture rotation for sustaining the quality and productivity of a Typic Argiudoll. *Soil Sci. Soc. Am. J.* 61:1466-1472.
- Gupta, V.V.S.R., P.R. Grace, and M.M. Roper. 1994. Carbon and nitrogen mineralization as influenced by long-term soil and crop residue management systems in Australia. p.

- 193-200. *In* J.W. Doran et al (eds) Defining soil quality for a sustainable environment. SSSA Spec. Publ. No 35. Soil Sci Soc. Am., Madison, WI.
- Han, S., R.G. Evans, T. Hodges, and S.L. Rawlins. 1995. Linking a geographic information system with a potato simulation model for site-specific management. *J. Environ. Qual.* 24:772-777.
- Han, S., S.M. Schneider, R.G. Evans, and S.L. Rawlins. 1996. Spatial variability of soil properties on two center pivot irrigated fields. p. 97-106. *In* P.C. Robert et al. (ed.) Precision Agriculture. ASA Misc. Publ., ASA, CSSA, and SSSA, Madison, WI.
- Hanks, J. and J.T. Ritchie. 1991. Modeling plant and soil systems. *Agron. Monogr.* 31. ASA, CSSA, and SSSA, Madison, WI.
- Hanna, A.Y., P.W. Harlan, and D.T. Lewis. 1982. Soil available water as influenced by landscape position and aspect. *Agron. J.* 74:999-1004.
- Hergert, G. W., W.L. Pan, D.R. Huggins, J.H. Grove, and T.R. Peck. 1997. Adequacy of current fertilizer recommendations for site-specific management. p. 283-300. *In* F.J. Pierce and E.J. Sadler. (ed.) The state of site-specific management for agriculture. ASA Misc. Publ., ASA, CSSA, and SSSA, Madison, WI.
- Hill, R.L and M. Meza-Montalvo. 1990. Long-term well traffic effects on soil physical properties under different tillage systems. *Soil Sci. Soc. Am. J.* 54:865-870.
- Hodges, T., D. Botner, C. M. Sakamoto, and J. Hays Haug. 1987. Using the CERES-Maize model to estimate production for the U.S. Corn-Belt. *Agric. for Metereol.* 40:293-303.
- Hubbard, R.K., W.L. Hargrove, R.R. Lowrance, R.G. Williams, and B.G. Mullinix. 1994. Physical properties of a clayey coastal plain soil as affected by tillage. *J. Soil and Water Conserv.* 49:276-283.
- IBSNAT. 1989. Decision Support System for Agrotechnology Transfer (DSSAT)-User's Guide. IBSNAT Project, Dept. Agronomy and Soil Sci., University of Hawaii, Honolulu.
- Issaks, E.H. and R.M. Srivastava. 1989. An introduction to applied geostatistics. Oxford Univ. Press, Oxford.
- Jaynes, D.B., T.S. Colvin, and J. Ambuel. 1995. Yield mapping by eletromagnetic induction. p. 383-394. *In* P.C. Robert et al. (ed.) Site-specific management for agricultural systems. ASA, CSSA, and SSSA, Madison, WI.

- Jones J.W. and J.T. Ritchie. 1991. Crop growth models. In G.J. Hoffman, T.A. Howell, and K.H. Soloman (eds) Management of farm irrigation systems. ASAE, St Joseph, MI.
- Journel, A.G. and C.J. Huijbregts. 1978. Mining geostatistics. Academic Press, London.
- Kemper, W.D. and R.C. Rosenau. 1986. Aggregate stability and size distribution. p. 425-442. *In* A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA, Madison, WI.
- Khakural, B.R., G.D. Lemme, T. E. Schumacher, and M.J. Lindstrom. 1992. Effects of tillage systems and landscape on soil. *Soil Till. Res.* 25:43-52.
- Khakural, B.R., P.C. Robert, and D.J. Mulla. 1996. Relating corn/soybean yield to variability in soil and landscape characteristics. p. 117-128. *In* P.C. Robert et al. (ed.) Precision Agriculture. ASA Misc. Publ. ASA, CSSA, and SSSA, Madison, WI.
- Kiniry, J.R., J.R. Williams, R.L. Vanderlip, J.D. Atwood, D.C. Reicosky, J. Mulliken, W.J. Cox, H.J. Mascagni Jr., S.E. Hollinger, and W.J. Wiebold. 1997. Evaluation of two maize models for nine U.S. locations. *Agron. J.* 89:421-426.
- Kitur, B.K., K.R. Olson, J.C. Siemens, and S.R. Phillips. 1993. Tillage effects on selected physical properties of Grantsburg silt loam. *Commun. Soil Sci. Plant Anal.* 24:1509-1527.
- Klute, A. 1986. Water retention: Laboratory methods. p. 635-662. *In* A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA, Madison, WI.
- Lamb, J.A., R.H. Dowdy, J.L. Anderson, and G.W. Rehm. 1997. Spatial and temporal stability of corn grain yield. *J. Prod. Agric.* 10:410-414.
- Larson, W.E. and P.C. Robert. 1991. Farming by soil. p. 103-112. *In* R. Lal and F.J. Pierce (ed.) Soil management for sustainability. SWCS, Ankeny, Iowa.
- Lindstrom, M.J., W.B. Voorhees, and T.E. Schumacher. 1995. Soil properties across a landscape continuum as affected by planting wheel traffic. p. 351-363. *In* P.C. Robert et al. (ed.) Site-specific management for agricultural systems. ASA Misc. Publ. ASA, CSSA, and SSSA, Madison, WI.
- Mallants, D., B.P. Mohanty, D. Jacques, and J. Feyen. 1996. Spatial variability of hydraulic properties in a multi-layered soil profile. *Soil Sci.* 161:167-181.
- Mausbach, M.J., D.J. Lytle, and L.D. Spivey. 1993. Application of soil survey information to soil specific farming. p. 57-68. *In* P.C. Robert et al. (ed) Proc. of soil specific crop management: A workshop on research and development issues. SSSA Spec. Publ. Soil Sci. Soc. Am., Madison, WI.

- McGraw, T. and R. Hemb. 1995. Fertility variability in the Minnesota River Valley Watershed in 1993 as determined from grid testing results on 52,00 acres in commercial fields. p. 167-174. *In* P.C. Robert et al. (ed.) Site-specific management for agricultural systems. ASA Misc. Publ. ASA, CSSA, and SSSA, Madison, WI.
- Moore, I.D., P.E. Gessler, G.A. Nielsen, and G.A. Peterson. 1993. Terrain analysis for soil specific crop management. p. 27-52. *In* P.C. Robert et al. (ed) Proc. of Soil specific crop management: A Workshop on research and development issues. SSSA Spec. Publ. Soil Sci. Soc. Am., Madison, WI.
- Mulla, D.J., A.U. Bhatti, M.W. Hammond, and J.A. Benson. 1992. A comparison of winter wheat yield and quality under uniform versus spatially variable fertilizer management. *Agric. Ecosys. Environ.* 38:301-311.
- Mulla, D.J., and J.S. Schepers. 1997. Key processes and properties for site-specific soil and crop management. p. 1-18. *In* F.J. Pierce and E.J. Sadler. (ed.) The state of site-specific management for agriculture. ASA Misc. Publ. ASA, CSSA, and SSSA, Madison, WI.
- Nix H.A., 1983. Minimum data sets for agrotechnology transfer. Proceedings of the International Symposium on Minimum Data Sets for Agrotechnology Transfer. 21-23 March. ICRISAT AP 502324. India.
- Pang, X.P., J. Letey, and L. Wu. 1997. Yield and nitrogen uptake prediction by CERES-Maize model under semiarid conditions. *Soil Sci. Soc. Am. J.* 61:254-256.
- Pannatier, Y. 1996. Variowin: software for spatial data analysis in 2D. Springer-Verlag, New York, Inc., Edwards Brothers, Inc., Ann Arbor, MI.
- Passioura J.B., 1996. Simulation Models: Science, snake oil, education and engineering? *Agron. J.* 88:690-695.
- Pierce, F.J. and D.D. Warncke. 1994. Site-specific management: An overview. p.3-6. *In* Site-specific management in agriculture. Proc. Workshop. Kellogg Center, MSU, East Lansing, MI. March, 7. 1994.
- Pierce, F.J., D.D. Warncke, and M.W. Everett. 1995. Yield and nutrient variability in glacial soils of Michigan. p. 133-154. *In* P.C. Robert et al. (ed.) Site-specific management for agricultural systems. ASA Misc. Publ. ASA, CSSA, and SSSA, Madison, WI.
- Pierce, F.J. and E.J. Sadler (ed.). 1997. The state of site-specific management for agriculture. ASA Misc. Publ. ASA, CSSA, and SSSA, Madison, WI.

- Pierce, F.J., M. C. Fortin, and M.J. Staton. 1994. Periodic plowing effects on soil properties in a no-till farming system. *Soil Sci. Soc. Am. J.* 58:1782-1787.
- Poier, K.R. and J. Richter. 1992. Spatial distribution of earthworms and soil properties in an arable loess soil. *Soil Biol. Biochem.* 24:1601-1608.
- Reinert, D.J. 1990. Soil structural form and stability induced by tillage in a Typic Hapludalf. Ph.D. diss. Michigan State University, East Lansing, MI.
- Richardson, C.W. and K.W. King. 1995. Erosion and nutrient losses from zero tillage on a clay soil. *J. Agric. Eng. Res.* 61:81-86.
- Ritchie, J.T., D.C. Godwin, and S. Otter-Nacke. 1985. CERES-Wheat: A simulation model of wheat growth and development. Texas A&M University Press, College Station, TX.
- Ritchie, J.T., D.C. Goldwim, and U. Singh. 1990. Soil and weather inputs for the IBSNAT crop models. p. 31-45. *In* Procedures of the IBSNAT symposium: Decision support system for agrotechnology transfer. Part I; Symposium Proceedings. Las Vegas, NV. 16-18 Oct. 1989. Dept. of Agronomy and Soil Science, College of Tropical Agriculture and Human Resources, University of Hawaii, Honolulu, HI.
- Ritchie, J.T., and J. Crum. 1989. Converting soil survey characterization data into IBSNAT crop model input. p. 155-167. *In* J. Bouma and A.K. Bregt (ed.) Land qualities in space and time. PUDOC, Wageningen, The Netherlands.
- Ritchie, J.T., U. Singh, D.C. Godwin and L. Hunt. 1989. A user's guide to CERES-Maize-V.2.10. Muscle Shoals, AL. International Fertilizer Development Center.
- Robert, P. 1993. Characterization of soil conditions at the field level for soil specific management. *Geoderma* 60:57-72.
- Robert, P. C., R.H. Rust, and W.E. Larson. 1993. Proceedings of soil specific crop management: A workshop on research and development issues. SSSA Spec. Publ. Soil Sci. Soc. Am., Madison, WI.
- Sadler, E.J. and G. Russell. 1997. Modeling crop yield for site-specific management. p. 69-79. *In* F.J. Pierce and E.J. Sadler. (ed.) The state of site-specific management for agriculture. ASA Misc. Publ. ASA, CSSA, and SSSA, Madison, WI.
- SAS Institute 1990. SAS/STAT user's guide. Version 6. SAS Inst., Cary, NC.
- Seta, A.K., R.L. Blevins, W.W. Frye, and B.J. Barfield. 1993. Reducing soil erosion and agricultural chemical losses with conservation tillage. *J. Environ. Qual.* 22:661-665.

- Spomer, R.G., and R.F. Piest. 1982. Soil productivity and erosion of Iowa loess soils. Trans. ASAE 25:1295-1299.
- Staricka, J.A., R.R. Almaras, and W.W. Nelson. 1991. Spatial variation of crop residue incorporated by tillage. Soil Sci. Soc. Am. J. 55:1668-1674.
- Stone, J.R., J.W. Gilliam, D.K. Cassel, R.B. Daniels, L.A. Nelson, and H.J. Kleiss. 1985. Effects of erosion and landscape position on the productivity of Piedmont soils. Soil Sci. Soc. Am. J. 49:987-991.
- Sudduth, K.A., J.W. Hummel, and S.J. Birrel. Sensors for site-specific management. p. 183-210. In F.J. Pierce and E.J. Sadler. (ed.) The state of site-specific management for agriculture. ASA Misc. Publ. ASA, CSSA, and SSSA, Madison, WI.
- Swayer, J.E. 1994. Concepts of variable rate technology with considerations for fertilizer application. J. Prod. Agric. 7:195-201.
- Threlkeld, G.W. and J.E. Feenstra. 1974. Soil Survey of Shiawassee County, Michigan. U.S. Gov. Print Office, Washington, D.C.
- Trangmar, B.B., R.S. Yost, and G. Uehara. 1985. Application of geostatistics to spatial studies of soil properties. Advances in Agronomy. 38:45-94.
- Van Uffelen, C.G.R., J. Verhagen, and J. Bouma. 1997. Comparison of simulated crop yield patterns for site-specific management. Agric. Syst. 54:207-222.
- Verhagen, J. and J. Bouma. 1997. Modeling soil variability. p. 55-67. In F.J. Pierce and E.J. Sadler. (ed.) The state of site-specific management for agriculture. ASA Misc. Publ. ASA, CSSA, and SSSA, Madison, WI.
- Voorhees, W.B., R.R. Almaras, and M.J. Lindstrom. 1993. Tillage considerations in Managing Soil Variability. p. 95-111. In P.C. Robert et al. (ed) Procedures. of Soil Specific Crop Management: A Workshop on Research and Development Issues. SSSA Spec. Publ. Soil Sci. Soc. Am., Madison, WI.
- Waddell, J.T. and R.R. Weil. 1996. Water distribution in soil under ridge-till and no-till corn. Sci. Soc. Am. J. 60:230-237.
- Webster, R. Quantitative spatial analysis of soil in the field. 1985. Advances in Soil Sci. 3:1-70.
- Webster, R. and M.A. Oliver. 1990. Statistical methods in soil and land resource survey. Oxford Univ. Press, New York.
- Wollenhaupt, D. J. Mulla, and C.A. Gotway Crawford. 1997. Soil sampling and interpolation techniques for mapping spatial variability of soil properties. p. 19-53. In F.J.

Pierce and E.J. Sadler. (ed.) The state of site-specific management for agriculture. ASA Misc. Publ. ASA, CSSA, and SSSA, Madison, WI.

Yule, I.J., P.J. Cain, E.J. Evans, and C. Venus. 1996. A spatial inventory approach to farm planning. *Computers and Electronics in Agriculture*. 14:151-161.

Wu, Y., C.M. Sakamoto, and D.M. Botner. 1989. On the application of the CERES-Maize model to the North China Plain. *Agric. for Meteorol.* 49:9-22.