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Spatial Variability Analysis and Reclamation of Saline-Sodic Soils in the Northern Great Plains

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SPATIAL VARIABILITY ANALYSIS AND RECLAMATION OF SALINE-SODIC

SOILS IN THE NORTHERN GREAT PLAINS

BY

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SPATIAL VARIABILITY ANALYSIS AND RECLAMATION OF SALINE SODIC SOILS IN THE NORTHERN GREAT PLAINS

This dissertation is approved as a creditable and independent investigation by a candidate for the Doctor of Philosophy in Plant Science degree and is acceptable for meeting the dissertation requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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CONTENTS

ABBREVIATIONS

% – percent
″ – degree
′ – minutes
° – degree
^{0}C – degree Centigrade
A – cross-sectional area of the soil columns
a – range of spatial dependence
ac – acres
ANOVA – analysis of variance
C – partial sill semi-variance
C_0 – nugget Semi-variance
Ca^{2+} – calcium ion
CC – cover crop
CEC – cation exchange capacity
CIG – Conservation Innovation Grant
Cl^- – chloride ion
cm – centimeter
CO_2 – carbon dioxide
CO_3^{2-} – carbonate ion
CS – cropping system
CV – coefficient of variation
DEM – digital elevation map
dS/m– deciSiemens per meter
EC – Emergence (crop)
EC – electrical conductivity
ECa – apparent electrical conductivity
ECe – saturated paste extraction electrical conductivity
ESP – exchangeable sodium percentage
GPS – global positioning system
h – lag distance
ha – hectare
HCO_3^- – bicarbonate ion
IDW – inverse distance weighting
IR – infiltration rate
k – class of nearest neighbor
K^+ – potassium ion
kg/ha – kilogram per hectare
m – meters
M – molarity
Mg^{2+} – magnesium
MIR– mid-infrared
mL – milliliters
MLRA – Major Land Resource Area

mm – millimeters
MSR – multispectral radiometer
N – North
n– number of samples
Na^+ - sodium ion
NCC – non cover crop
NDSU – North Dakota State University
NDVI – Normalized Difference Vegetation Index
NGP– Northern Great Plains
NIR– near-infrared
nm – nanometer
NO_3^- – nitrate ion
NRCS - Natural Resources Conservation Service
NTU – Nephelometric Turbidity Unit
O_2 – oxygen
pH – a measure of acidity or basicity (alkalinity)
r – correlation coefficient
R1 – beginning flowering
RMSE – Root Mean Square Error
S – elemental sulfur
s^{-1} – per second
SA – surface amendment
SAR – sodium adsorption ratio
SD – South Dakota, USA
SDSU – South Dakota State University
SM – soil moisture
SO_4^{2-} – sulfate ion
SOM – soil organic matter
USA – United States of America
USDA – United States Department of Agriculture
USGS – United States Geological Survey
V1 – first-leaf growth stage
V4 – four visible leaf collars
V6 – sixth-leaf growth stage
γ – semi-variance
ΔQ – volume of water collected
Δt – change in time

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ABSTRACT

SPATIAL VARIABILITY ANALYSIS AND RECLAMATION OF SALINE SODIC-SOILS IN

THE NORTHERN GREAT PLAINS

GIRMA A. BIRRU

2016

Increased spring rainfall and higher temperatures when combined with changing land-uses and extensive tile drainage installation have contributed to the development of sodic and saline/sodic soils in the Northern Great Plains. The objectives of this dissertation were: 1) determine the impact of surface chemical treatments and cover crop on crop yields and soil remediation; 2) determine and describe soil spatial variability and develop a model to identify saline-sodic soils; and 3) evaluate cation impact on dispersion of bentonite clay and selected soils. The research was conducted between 2013 and 2016 at Redfield (Argiustolls, Natrudolls, Calciustolls), White Lake (Argiudolls, Natrudolls), and Pierpont (Hapludolls, Natrudolls), in eastern South Dakota. A randomized complete block design with 4 replications was used. Treatments were cover cropping and surface amendments [gypsum, calcium chloride, elemental sulfur (S), and no amendments]. A mixture of barley (*Horedeum vulgare)* and sugar beet (*Beta vulgaris)* was used as the cover crop. At 169 sampling points, yield, soil properties, and reflectance were measured. Spatial class was developed using nugget to sill ratio. The impacts of chemical amendments on reducing soil dispersion were determined. Surface chemical amendment and cover crop treatments did not show significant differences in crop yield and soil properties in most locations. Hence, the amendments did not work in the Northern Great Plain soils with a glacial parent material that has high salt, calcium carbonate, and gypsum levels. Other management strategies that can reduce soil pH and mimic the native prairie grasses (deep-

rooted perennial grasses that can use water from deeper in the soil profile) could be useful for future study. The exponential semivariogram model was found to be the optimal model for NDVI and yield with the spatial dependence (nugget/sill ratio) of 14.4 and 0%, respectively. Similarly, the exponential model was the optimum fit for mollic depth, lime depth, pH, EC, and SAR with nugget to sill ratio of 0, 0, 45, 17 and 49 respectively. Local *Moran's I* and semivariogram modelling of soil attributes and NDVI data could help locate saline hot spots and quantify spatial heterogeneity respectively in saline-sodic soils. Higher turbidity was recorded in Na salt treated soil and bentonite clay than Ca and Mg salts. Turbidity was useful in measuring clay dispersion and could be used as an indicator of clay dispersion in salt-affected soils.

Keywords: Argiustolls, bentonite clay, Calciustolls, dispersion, Hapludolls, Natrudolls, NDVI, semivariograms, SAR, saline-sodic soil, soil spatial variability, surface amendments, turbidity, reclamation, water infiltration.

1. **CHAPTER I**

INTRODUCTION AND LITRATURE REVIEW

Rapid world population growth has increased the demand for agricultural products and has sometimes resulted in natural resource degradation. To maintain the food supply and meet the growing world population, agricultural production has to grow substantially (Foley *et al*., 2011; Tscharntke *et al*., 2012). In the last few decades, suitable cultivable land for crop production has decreased significantly and the alternative option is improving the productivity of degraded land including salt-affected soils (Ladeiro, 2012; Rengasamy, 2006).

Estimates identify at least 950 million ha of the world's soils that are salt-affected with different proportions of saline and sodic soil (Szabolcs, 1994). These hundreds of millions of hectares of land are not used for agricultural production due to high levels of salts (Northcote and Srene, 1972) and the increased incidence of salt-affected soils has resulted in environmental quality degradation and reduced crop yields (Rengasamy, 2006). Salt-affected soils are found almost in all climatic regions, where evapotranspiration exceeds precipitation at least some portion of the year (Rengasamy, 2006; Sumner and Naidu, 1998).

Secondary dryland salinity (human-induced salinity in non-irrigated areas) has become a major concern in the Northern Great Plains (NGP) region of USA (South Dakota, North Dakota, and Montana) and Canada (the prairie provinces of Manitoba, Saskatchewan, and Alberta) (Pannell and Ewing, 2006). Thus, these salt-affected soils require special management measures to improve their productivity and to reduce their environmental impact (Allen *et al*., 1998; Gabrijel *et al*., 2011). Therefore, a comprehensive understanding of the interrelationship between different environmental conditions that affect saline and sodic soils expansion is vital to

designing effective and sound management strategies and to reduce the expansion of the problem.

1.1 Source and Classification

Detailed reviews of the chemistry and formation of salt-affected soils have been reported (McBride, 1994; Suarez *et al*., 2005). Geochemical weathering of parent rock materials is the main source of salts in most soils (Maas *et al*., 1999). However, the expansion of salts in soils and water bodies is mainly affected by land-use (Suarez *et al*., 2005) and precipitation changes. During weathering, the primary minerals react with water and O_2 and CO_2 to form secondary minerals and salts which are transported by water to depressions in the landscape and oceans (Maas *et al*., 1999; Suarez *et al*., 2005). Salts consist mostly of various proportions of Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^- and occasionally K^+, CO_3^{2-}, and NO_3^- ions (McBride, 1994).

The processes of salinization and alkalization of soils are the consequences of a number of factors of surface and ground waters, soil physical properties, climate, relief, geomorphology, and man's and other biological activities (Maas *et al*., 1999). Similarly, salinization and alkalization of NGP soils are the result of a combination of several factors including: 1) the weathering of primary materials with high salt levels (Cerling and Quade, 1993; Kohut and Dudas, 1993); 2) changes in land use and vegetation (conversion of grass land to cropland) (Anderson *et al*., 2015; Kim *et al*., 2012); 3) increases in precipitation (Karl and Knight, 1998); and 4) changes in land management practices (no-till, summer fallow, and expansion tile drainage) (Karlen *et al*., 1997).

Classification of salt-affected soils is based on their chemical properties and ease of reclamation. The key chemical properties are pH, electrical conductivity (EC), and exchangeable

sodium percentage (ESP) or sodium adsorption ratio (SAR) (Rhoades, 1982; Szabolcs *et al*., 1974). According to the US Salinity Laboratory Staff, (1954) salt-affected soils are traditionally classified into three groups. These are: 1) saline soils; 2) saline-sodic soils; and 3) sodic soils. Saline soils contain soluble salt levels that can affect the growth and productivity of most crop plants (US Salinity Laboratory Staff, 1954; Wallender and Tanji, 2011). Saline soils are composed mainly of the ions Cl^-, SO_4^{2-} , Na^+, Ca^{2+}, Mg^{2+} and small amounts of NO_3^-, HCO_3^-, and K^+. Saline-sodic soils contain both soluble salts and exchangeable sodium in higher quantities that affect growth and productivity of the of crop plants (US Salinity Laboratory Staff, 1954; Wallender and Tanji, 2011). Electrical conductivity (EC) is the common method of estimating salinity levels in soils. In most cases, the uncontrolled removal of soluble salts from saline-sodic soils can result in the formation of sodic (dispersed) soils (Kelley, 1951). Soils that contain high levels of exchangeable sodium on their exchange complex which can affect the growth and production of most crop plants and dispersed soil structure are sodic soils (Sumner and Naidu, 1998). Commonly, sodic soils have very low permeability (Kelley, 1951; Sumner, 1993; Sumner and Naidu, 1998). The surface horizons of sodic soils are often dense (compacted) with poor (dispersed and columnar) subsurface structure. Soil alkalinity is determined by the amount of exchangeable sodium percentage (ESP), the concentration of exchangeable sodium (Na^+) expressed as percent of Na^+ retained by the soils cation exchange capacity (CEC) or by the sodium adsorption ratio (SAR).

1.2 Plant Response and Salt Affected Soils

Salt stress affects plants in a variety of ways including reducing growth rate (stunted growth and darker green leaf color) and changes in plant physiology (Maas and Hoffman, 1977;

Munns, 1993, 2002; Netondo *et al*., 2004; Volkmar *et al*., 1998). The level of injury and reduction in growth varies among crop plants (Maas *et al*., 1999). However, a high concentration of a single salt is likely to cause specific ion effect (toxicity or nutritional imbalances) (Bernstein, 1975; Grattan and Grieve, 1999; Lauchli and Epstein, 1990; Shainberg and Letey, 1984). The osmotic effect (due to high salinity levels) is the main cause of annual crop yield reduction in saline soils (Maas *et al*., 1999; Stavridou *et al*., 2016). Whereas the impact of high sodium levels is on soil structure, nutrient availability, and plant growth (Bernstein, 1975; Bertness and Hacker, 1994; Bronick and Lal, 2005)

1.3 Reclamation and Management

Reclamation and management strategies of saline, sodic, or saline-sodic soils should be developed based on the baseline data of a specific site (Gupta and Abrol, 1990; Qadir and Oster, 2004; Qadir *et al*., 2008). The key factor in reclamation of saline soil is water movement into and through soils (Oster *et al*., 1996). Reclamation can be done by the combination of one or more of the following practices: tillage and other cultural practices, water management, tolerant crops and cropping systems, and use of soil amendments to improve crop productivity (Kelley, 1951; Oster *et al*., 1996).

Some of the suggested strategies and methods to control salinity and sodicity in the short-term and medium-term include: the use of quality water related measures including post-planting leaching; mulching; application of farmyard manure; maintaining high levels of available water in the plant root zone; use of good quality irrigation water; establishing and rehabilitating sub-surface drainage systems and drainage canals; and proper land drainage (Gupta and Abrol, 1990; Haque, 2006; Heuperman, 1999; Qadir *et al*., 2003). Additional strategies could include

selection and seedbed preparation including avoiding cultivation of lands with high water tables and hard pans; avoiding irregular water intake to prevent accumulation of salts; and minimum tillage to avoid soil compaction (Abrol *et al.*, 1988; Lal, 2000) . There are also suggested biological and agronomic management measures that could help combat the effect of salt-affected soil including the selection of salt tolerant crops, growing salinity and sodicity ameliorating crop species, and selecting proper seeding or planting methods (Qadir and Oster, 2004; Rietz and Haynes, 2003).

Some of the strategies and methods to control salinity and sodicity in the long-term start with field observations, investigating the sources, soil classification studies, irrigation effects, determine suitable management practices (irrigation, drainage, leaching, groundwater management, land levelling, and cultural practices), evaluating the agronomic practices, and identifying representative area(s) to test the prescribed practices (Abrol *et al.*, 1988; Oster *et al.*, 1996; Qadir and Oster, 2004).

1.4 Objectives

Experiment 1 (Chapter II): To compare the impact of surface chemical treatments, and cover crop on crop yields and soil quality.

Experiment 2 (Chapter III): to select the appropriate model that can define or predict spatial variability of NDVI and yield and to compare the effectiveness of spatial interpolation methods.

Experiment 3 (Chapter IV): To evaluate the effectiveness of surface chemical amendments and cover crops on improving water infiltration in saline-sodic soils and to evaluate the effect of variable cation concentrations on the dispersion of bentonite clay and selected soil samples.

Experiment 4 (Chapter V): Describe spatial variability of selected soil properties.

1.5 Literature Cited

Abrol, I., J. S. P. Yadav, and F. Massoud. 1988. Salt-affected soils and their management. Food and Agriculture Organozation. Rome, Italy.

Allen, R. G., L. S. Pereira, D. Raes, and M. Smith. 1998. FAO Irrigation and drainage paper No. 56. Food and Agriculture Organization of the United Nations. Rome, Italy. p. 26-40.

Anderson, E. K., T. B. Voigt, S. Kim, and D. Lee. 2015. Determining effects of sodicity and salinity on switchgrass and prairie cordgrass germination and plant growth. Industrial Crops and Products. 64: 79-87.

Bernstein, L. 1975. Effects of salinity and sodicity on plant growth. Annual Review of Phytopathology 13: 295-312.

Bertness, M. D., and S. D. Hacker. 1994. Physical stress and positive associations among marsh plants. American Naturalist 144: 363-372.

Bronick, C. J., and R. Lal. 2005. Soil structure and management: a review. Geoderma 124: 3-22.

Cerling, T. E., and J. Quade. 1993. Stable carbon and oxygen isotopes in soil carbonates. Climate change in continental isotopic records. Geopgysical Monographp 78: 217-231.

Foley, J. A., N. Ramankutty, K. A. Brauman, E. S. Cassidy, J. S. Gerber, M. Johnston, N. D. Mueller, C. O'Connell, D. K. Ray, and P. C. West. 2011. Solutions for a cultivated planet. Nature 478: 337-342.

Gabrijel, O., R. Zed, and V. Szilvia. 2011. Soil salinisation and salt stress in crop production. http://www.intechopen.com/books/abiotic-stress-in-plants-mechanisms-and-adaptations/soil-salinisation-and-salt-stress-in-crop-production (accessed 08/09/2016).

Grattan, S., and C. Grieve. 1999. Mineral nutrient acquisition and response by plants grown in saline environments. Handbook of plant and crop stress. Marcel Dekker, Inc. 2: 203-229.

Gupta, R. K., and I. Abrol. 1990. Salt-affected soils: their reclamation and management for crop production. Advances in Soil Science, Springer, 11: 223-288.

Haque, S. 2006. Salinity problems and crop production in coastal regions of Bangladesh. Pakistan Journal of Botany, 38: 1359-1365.

Heuperman, A. 1999. Hydraulic gradient reversal by trees in shallow water table areas and repercussions for the sustainability of tree-growing systems. Agricultural Water Management 39: 153-167.

Karl, T. R., and R. W. Knight. 1998. Secular trends of precipitation amount, frequency, and intensity in the United States. Bulletin of the American Meteorological Society. American Meteorological Society 79: 231-241.

Karlen, D., M. Mausbach, J. Doran, R. Cline, R. Harris, and G. Schuman. 1997. Soil quality: a concept, definition, and framework for evaluation (a guest editorial). Soil Science Society of America Journal 61: 4-10.

Kelley, W. P. 1951. Alkali soils their formation, properties and reclamation. Reinhold Publishing Corporation. Science 114: 558.

Kim, S., A. L. Rayburn, T. Voigt, A. Parrish, and D. Lee. 2012. Salinity effects on germination and plant growth of prairie cordgrass and switchgrass. Bioenergy Research 5: 225-235.

Kohut, C. K., and M. Dudas. 1993. Evaporite mineralogy and trace-element content of salt-affected soils in Alberta. Canadian Journal of Soil Science 73: 399-409.

Ladeiro, B. 2012. Saline agriculture in the 21st century: Using salt contaminated resources to cope food requirements. Journal of Botany 2012: 7-10.

Lal, R. 2000. Physical management of soils of the tropics: priorities for the 21st century. Soil Science 165: 191-207.

Lauchli, A., and E. Epstein. 1990. Plant responses to saline and sodic conditions. Agricultural salinity assessment and management 71: 113-137.

Maas, E. V., S. Grattan, R. Skaggs, and J. v. Schilfgaarde. 1999. Crop yields as affected by salinity: In R. Skaggs and V. Schilfgaarde. editors. Agricultural drainage. SAS-SSSA Monograph 38 p. 55-108.

Maas, E. V., and G. Hoffman. 1977. Crop salt tolerance\-current assessment. Journal of the Irrigation and Drainage Division 103: 115-134.

McBride, M. B. 1994. Environmental chemistry of soils. Oxford University Press. New York. 6th ed. p 406.

Munns, R. 1993. Physiological processes limiting plant growth in saline soils: some dogmas and hypotheses. Plant, Cell and Environment 16: 15-24.

Munns, R. 2002. Comparative physiology of salt and water stress. Plant, cell and environment 25: 239-250.

Netondo, G. W., J. C. Onyango, and E. Beck. 2004. Sorghum and salinity: I. Response of growth, water relations, and ion accumulation to NaCl salinity. Crop Science 44: 797-805.

Northcote, K. H., and J. Srene. 1972. Australian soils with saline and sodic properties. Melbourne. CSIRO Soil Publication 27: 28-30.

Oster, J., I. Shainberg, and I. Abrol. 1996. Reclamation of salt-affected soil. In M., Agassi ed. Soil erosion, conservation and rehabilitation. Marcel Deker Inc. p. 315-352.

Pannell, D. J., and M. A. Ewing. 2006. Managing secondary dryland salinity: Options and challenges: Agricultural Water Management 80: 41-56.

Qadir, M., and J. Oster. 2004. Crop and irrigation management strategies for saline-sodic soils and waters aimed at environmentally sustainable agriculture. Science of the Total Environment 323: 1-19.

Qadir, M., A. S. Qureshi, and S. Cheraghi. 2008. Extent and characterisation of salt-affected soils in Iran and strategies for their amelioration and management. Land Degradation and Development 19: 214-227.

Qadir, M., D. Steffens, F. Yan, and S. Schubert. 2003. Sodium removal from a calcareous saline–sodic soil through leaching and plant uptake during phytoremediation. Land Degradation and Development 14: 301-307.

Rengasamy, P. 2006. World salinization with emphasis on Australia. Journal of Experimental Botany 57: 1017-1023.

Rhoades, J., 1982, Soluble salts. Methods of soil analysis. Part 2. Chemical and microbiological properties. ASA-SSSA, Madisson, WI, USA. Agronomy Monograph 9.2. p. 167-179.

Rietz, D., and R. Haynes. 2003. Effects of irrigation-induced salinity and sodicity on soil microbial activity. Soil Biology and Biochemistry 35: 845-854.

Shainberg, I., and J. Letey. 1984. Response of soils to sodic and saline conditions, University of California, Division of Agriculture and Natural Resources. Hilgardia 52:1-57.

Stavridou, E., A. Hastings, R. J. Webster, and P. R. Robson. 2016. The impact of soil salinity on the yield, composition and physiology of the bioenergy grass Miscanthus x giganteus. Global Change Bioenergy. http://www.readcube.com/articles/10.1111/gcbb.12351 (accesed 08/09/2016).

Suarez, D. L., M. Tabatabai, D. Sparks, L. Al-Amoodi, and W. Dick. 2005. Chemistry of salt-affected soils: Chemical processes in soils. SSSA, Madison, WI. Series 8: 689-705.

Sumner, M. E. 1993. Sodic soils-New perspectives. Soil Research 31: 683-750.

Sumner, M. E., and R. Naidu. 1998. Sodic soils: distribution, properties, management and environmental consequences. 6th ed. Oxford University Press. New York.

Szabolcs, I., M. T. Akadémia, and K. Vállalat. 1974. Salt affected soils in Europe. Martinus Nijhoff the Haguea. and Research Institute for Soil Science and Agricultural chemistry of Hungarian Acadamy of Sciences.-Budapest. p. 9-42.

Szabolcs, I. 1994. Soils and salinization: Handbook of plant and crop stress. Marcel Dekker, New York, p. 3-11.

Tscharntke, T., Y. Clough, T. C. Wanger, L. Jackson, I. Motzke, I. Perfecto, J. Vandermeer, and A. Whitbread. 2012. Global food security, biodiversity conservation and the future of agricultural intensification. Biological Conservation 151: 53-59.

US Salinity Laboratory Staff. 1954. Diagnosis and Improvement of Saline and Alkali Soils. In: L. Richards, editor Agricultural Handbook 60. USDA, Riverside, CA.

Volkmar, K., Y. Hu, and H. Steppuhn. 1998. Physiological responses of plants to salinity: a review. Canadian Journal of Plant Science. 78: 19-27.

Wallender, W. W., and K. K. Tanji. 2011. Agricultural salinity assessment and management. American Society of Civil Engineers (ASCE). Reston, USA.

2. CHAPTER II

CROP YIELD AND SOIL PROPERTIES AS AFFECTED BY SOIL SURFACE

CHEMICAL AMENDMENTS AND COVER CROP

Abstract

Changing climatic conditions when combined with an opportunity to install tile drainage has placed many Northern Great Plains (NGP) soils at the tipping point of sustainability. A field study was conducted to compare the impact of surface chemical treatments and cover crop on crop yields and soil quality. The eastern South Dakota study locations were White Lake (dominant soils: Argiustolls, Natrudolls, and Calciustolls), Redfield (dominant soils: Argiudolls and Natrudolls) and Pierpont (dominant soils: Hapludolls and Natrudolls). A randomized complete block design with four replications was used. The treatments were cover crop and surface amendments. A barley (*Hordeum vulgare* L.) and sugar beet (*Beta vulgaris* subsp. vulgaris) mixture was seeded as the cover crop at the rate of 34 kg ha^{-1} and 4.5 kg ha^{-1}, respectively. Soil surface amendments were gypsum ($CaSO_4 \cdot 2H_2O$), $CaCl_2$, and elemental sulfur. No amendment was used as a control. Grain yield, stover weight, and other agronomic traits were measured. Initial and final soil samples from each plot and three soil depths were analyzed for basic soil parameters. Soil chemical properties improved when compared with baseline data in all locations and years for surface chemical amendments. However, the surface amendments did not show any significant difference in most locations years indicating these treatments did not work for glacial parent material soils with high salt levels (calcium carbonate and gypsum). Other management strategies that can reduce soil pH and mimic the native prairie grasses (deep-rooted perennial grasses that can use water deeper in the soil profile) could be

useful for future study. Generally, the spatial area of saline and saline-sodic soils is increasing in the NGP region of the United States resulting in a significant reduction of productive of arable land due to reduced soil organic matter which affects soil chemical properties and degrades soil structure and increases the downstream sediment deposition due to the erosion of sodic soils.

Keywords: saline-sodic soil, saline soil, sodic soil, sodium adsorption ratio (SAR), gypsum, sulfur, calcium chloride, Northern Great Plains, Argiustolls, Calciustolls, Natrudolls, Hapludolls, electrical conductivity (EC).

2.1 Introduction

Over 950 million ha of the world's soils are salt-affected (with different proportions of saline and sodic soils, [(Szabolcs, 1994). Soil salinity and sodicity are major forms of land degradation affecting the world soils (Qadir and Schubert, 2002; Rengasamy, 2006). Secondary dryland salinity (human-induced salinity in non-irrigated areas) has become a major concern in the North America Northern Great Plains, NGP (Pannell and Ewing, 2006).

Factors attributing to increasing salinity include changes in land use and vegetation, mainly the conversion of grass land to cropland (Reitsma *et al*., 2015; Reitsma *et al.*, 2016); increases in precipitation (Karl and Knight, 1998); changes in management practices (no-till, summer fallow, and expansion of tile drainage) (Karlen *et al.*, 1997); and parent materials containing high level of salts (Cerling and Quade, 1993) mainly Pierre shale (Malo *et al*., 2010). These factors contribute to higher exchangeable sodium concentrations in soil exchange sites which lead to natric horizon formation and soil dispersion. Ultimately, yields can be reduced and environmental quality can be diminished (Chi *et al.*, 2012; Hulugalle *et al*., 2010; Rengasamy, 2006). In the NGP regions, drainage has been used to increase the productivity of wet soils by removing excess water from the root zone (Olson and DeBoer, 1988). Installation of tile drainage has increased in recent years and there have been concerns as to the negative impact of tile drainage on the conversion of a large area of saline soils to sodic soils. However, the effect of integrated soil and water management and agronomic practices on crop productivity and soil health in salt-affected soils of these areas was not investigated. Therefore, this study was conducted to determine the effectiveness of selected soil surface amendments and cover crop in reducing sodicity, improving the soil physical and chemical properties, and improving crop yield in saline-sodic and sodic soils in Eastern South Dakota.

2.2 Materials and Methods

2.2.1 Description of the study sites

A three-year field study (2013 to 2015 growing seasons) was conducted near Redfield, SD (44°58′10″N, -98°27′52″W) and near White Lake, SD (43°40′31″N, -98°45′50″W). Additional sites were selected in 2014 and a two-year field study (2014 to 2015 growing seasons) was conducted near Pierpont, SD (45°30′31″N, -97°53′50″W). The study sites were selected to provide a range of possible salt levels. The dominant soils at the Redfield study site were Harmony-Aberdeen silty clay loams (0-2 % slopes), Winship-Tonka silt loams (0-1 % slopes), and Great Bend-Beotia silt loams (0-2 % slopes). The dominant soils at White Lake were Beadle-Dudley complex (0-3 % slopes), Delmont-Talmo complex (6-15 % slopes), and Houdek and Ethan loams (2-6 % slopes) (USDA-NRCS, 2016a; 2016b). Kranzburg-Brookings silt loams and Nahon-Aberdeen-Exline silt loams with slopes of 2 to 6 % and 0 to 2 % slopes, respectively, were the dominant soil series at the Pierpont study site. Detailed classification of soils is provided in the Appendix II (Table 1). The baseline soil chemical properties are presented in Table 2.1.

Table 2.1 Initial (baseline) average soil chemical composition of the research plots in Redfield (2013), White Lake (2013), and Pierpont (2014), SD.

Sites	Soil class	Electrical Conductivity (EC) (dS/m)			Soil pH			Sodium Adsorption Ratio (SAR)		
		Depth (cm)								
		0-7.5	7.5-15	15-30	0-7.5	7.5-15	15-30	0-7.5	7.5-15	15-30
Redfield*	Saline	8.0	6.2	6.5	7.3	7.8	7.8	3.6	3.3	3.0
White Lake**	Saline-sodic	10.2	8.2	7.3	7.6	7.4	7.5	17.0	17.8	12.3
Pierpont***	Saline-sodic	20.0	19.0	18.0	7.9	7.5	7.5	19.0	23.0	16.0

*44°58′10″N, -98°27′52″W (Dominant soils: Hapludolls, Natrudolls, Argiudolls).
**43°40′31″N, -98°45′50″W (Dominant soils: Argiustolls, Natrustolls, Haplustolls, Calciustolls).
***45°30′31″N, -97°53′50″W (Dominant soils: Hapludolls, Natrudolls).
Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.
n= 4 (Redfield); n=5 (White Lake); n=5 (Pierpont).

Table 2.2 Surface amendment application rates by location.

Salt Treatment	Rate applied in kg ha^{-1} (0-15 cm soil depth)			
	Redfield*	White Lake**	Pierpont*** (East)	Pierpont (West)
Gypsum (CaSO$_4$·2H$_2$O)	4980	4970	8735	6119
CaCl$_2$	4258	4281	7517	5224
Elemental S	923	922	1616	1139
No Salt	0	0	0	0

*44°58′10″N, -98°27′52″W (Dominant soils: Hapludolls, Natrudolls, Argiudolls).
**43°40′31″N, -98°45′50″W (Dominant soils: Argiustolls, Natrustolls, Haplustolls, Calciustolls).
***45°30′31″N, -97°53′50″W (Dominant soils: Hapludolls, Natrudolls).
Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.

2.2.2 Experimental design and treatments

The research design used at all sites (Redfield, White Lake, and Pierpont) was a randomized complete block design with 4 replications. The treatments were cover cropping (includes cover crop and non-cover crop) and surface chemical amendments [gypsum (CaSO$_4$·2H$_2$O), calcium chloride (CaCl$_2$), elemental sulfur (S) and control (no-application)]. The area of each plot was 9 m x 9 m for Redfield and 9 m by 6 m in White Lake and Pierpont. The

rate of application of the surface chemical amendments was determined based on the initial soil test results. The surface amendment application rate was calculated from the amount of calcium (Ca^{2+}) required to be replace sodium (Na^+) at each study location for the 0 to 15 cm soil depth. The target exchangeable sodium percentage (ESP) value of the soil was 5 (at this ESP the effect of Na^+ on plants and soils is minimal) (Horneck *et al*., 2007) and is critical value for most NGP soils (Kharel, 2016). The chemical amendment applications rates at each site are presented in Table 2.2. Surface treatments were broadcast onto the soil surface and incorporated using a hand-operated motorized rototiller before planting.

A combination of sugar beet (*Beta vulgaris)* and barley (*Horedeum vulgare)* was used as an in-season cover crop. The seeding rates for sugar beet and barley were 34 kg/ha and 4.5 kg/ha. Cover crop planting at each site depended on the growth stage of the main crop (June). Accordingly, for the corn (*Zea mays*) and sorghum (*Sorghum bicolor*) crops the cover crop was planted when the main crop growth stage was between V4 (four visible leaf collars) and V6 (sixth leaf growth stage). Whereas, for soybeans (*Glycine max*) cover crops were seeded between n V stage- nth trifoliate (V stages continue with the unfolding of trifoliate leaves and the final number of trifoliate depends on the soybean variety and the environmental conditions) and R1 (beginning flowering **-** plants have at least one flower on any node (Clark, 2008; Fehr *et al*., 1971; Vaughan and Evanylo, 1998).

2.2.3   Data collection and analysis

Soil Sampling and Chemical Analysis

Soil samples were taken from each plot in each fall and spring seasons from 2013 to 2015. Soil sampling was done at start of the cropping season (May/June) and after harvest

(October/November). Soil samples from three different depths (0-7.5, 7.5-15, and 15-30 cm) consisted of 10 subsamples collected with a 1.9 cm diameter soil probe. Each sample was dried at 40°C, ground, sieved (<2 mm), stored in plastic bags, and analyzed for pH, electrical conductivity (EC), water soluble cations, sodium adsorption ratio (SAR), carbon, ammonium and nitrate-N (Page, 1982)

Water soluble cation concentrations (Na^+, Ca^{2+}, and Mg^{2+}), EC, and pH and were determined from a saturated extract. One hundred and fifty grams of air-dry soil was weighed and mixed with distilled water until saturated. The mixture was covered and allowed to equilibrate for 24 hours. After 24 hours, the soil solution was extracted using a Büchner funnel apparatus and vacuum. All extracts were stored at 4°C until they were analyzed for pH, EC, Ca, Mg, and Na (PC 2700, Oakton Instruments, Vernon Hills, IL) (Rhoades, 1982). Sodium adsorption ratio (SAR) was calculated using Equation 2.1.

$$SAR = \frac{[Na^+]}{\left(\frac{[Ca^{2+}] + [Mg^{2+}]}{2}\right)^{1/2}} \tag{2.1}$$

Yield and other agronomic traits

The plots were planted with corn (*Zea mays*), sorghum (*Sorghum bicolor*), and soybean (*Glycine max*), fertilized, and pesticides applied by the producer collaborators (Table 2.3). Grain and stover harvest for corn and sorghum were done by hand and, soybean harvest was conducted by a combine. A total area of 1.5 m x 3 m (5.25 m²) for corn and sorghum were harvested to estimate grain yield and stover biomass. Whereas, a 12 m² area of soybeans was harvested and converted to yield on a hectare basis.

Table 2.3 Crops planted and agronomic management practices at the study locations.

Site	2013		2014		2015	
	Crop	Row Spacing (cm)	Crop	Row x Plant Spacing (cm)	Crop	Row Spacing (cm)
Redfield*	Corn	75	Soy	50	Soy	50
White Lake**	Sor	75	Corn	75	Soy	50
Pierpont***	-	-	-	-	Corn	75

Soy = soybean (*Glycine max*); Sor = sorghum (*Sorghum bicolor*)
*44°58′10″N, -98°27′52″W (Dominant soils: Hapludolls, Natrudolls, Argiudolls).
**43°40′31″N, -98°45′50″W (Dominant soils: Argiustolls, Natrustolls, Haplustolls, Calciustolls).
***45°30′31″N, -97°53′50″W (Dominant soils: Hapludolls, Natrudolls).
Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.

Chlorophyll content and stomatal conductance

Stomatal conductance was measured using Leaf Porometer-Model SC-1. Five plants from each plot were measured from 11 am to 1 pm when the sun was overhead on a sunny day. The third leaf from the top was measured for all plants. Chlorophyll content was measured using MINOLTA chlorophyll meter, SPAD-502. A fully matured leaf was measured for chlorophyll content. Eight plants per plots were measured.

2.2.4   Statistical analysis

Data was analyzed using SAS version, SAS Institute, Cary, NC (SAS, 2007). Differences found between the different treatments were subjected to an analysis of variance (ANOVA).

2.3 Results and Discussion

2.3.1 Crop response

Average growing season (April to October) precipitation and temperature for each research sites are shown Table 2.4. The monthly precipitation and temperature of the two study sites are plotted in Figure 2.1, 2.2, 2.3, 2.4, and 2.5. Note that White Lake precipitation was at least 15 cm below average in all years studied, while at Redfield the precipitation was either much lower or much higher than long-term average. The growing season temperatures were near average for White Lake and much warmer for Redfield.

Table 2.4 Climatic data of the research sites over 2013 to 2015 years and long-term average.

Research Sites	Average April to October Precipitation (mm)				Average April to October Temperature (^{0}C)			
	2013	2014	2015	Long-term average	2013	2014	2015	Long-term average
Redfield*	-	46	81	60 (25-year)	-	15	17	14 (25 year)
White Lake**	51	46	54	69 (30 year)	15	16	17	16(30 year)
Pierpont***	66 (9 years average)				16 (9 years average)			

*44°58′10″N, -98°27′52″W (Dominant soils: Hapludolls, Natrudolls, Argiudolls).
**43°40′31″N, -98°45′50″W (Dominant soils: Argiustolls, Natrustolls, Haplustolls, Calciustolls).
***45°30′31″N, -97°53′50″W (Dominant soils: Hapludolls, Natrudolls).
Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.
Source of climate information: South Dakota Climate and Weather, 2016.
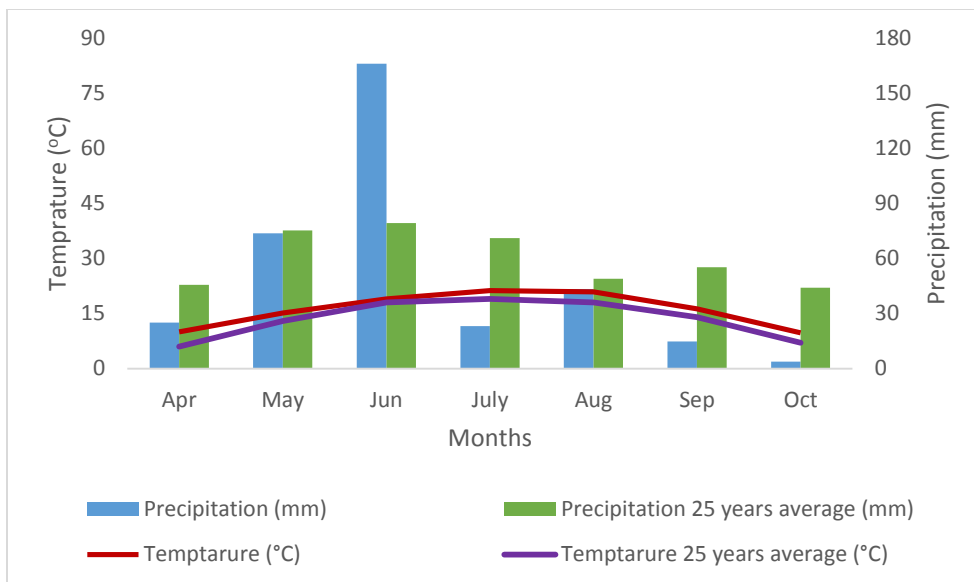
Figure 2.1 Twenty-five year and 2014 average monthly temperature and precipitation at Redfield, SD.

Redfield GPS: 44°58′10″N, -98°27′52″W.
Source:South Dakota Climate and Weather, 2016.
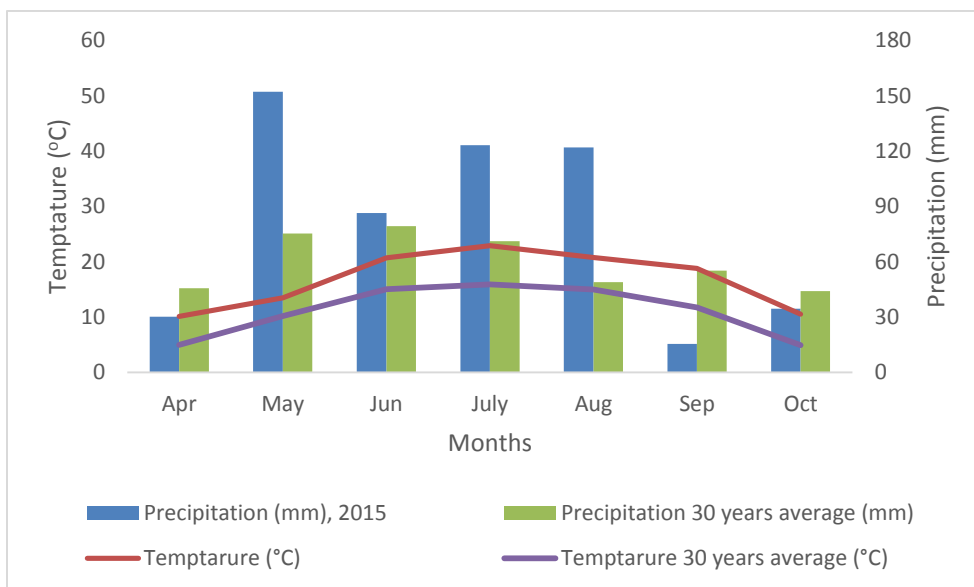
Figure 2.2 Twenty-five year and 2015 average monthly temperature and precipitation at Redfield, SD.

Redfield GPS: 44°58′10″N, -98°27′52″W.
Source: South Dakota Climate and Weather, 2016
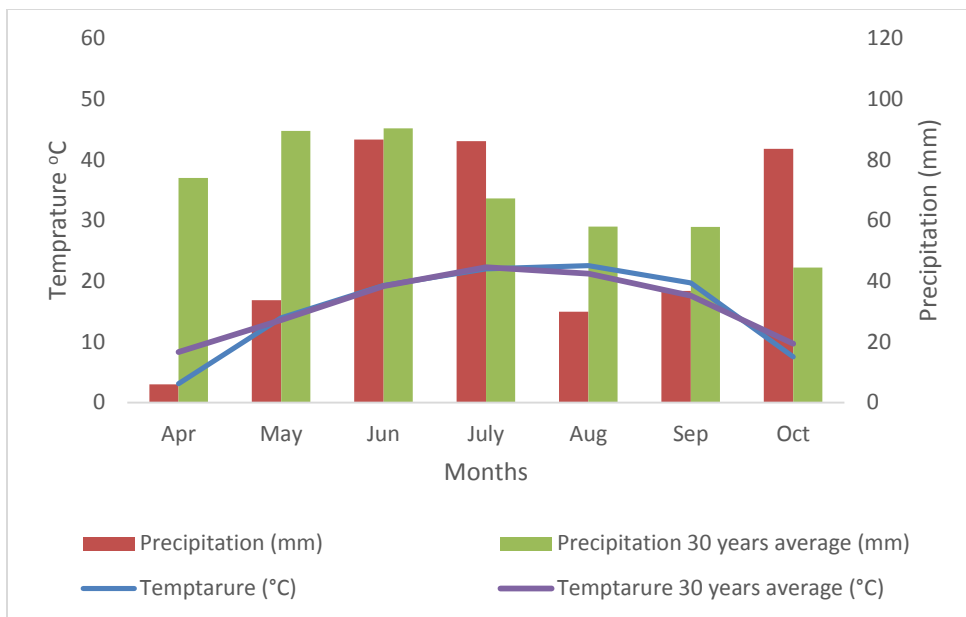
Figure 2.3 Thirty-year and 2013 average monthly temperature and precipitation at White Lake, SD.

White Lake GPS:43°40′31″N, -98°45′50″W.
Source: South Dakota Climate and Weather, 2016.
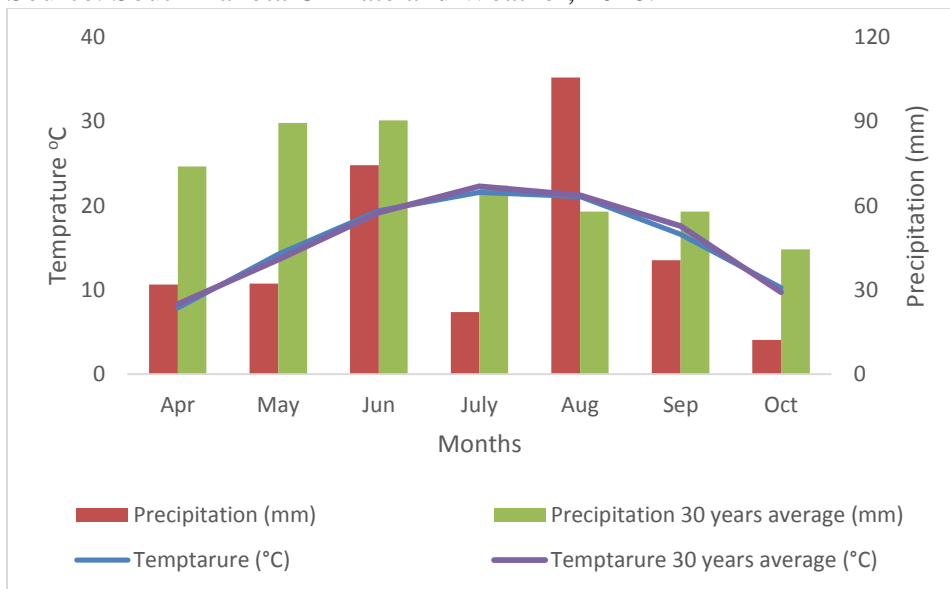
Figure 2.4 Thirty-year and 2014 average monthly temperature and precipitation at White Lake, SD.

White Lake GPS:43°40′31″N, -98°45′50″W.
Source: South Dakota Climate and Weather, 2016.
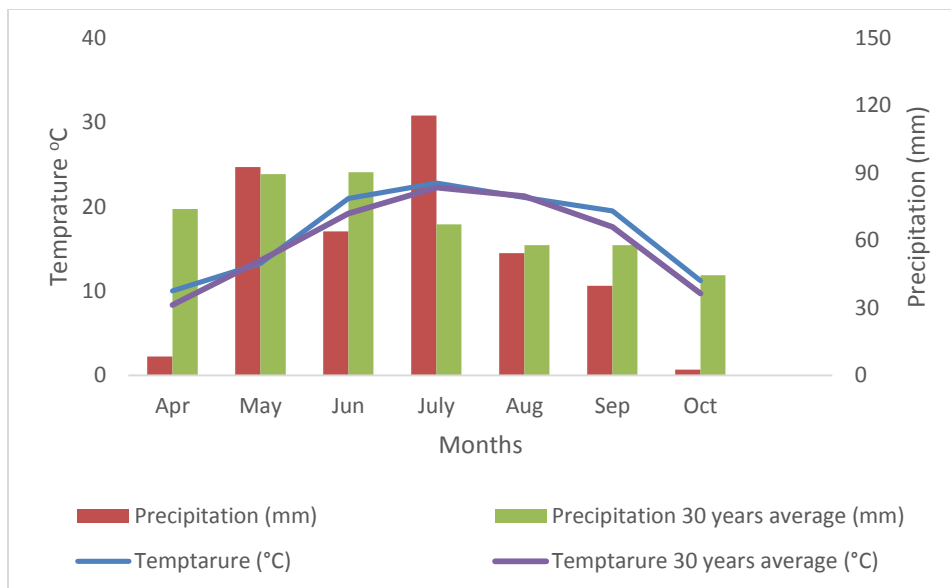
Figure 2.5 Thirty-year and 2015 average monthly temperature and precipitation at White Lake, SD.

White Lake GPS:43°40′31″N, -98°45′50″W.
Source: South Dakota Climate and Weather, 2016.

In 2013 and 2015 at Redfield, there were no significant differences in corn yield due to the treatments, surface amendments, or cover crop. There was also no significant difference on the interaction of the treatments (Table 2.5). Similarly, there was no significant difference in stover weight due to treatments, surface amendments, or cover crop.

However, in 2014, one year after treatment application, there was a significant yield decline in soybean yields for $CaCl_2$ among the surface amendments treatments ($p < 0.001$; Table 2.5). The highest soybean yields were obtained from sulfur treated plots followed by gypsum, control, and calcium chloride. The cover crop treatments were not significantly different. During the three growing seasons there was no significant yield increase in grain yield between the

control and the three treatments tested and $CaCl_2$ actually significantly lowered soybean yields in 2014.

Grain yields of sorghum (2013) and soybean (2015) in White Lake were not significantly affected by the surface amendments and cover crop treatments (Table 2.6). The cover crop treatments gave numerically better (75% of the time) grain yield than the non-cover crop treatments in White Lake 2013 (Table 2.6). The one-year (2015) field trial at Pierpont showed no significant differences in both corn grain yield and stover weight due to surface amendments or cover crop and there was also no significant difference in the interaction of the treatments. The cover crop treatments numerically increased both grain yield and stover weight (Table 2.7), but were not statistically different.

These data demonstrate slight numerical (but not statistically significant) increases in grain yield and stover weight in surface amendments plots (mainly sulfur and gypsum) when compared to the control that may have resulted from slight change in soil chemical properties (reduction in soil pH, EC, and exchangeable sodium), soil physical properties (infiltration and water hydraulic conductivity of the soil), or a combination of one or more factors. In sodic soils with high levels of lime, sulfur reacts with lime and produce gypsum, a soluble Ca^{2+} form, which can then replace exchangeable Na^+ (Stroehlein *et al*., 1978). The variable responses of the treatments over the years could be attributed to differences precipitation, temperature, and soil parent materials at each research site. For instance, in year 2015 annual rainfall increased from the previous years (see Table 2.4 and Figures 2.1, 2.2, 2.3, 2.4, and 2.5). That may have resulted leaching of soluble salts from the topsoil. Previous work has shown improving sodic soil productivity with the application of gypsum and sulfuric acid (Abrol and Bhumbla, 1979; Noble and Kleinig, 1971; Shainberg *et al*., 1989; Stroehlein *et al*., 1978). In addition to increasing the

solubility of Ca^{2+}, sulfuric acid increases the availability of essential plant nutrients (Fe, Mn, Zn and P) by lowering soil pH. Availability of nutrients as a result of lowering pH could be cited as an advantage of sulfur (sulfuric acid) application over using gypsum as amendment (Gupta and Abrol, 1990; Qadir *et al*., 2001; Ryan *et al*., 1975). Therefore, the results of this study showed that adding amendments like sulfur to NGP sodic soils could be more effective than gypsum or calcium chloride when reclaiming saline-sodic soils. However, in general the chemical amendments in NGP soils did not work as anticipated.

Table 2.5 Grain yield and dry stover weight as affected by surface amendment and cover crop treatments at Redfield, South Dakota.

Treatments at Redfield*	Corn, 2013				Soybean, 2014		Soybean, 2015	
	Grain Yield (kg/ha)	n	Stover Yield (kg/ha)	n	Grain Yield (kg/ha)	n	Grain Yield (kg/ha)	n
Surface Treatment (ST)								
$CaCl_2$ ‡	6340 ± 1240 [a]†	8	3470 ± 1150^a	7	1540 ± 1050^b	18	2420 ± 1070^a	17
No-treatment	6910 ± 1190 [a]	6	3550 ± 630^a	4	2360 ± 880^a	15	2260 ± 920^a	9
Gypsum ($CaSO_4 \cdot 2H_2O$)	6850 ± 1480^a	8	3570 ± 910^a	7	2740 ± 1080^a	17	2290 ± 920^a	16
Sulfur (S)	6920 ± 1020^a	7	3130 ± 500^a	6	2790 ± 1260^a	17	2580 ± 1170^a	18
Cropping System (CS)								
Cover crop	6810 ± 1300 [a]	14	3324 ± 950^a	14	2180 ± 1180^a	34	2324 ± 1090^a	31
No-cover crop	6700 ± 1180 [a]	15	3534 ± 700^a	10	2530 ± 1180 [a]	33	2452 ± 990^a	29
ANOVA P>F								
ST	0.662		0.630		0.001		0.640	
CS	0.785		0.447		0.105		0.529	
ST*CS	0.281		0.112		0.397		0.554	

†Means with different letters within a column, treatment are significantly different at $P < 0.05$.
‡ Surface Treatment =ST; Cropping System =CS.
*44°58′10″N, -98°27′52″W (Dominant soils: Hapludolls, Natrudolls, Argiudolls).
Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.

Table 2.6 Grain yield and dry stover weight as affected by surface amendment and cover crop treatments at White Lake, South Dakota.

Treatments at White Lake**	Sorghum, 2013		Soybean, 2015	
	Grain Yield (kg/ha)	n	Grain Yield (kg/ha)	n
Surface Treatment (ST)				
$CaCl_2$ ‡	3150 ± 1650^a†	10	1720 ± 1270^a	8
No-treatment	3100 ± 1360^a	14	1450 ± 1070^a	9
Gypsum ($CaSO_4 \cdot 2H_2O$)	3370 ± 1940^a	13	1950 ± 1090^a	7
Sulfur (S)	3480 ± 2310^a	18	1900 ± 1060^a	9
Cropping System (CS)				
Cover crop	3549 ± 1740^a			
No-cover crop	2996 ± 1930^a			
ANOVA P>F				
ST	0.918		0.807	
CS	0.240		-	
ST*CS	0.923		-	

†Means with different letters within a column, treatment are significantly different at $P < 0.05$.
‡ Surface Treatment =ST; Cropping System =CS.
**43°40′31″N, -98°45′50″W (Dominant soils: Argiustolls, Natrustolls, Haplustolls, Calciustolls).
Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.

Table 2.7 Comparison of grain yield and dry stover weight as affected by surface amendment and cover crop treatments at Pierpont, South Dakota.

Treatments at Pierpont***	Corn, 2015				
	Grain Yield (kg/ha)	n	Stover Yield (kg/ha)	n	
Surface Treatment (ST) ‡					
$CaCl_2$	1970 ± 1580^a†	9	1900 ± 1120^a	13	
No-treatment	1410 ± 1130^a	11	1460 ± 680^a	11	
Gypsum ($CaSO_4 \cdot 2H_2O$)	2300 ± 1550^a	10	2240 ± 1290^a	13	
Sulfur (S)	1660 ± 1100^a	11	1940 ± 1790^a	18	
Cropping System (CS)					
Cover crop	2160 ± 1490^a	22	2160 ± 1690^a	27	
No-cover crop	1500 ± 1100^a	21	1615 ± 840^a	27	
ANOVA P>F					
ST	0.097		0.610		
CS	0.447		0.185		
ST*CS	0.822		0.640		

†Means with different letters within a column, treatment are significantly different at $P < 0.05$.
‡ Surface Treatment =ST; Cropping System =CS.
***45°30′31″N, -97°53′50″W (Dominant soils: Hapludolls, Natrudolls).
Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.

Chlorophyll content and stomatal conductance

This study showed significant differences in final sorghum populations at White Lake among the surface amendments (Table 2.8). However, there were no significant differences in plant populations due to cover crop treatment and the interaction at White Lake 2013. Chlorophyll contents for White Lake were not significantly different for surface amendments for both years (2013 and 2015). There were no significant differences in stomatal conductance for surface amendments in 2013. In 2015, there were significant differences in soybean stomatal conductance due to surface treatments (Table 2.8).

During the three years of study (corn [2013] and soybean [2014, 2015]) final plant populations, chlorophyll content, and stomatal conductance measurements at Redfield, SD indicate that there were no significant differences in all studied parameters due to surface amendments or cover crop (Table 2.9). Cover crop did numerically enhance stomatal conductance and plant populations.

2.3.2 Soil chemical properties

Surface chemical amendments and cover crop did not show significant differences in improving the topsoil properties. Surface soil (0 – 0.5 cm) chemical properties appeared to improve (Tables 2.10, 2.11, and 2.12) when compared with the baseline data (Table 2.1). At White Lake surface soil pH reduced from 7.6 to 7.3, EC from 10.2 dS/m to 7.9 dS/m, and SAR from 17 to 12.6 in sulfur treated plots over the study period. However, when treatments at all depths and cover crops were compared to the control there were no significant differences in pH, EC, or SAR. Similarly, in Redfield, the surface soil (0 – 7.5 cm) pH was reduced from 7.3 to 7.1 (gypsum treated plots), EC from 8.0 dS/m to 4.9 dS/m, and SAR from 3.6 to 1.3 during the three-

year period. However, when treatments at all depths and cover crop were compared to the control there were no significant differences in pH, EC, or SAR (except for SAR in soybeans at 7.5 cm depth in 2015). Soil chemical properties changes due to surface chemical amendments and cover crops at different depth are presented in Figures 2.6 to 2.12.

The changes in soil chemical properties were attributed to the increase in precipitation that may have leached the salts from the topsoil and also a slight positive impact of sulfur and gypsum on soils, acidifying the soil and making the existing Ca^{2+} more available in the exchange complex. The Ca^{2+} then replaces Na^+ resulting in reductions of soil pH and SAR. Gypsum decreases the ratio of sodium to other soluble salts and as a result, reduces sodicity and increases Ca^{2+} exchange system (Frenkel *et al*., 1989).

Other research on different soils have shown improvement in soil chemical properties after application of gypsum and sulfuric acid (Hamza and Anderson, 2003; Rengasamy and Olsson, 1991; Shainberg *et al*., 1989; Shanmuganathan and Oades, 1983). There have been reports of increased yield (Abrol and Bhumbla, 1979; Noble and Kleinig, 1971; Shainberg *et al*., 1989) and increased seed emergence (Lauchli and Epstein, 1990; McKenzie *et al*., 1993) under specific soil treatments.

Table 2.8 Plant population and selected physiological measurements of sorghum (*Sorghum bicolor*) and soybean (*Glycine max*) as affected by surface amendment and cover crop treatments in White Lake, SD in 2013 and 2015

| Treatments at White Lake** | Sorghum, 2013 | | | | | | Soybeans, 2015 | | | |
	Number of Plants/ha	n	Chlorophyll Content (%)	N	Stomatal conductance (mmol m⁻² s⁻¹)	n	Chlorophyll Content (%)	n	Stomatal conductance (mmol m⁻² s⁻¹)	n
Surface Treatment (ST) ‡										
CaCl$_2$	21310^{ab}†	12	50 ± 5^a	12	213 ± 87^a	12	48 ± 5^a	12	225 ± 92^{ab}	12
No-treatment	16810^b	15	50 ± 3^a	10	209 ± 84^a	12	48 ± 4^a	10	225 ± 85^{ab}	12
Gypsum (CaSO$_4$·2H$_2$O)	25800^{ab}	13	51 ± 4^a	12	214 ± 63^a	12	49 ± 5^a	12	187 ± 66^b	12
Sulfur (S)	32510^a	17	50 ± 3^a	12	206 ± 98^a	12	50 ± 7^a	10	291 ± 180^a	12
Cropping System (CS)										
Cover crop	20490^a	28	-		-		-		-	
No-cover crop	27720^a	29	-		-		-		-	
ANOVA P>F										
ST	0.154		0.923		0.991		0.830		0.172	
CS	0.173		-		-		-		-	
ST*CS	0.977		-		-		-		-	

†Means with different letters within a column, treatment are significantly different at *P* < 0.05.

‡ Surface Treatment =ST; Cropping System =CS.

**43°40′31″N, -98°45′50″W (Dominant soils: Argiustolls, Natrustolls, Haplustolls, Calciustolls).

Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.

Measurements were done between V4 (four leaves) and V6 (six leaves) stage for sorghum and R1 (flowering) stage for soybean.

Table 2.9 Plant population and selected physiological measurements of corn (*Zea mays*) and soybean (*Glycine max*) as affected by under surface amendment and cover crop treatments in Redfield, SD in 2013, 2014, and 2015.

| Treatments at Redfield* | Corn, 2013 | | | | | | Soybean, 2014 | | Soybean, 2015 | | | |
	Number of Plants/ha	n	Chloro-phyll Content (%)	n	Stomatal conductance (mmol m^{-2} s^{-1})	N	Chloro-phyll Content (%)	n	Chloro-phyll Content (%)	n	Stomatal conductance (mmol m^{-2} s^{-1})	n
Surface Treatment (ST) ‡												
CaCl$_2$	33970 ± 6520 [a]†	14	43 ± 5 [a]	15	234 ± 92 [a]	15	38 ± 6 [a]	18	46 ± 15 [a]	11	364 ± 129 [a]	9
No-treatment	35070 ± 5350 [a]	18	44 ± 6 [a]	18	236 ± 59 [a]	18	37 ± 5 [a]	18	48 ± 9 [a]	12	352 ± 107 [a]	10
Gypsum (CaSO$_4$·2H$_2$O)	34720 ± 6070 [a]	17	45 ± 6 [a]	18	242 ± 68 [a]	18	39 ± 5 [a]	18	49 ± 14 [a]	12	379 ± 108 [a]	11
Sulfur (S)	36550 ± 5800 [a]	15	44 ± 5 [a]	18	226 ± 117[a]	18	39 ± 6 [a]	16	49 ± 11 [a]	10	413 ± 99 [a]	8
Cropping System (CS)												
Cover crop	35587 ± 5471 [a]	33	43 ± 5 [a]	35	259 ± 74 [a]	35	39 ± 5 [a]	35	48 ± 15 [a]	22	407 ± 110 [a]	19
No-cover crop	34571 ± 6222 [a]	31	43 ± 6 [a]	34	225 ± 94 [a]	34	38 ± 6 [a]	35	49 ± 15 [a]	23	344 ± 102 [a]	19
ANOVA P>F												
ST	0.462		0.543		0.855		0.740		0.710		0.692	
CS	0.361		0.731		0.078		0.675		0.261		0.084	
ST*CS	0.952		0.664		0.793		0.443		0.802		0.703	

†Means with different letters within a column, treatment are significantly different at *P* < 0.05.
‡ Surface Treatment =ST; Cropping System =CS.
*44°58′10″N, -98°27′52″W (Dominant soils: Hapludolls, Natrudolls, Argiudolls).
Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.
Measurements were done between V4 (four leaves) and V6 (six leaves) stage for sorghum and R1 (flowering) stage for soybean.

Table 2.10 Soil pH change by depth at White Lake and Redfield, SD.

| | Soil pH After Harvest | | | | | | | | | | | |
| | Soybean (*Glycine max*), 2015 at White Lake** | | | | | | Soybean (*Glycine max*), 2015 at Redfield* | | | | | |
Treatments	0-7.5cm	n	7.5-15cm	n	15-30cm	n	0-7.5cm	n	7.5-15cm	n	15-30cm	n
Baseline soil pH	7.6 ± 0.2	6	7.8 ± 0.1	6	7.8 ± 0.2	6	7.3 ± 0.3	5	7.8 ± 0.4	5	7.8 ± 0.3	5
Surface Treatment (ST)‡												
No-treatment	7.4 ± 0.5 [a]†	8	7.4 ± 0.3 [a]	7	7.5 ± 0.3 [a]	9	7.1 ± 0.6 [a]	13	7.7 ± 0.3 [a]	15	7.7 ± 0.3 [a]	15
Gypsum (CaSO$_4$·2H$_2$O)	7.5 ± 0.3 [a]	9	7.4 ± 0.4 [a]	9	7.4 ± 0.1 [a]	3	7.1 ± 0.5 [a]	17	7.7 ± 0.4 [a]	15	7.6 ± 0.2 [a]	17
Sulfur (S)	7.3 ± 0.3 [a]	6	7.4 ± 0.3 [a]	7	7.4 ± 0.5 [a]	8	7.8 ± 0.5 [a]	18	7.6 ± 0.3 [a]	18	7.6 ± 0.3 [a]	18
Cropping System (CS)												
Cover crop	7.3 ± 0.3 [a]	6	7.5 ± 0.3 [a]	8	7.5 ± 0.4 [a]	7	8.0 ± 0.6 [a]	25	7.8 ± 0.4 [a]	24	7.7 ± 0.3 [a]	26
No-cover crop	7.5 ± 0.4 [a]	17	7.4 ± 0.4 [a]	15	7.4 ± 0.4 [a]	13	7.8 ± 0.6 [a]	23	7.6 ± 0.3 [b]	24	7.6 ± 0.2 [a]	24
ANOVA P>F												
ST	0.426		0.623		0.711		0.438		0.641		0.790	
CS	0.463		0.526		0.882		0.307		0.221		0.189	
ST*CS	0.528		0.396		0.642		0.425		0.422		0.368	

†Means with different letters within a column, treatment are significantly different at $P < 0.05$.

‡ Surface Treatment =ST; Cropping System =CS.

*44°58′10″N, -98°27′52″W (Dominant soils: Hapludolls, Natrudolls, Argiudolls).

**43°40′31″N, -98°45′50″W (Dominant soils: Argiustolls, Natrustolls, Haplustolls, Calciustolls).

Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.

Note: Baseline soil samples were taken in May 2013.

Table 2.11 Electrical conductivity (EC) change by soil depth at White Lake and Redfield, SD.

Treatments	After Harvest EC (dS/m)											
	Soybean (*Glycine max*), 2015 at White Lake**						Soybean (*Glycine max*), 2015 at Redfield*					
	0-7.5cm	n	7.5-15cm	n	15-30cm	n	0-7.5cm	n	7.5-15cm	n	15-30cm	n
Baseline (EC in dS/m)	10.2 ± 2.4	6	8.2 ± 1.0	6	7.3 ± 1.1	6	8.0 ± 2.4	5	6.2 ± 2.1	5	6.5 ± 2.5	5
Surface Treatment (ST)‡												
No-treatment	9.2 ± 3.5 [a†]	8	8.7 ± 2.7 [a]	7	8.5 ± 1.7 [a]	9	5.6 ± 3.8 [a]	13	4.9 ± 3.1 [a]	15	4.8 ± 2.6 [a]	15
Gypsum ($CaSO_4 \cdot 2H_2O$)	9.8 ± 3.2 [a]	9	9.2 ± 1.8 [a]	9	9.4 ± 1.3 [a]	3	5.4 ± 2.5 [a]	17	5.7 ± 2.8 [a]	15	4.9 ± 2.0 [a]	17
Sulfur (S)	7.9 ± 6.2 [a]	6	7.7 ± 3.3 [a]	7	8.2 ± 1.9 [a]	8	4.9 ± 3.0 [a]	18	4.2 ± 3.2 [a]	18	4.3 ± 2.5 [a]	18
Cropping System (CS)												
Cover crop	7.3 ± 2.0 [a]	6	8.2 ± 2.7 [a]	8	9.3 ± 1.0 [a]	7	5.6 ± 3.3 [a]	25	5.1 ± 3.1 [a]	24	4.6 ± 2.5 [a]	26
No-cover crop	9.8 ± 3.9 [a]	17	8.7 ± 2.2 [a]	15	8.1 ± 1.8 [a]	13	5.0 ± 2.6 [a]	23	4.8 ± 3.1 [a]	24	4.7 ± 2.8 [a]	24
ANOVA P>F												
ST	0.336		0.336		0.396		0.594		0.229		0.640	
CS	0.131		0.131		0.085		0.346		0.614		0.860	
ST*CS	0.425		0.425		0.905		0.463		0.343		0.211	

†Means with different letters within a column, treatment are significantly different at $P < 0.05$.

‡ Surface Treatment =ST; Cropping System =CS.

*44°58′10″N, -98°27′52″W (Dominant soils: Hapludolls, Natrudolls, Argiudolls).

**43°40′31″N, -98°45′50″W (Dominant soils: Argiustolls, Natrustolls, Haplustolls, Calciustolls).

dS/m = decisiemens per meter

Source of soil information: USDA-NRCS, Soil Survey Division, 2016.

Note: Baseline soil samples were taken in May 2013.

Table 2.12 Sodium adsorption ratio (SAR) change by soil depth at White Lake and Redfield, SD.

	After Harvest SAR											
	Soybean (*Glycine max*), 2014 at White Lake**						Soybean (*Glycine max*), 2015 at Redfield*					
Treatments	0-7.5cm	n	7.5-15cm	n	15-30cm	n	0-7.5cm	n	7.5-15cm	n	15-30cm	n
Base line	17 ± 5.2	6	17.8 ± 4.1	6	12.3 ± 2.3	6	3.6 ± 1.5	5	3.3 ± 1.0	5	3.0 ± 2.6	5
Surface Treatment (ST)												
No-treatment	13.6 ± 3.8 [a]	10	12.4 ± 2.7 [a]	11	12.5 ± 2.2 [a]	9	2.5 ± 1.9 [a]	13	3.1 ± 4.2 [a]	15	3.0 ± 2.0 [a]	15
Gypsum ($CaSO_4 \cdot 2H_2O$)	13.7 ± 4.3 [a]	11	11.3 ± 4.2 [a]	11	10.4 ± 3.7 [a]	10	1.8 ± 1.1 [ab]	17	3.6 ± 3.6 [a]	15	2.8 ± 2.0 [a]	17
Sulfur (S)	12.6 ± 2.6 [a]	10	10.4 ± 4.4 [a]	10	10.5 ± 2.7 [a]	11	1.3 ± 0.8 [b]	18	2.5 ± 0.8 [a]	18	2.6 ± 2.1 [a]	18
Cropping System (CS)												
Cover crop	-		-		-		2.2 ± 1.5 [a]	25	2.8 ± 3.1 [a]	24	2.7 ± 1.9 [a]	26
No-cover crop	-		-		-		1.5 ± 1.0 [a]	23	3.3 ± 2.9 [a]	24	3.0 ± 2.1 [a]	24
ANOVA P>F												
ST	0.850		0.570		0.237		0.056		0.701		0.896	
CS							0.061		0.596		0.606	
ST*CS							0.056		0.285		0.063	

†Means with different letters within a column, treatment are significantly different at *P* < 0.05.
‡ Surface Treatment =ST; Cropping System =CS.
*44°58′10″N, -98°27′52″W (Dominant soils: Hapludolls, Natrudolls, Argiudolls).
**43°40′31″N, -98°45′50″W (Dominant soils: Argiustolls, Natrustolls, Haplustolls, Calciustolls).
Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.
Note: Baseline soil samples were taken in May 2013.
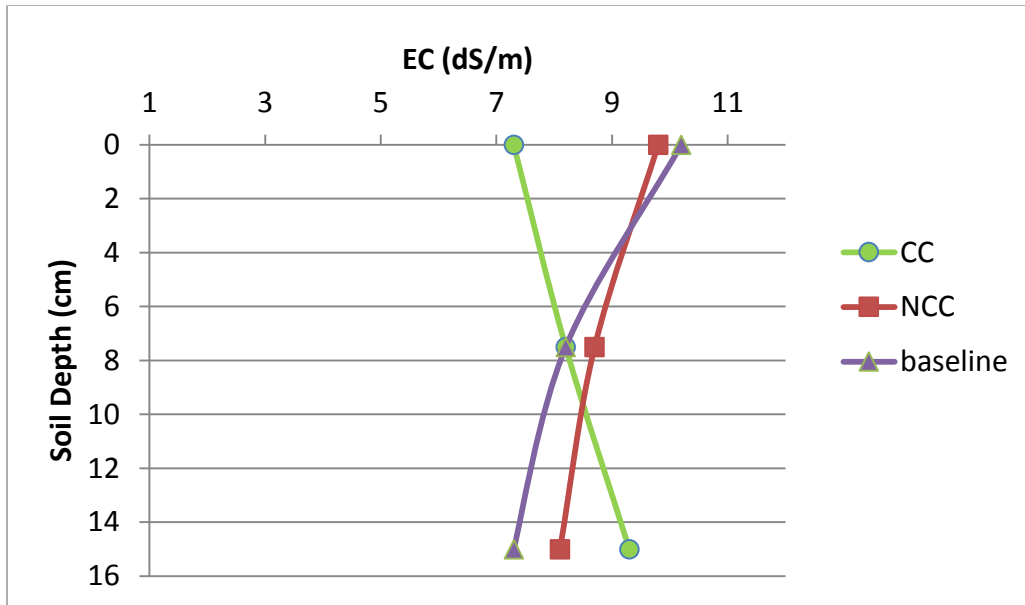
Figure 2.6 Electrical conductivity (EC) as affected by cover crop at different soil depths at White Lake, SD (3 years after treatment applied).
GPS: 43°40′31″N, -98°45′50″W (Dominant soils: Argiustolls, Natrustolls, Haplustolls, Calciustolls).
Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.
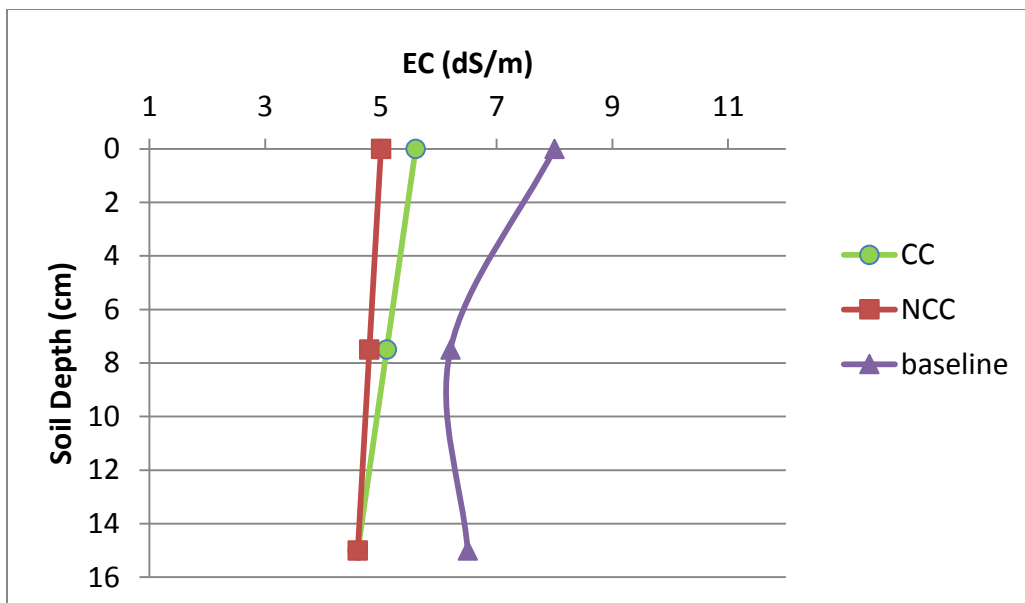
Figure 2.7 Electrical conductivity (EC) as affected by cover crop at different soil depths at Redfield, SD (3 years after treatment applied).
GPS: 44°58′10″N, -98°27′52″W (Dominant soils: Hapludolls, Natrudolls, Argiudolls).
Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.
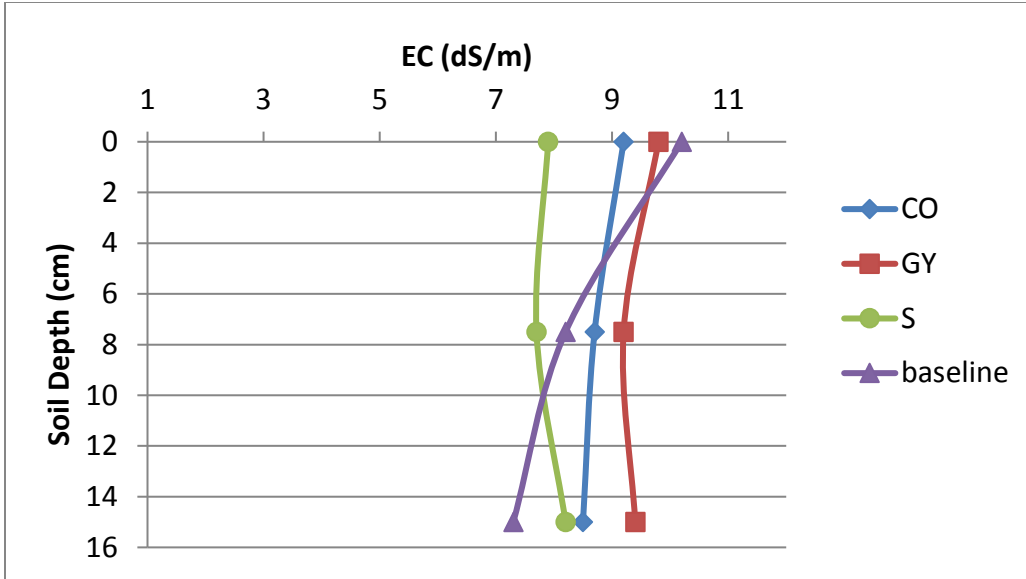
Figure 2.8 Electrical conductivity (EC) as affected by surface chemical amendments at different soil depths at White Lake, SD (3 years after treatment applied).

GPS: 43°40′31″N, -98°45′50″W (Dominant soils: Argiustolls, Natrustolls, Haplustolls, Calciustolls).
Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.
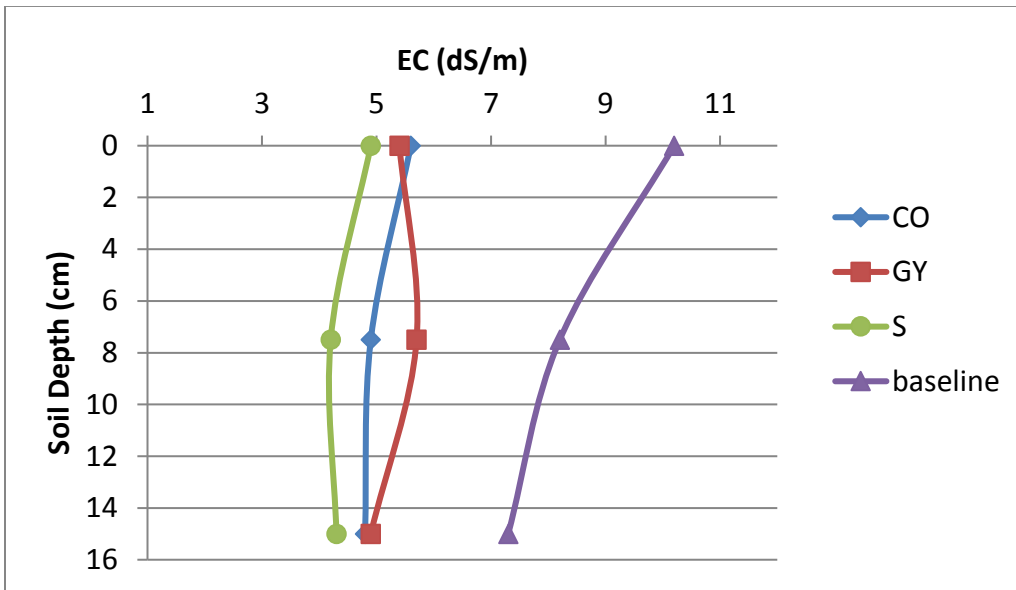
Figure 2.9 Electrical conductivity (EC) as affected by surface chemical amendments at different soil depths at Redfield, SD (3 years after treatment applied).

GPS: 44°58′10″N, -98°27′52″W (Dominant soils: Hapludolls, Natrudolls, Argiudolls).
Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.
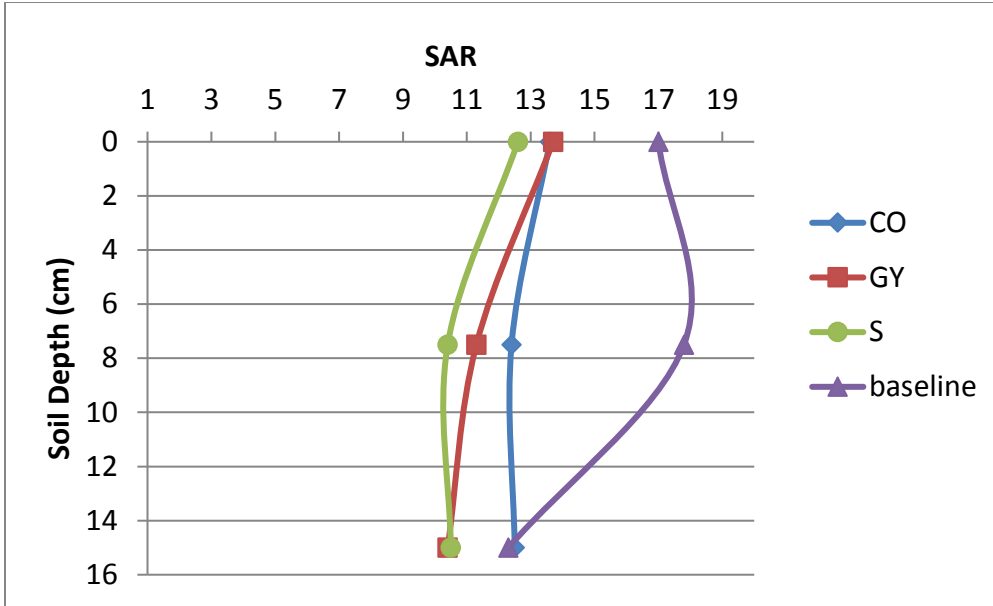
Figure 2.10 Sodium adsorption ratio (SAR) as affected by surface chemical amendments at different soil depths at White Lake, SD (3 years after treatment applied).
GPS: 43°40′31″N, -98°45′50″W (Dominant soils: Argiustolls, Natrustolls, Haplustolls, Calciustolls).
Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.
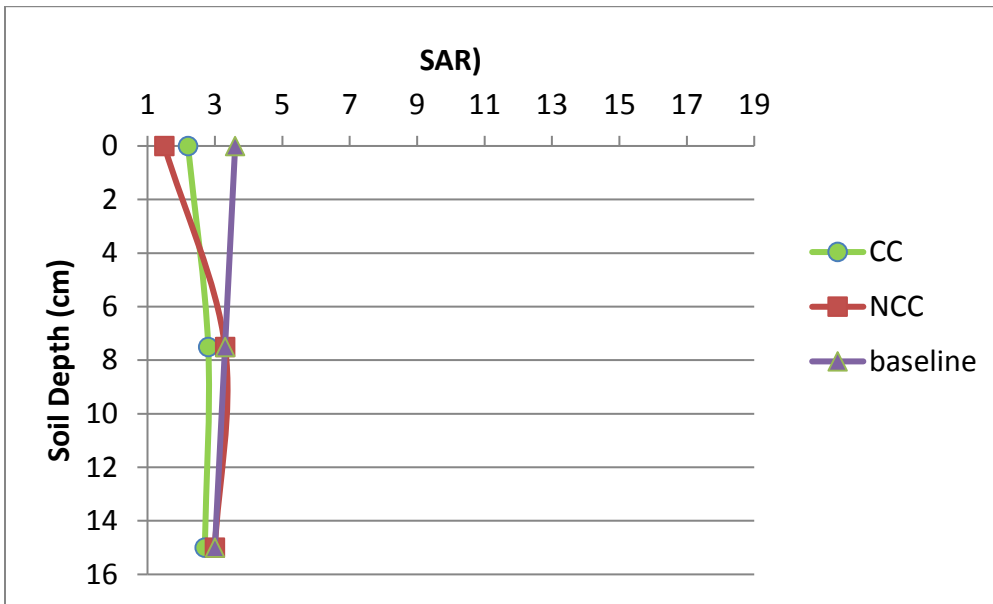
Figure 2.11 Sodium adsorption ratio (SAR) as affected by cover crop at different soil depths at Redfield, SD (3 years after treatment applied).
GPS: 44°58′10″N, -98°27′52″W (Dominant soils: Hapludolls, Natrudolls, Argiudolls).
Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.
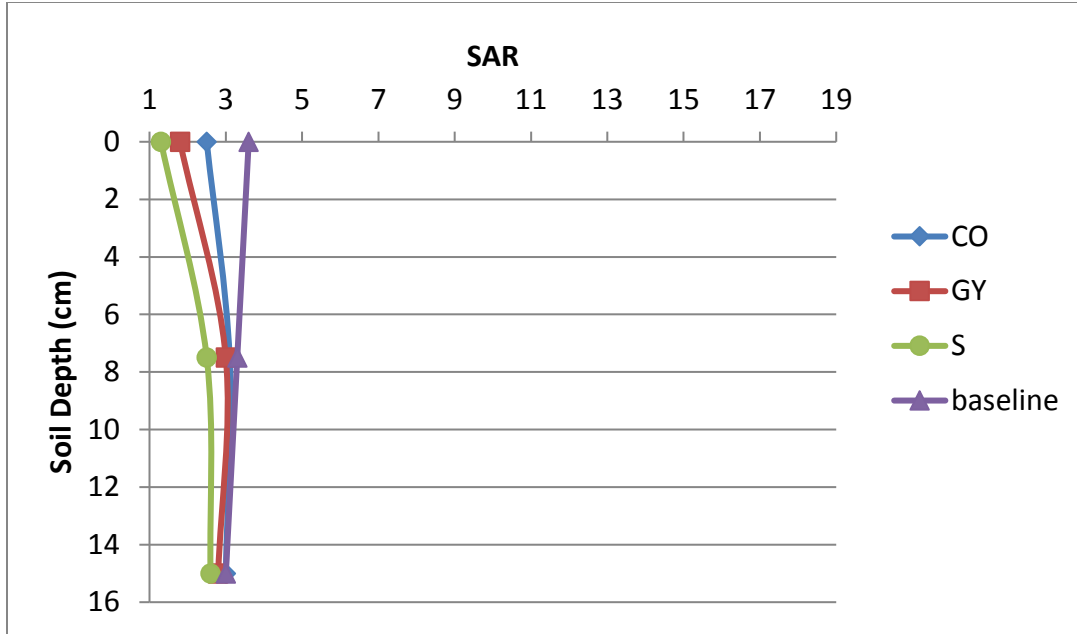
Figure 2.12 Sodium adsorption ratio (SAR) as affected by surface chemical amendments at different soil depths at Redfield, SD (3 years after treatment applied).
GPS: 44°58′10″N, -98°27′52″W (Dominant soils: Hapludolls, Natrudolls, Argiudolls).
Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.

2.4 Conclusions

The area coverage of saline and saline sodic soils is increasing in the NGP region of the United States and that is resulting in a significant reduction of productive of arable land (degraded soil organic levels, soil chemical properties, and soil structure) and increases the downstream sediment deposition (due to increased erosion rates associated with sodic soils).

The effects of chemical amendments on improving crop yield have been shown in earlier research in other parts of the world; however the information on the role of these amendments in NGP saline-sodic soils is scarce. The results of this study showed that the selected surface treatments of gypsum, $CaCl_2$, and sulfur did not significantly enhance crop yield and most soil properties studied. Although, there were a few encouraging responses of gypsum and elemental sulfur amendments, the effect of these treatments both on crop and soil has to be monitored for the long-term and under a larger variety of crops, parent materials, and climatic conditions.

The use of cover crops in saline-sodic soil management was mixed in increasing crop yields, improving soil quality (soil pH, EC, and exchangeable sodium), and water infiltration in some of the tested sites. Elemental sulfur and gypsum were usually, numerically better than calcium chloride and control. Information on the role of perennial and annual ameliorating crops in improving saline-sodic soils needs to be further examined in the future research. The effect of chemical amendments on nutrient availability the impacts of amendments (reclamation) on soil C level in the salt-affected areas of NGP soils are other important areas of future research. Designing a system that mimic the use of deep rooted prairie grasses that utilize the water in most of the year could be useful.

2.5 Literature Cited

Abrol, I., and D. Bhumbla. 1979. Crop responses to differential gypsum applications in a highly sodic soil and the tolerance of several crops to exchangeable sodium under field conditions. Soil Science 127: 79-85.

Cerling, T. E., and J. Quade, 1993, Stable carbon and oxygen isotopes in soil carbonates: Climate change in continental isotopic records. American Geophysical Union Monograph. 78:217-231.

Chi, C., C. Zhao, X. Sun, and Z. Wang. 2012. Reclamation of saline-sodic soil properties and improvement of rice (Oriza sativa L.) growth and yield using desulfurized gypsum in the west of Songnen Plain, northeast China. Geoderma 187: 24-30.

Clark, A. 2008. Managing cover crops profitably 3rd ed. Handbook Series Book 9. Sustainable Agriculture Network, Beltsville, MD.

Fehr, W., Caviness, C., Burmood, D., and Pennington, J. 1971. Stage of development descriptions for soybeans, Glycine max (L.) Merrill. Crop Science 11: 929-931.

Frenkel, H., Z. Gerstl, and N. Alperovitch. 1989. Exchange-induced dissolution of gypsum and the reclamation of sodic soils. Journal of Soil Science 40: 599-611.

Gupta, R. K., and I. Abrol. 1990. Salt-affected soils: their reclamation and management for crop production. Advances in Soil Science, Springer, p. 223-288.

Hamza, M., and W. Anderson. 2003. Responses of soil properties and grain yields to deep ripping and gypsum application in a compacted loamy sand soil contrasted with a sandy clay loam soil in Western Australia. Crop and Pasture Science 54: 273-282.

Horneck, D. A., J. W. Ellsworth, B. G. Hopkins, D. M. Sullivan, and R. G. Stevens. 2007. Managing salt-affected soils for crop production. A Pacific Northwest Extension publication.Oregon State University Extension Service. Oregon State University.

Hulugalle, N., T. Weaver, and L. Finlay. 2010. Soil water storage and drainage under cotton-based cropping systems in a furrow-irrigated Vertisol. Agricultural Water Management. 97: 1703-1710.

Karl, T. R., and R. W. Knight. 1998. Secular trends of precipitation amount, frequency, and intensity in the United States. Bulletin of the American Meteorological Society 79: 231-241.

Karlen, D., M. Mausbach, J. Doran, R. Cline, R. Harris, and G. Schuman. 1997. Soil quality: a concept, definition, and framework for evaluation (a guest editorial). Soil Science Society of America Journal 61: 4-10.

Kharel T. 2016. Soil Salinity Study in Northern Great Plains Sodium Affected Soil. Ph. D. Dissertation, Plant Science Department, South Dakota State University.

Lauchli, A., and E. Epstein. 1990. Plant responses to saline and sodic conditions. Agricultural salinity assessment and management 71: 113-137.

Malo, D.D., Ryu, J.-H., Kim, S. J., and Chung, D.Y. 2010. South Dakota Soils: Their Genesis, Classification, and Management. Chungnam National University Journal of Agricultural Science 37: 413-433.

McKenzie, D., T. Abbott, K. Chan, P. Slavich, and D. Hall. 1993. The nature, distribution and management of sodic soils in New-South-Wales. Soil Research 31: 839-868.

Noble, J., and C. Kleinig. 1971. Response by irrigated grain sorghum to broadcast gypsum and phosphorus on a heavy clay soil. Animal Production Science 11: 53-58.

Olson, D., and DeBoer, D. 1988. Field evaluation of DRAINMOD in South Dakota. American Society of Agricultural Engineers 18: 88-2571.

Pannell, D. J., and M. A. Ewing. 2006. Managing secondary dryland salinity: options and challenges. Agricultural Water Management 80: 41-56.

Page, A. L. 1982. Methods of soil analysis. Part 2. Chemical and microbiological properties, ASA-SSSA.Madison, WI..

Qadir, M., and S. Schubert, 2002, Degradation processes and nutrient constraints in sodic soils. Land Degradation and Development 13: 275-294.

Qadir, M., S. Schubert, A. Ghafoor, and G. Murtaza, 2001, Amelioration strategies for sodic soils: a review. Land Degradation and Development 12: 357-386.

Rengasamy, P. 2006. World salinization with emphasis on Australia. Journal of Experimental Botany 57: 1017-1023.

Rengasamy, P., and K. Olsson. 1991. Sodicity and soil structure: Soil Research 29: 935-952.

Rhoades, J., 1982, Cation exchange capacity: Methods of soil analysis. Part 2. Chemical and Microbiological Properties. ASA-SSSA, Madison, WI.

Reitsma, K., Dunn B., Mishra U., Clay S., DeSutter T., and Clay D. 2015. Land-use change impact on soil sustainability in a climate and vegetation transition zone. Agronomy Journal 107: 2363-2372.

Reitsma K., Clay D., Clay S., Dunn B., and Reese C. 2016. Does the US Cropland Data Layer Provide an Accurate Benchmark for Land-Use Change Estimates? Agronomy Journal 108: 266-272.

Ryan, J., J. Stroehlein, and S. Miyamoto. 1975. Effect of surface-applied sulfuric acid on growth and nutrient availability of five range grasses in calcareous soils. Journal of Range Management. 28: 411-414.

SAS. 2007. SAS user's guide: Statistics. SAS Inst., Cary, NC.

Shainberg, I., M. Sumner, W. Miller, M. Farina, M. Pavan, and M. Fey. 1989. Use of gypsum on soils: A review. Springer. Advances in Soil Sciences 9: 1-111.

Shanmuganathan, R., and J. Oades. 1983. Modification of soil physical properties by addition of calcium compounds. Soil Research 21: 285-300.

South Dakota Climate and Weather. 2016.

http://climate.sdstate.edu/climate_site/archive_data.htm (accessed 5/12/2016).

Stroehlein, J., S. Miyamoto, and J. Ryan, 1978, Sulfuric acid for improving irrigation waters and reclaiming sodic soils: University of Arizona, College of Agriculture, Tuscon, Arizona.

Szabolcs, I. 1994. Soils and salinization: Handbook of plant and crop stress. Marcel Dekker, New York, p. 3-11.

USDA-NRCS. 2016a. Major Land Resource Area Explorer. USDA-NRCS,

http://apps.cei.psu.edu/mlra/ (accessed 04/07/2016).

USDA-NRCS. 2016b. Web Soil Survey. USDA-NRCS,

http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx (accessed 04/07/2016).

Vaughan, J.D., and Evanylo, G.K. 1998. Corn response to cover crop species, spring desiccation time, and residue management. Agronomy Journal 90: 536-544.

3. CHAPTER III

SPATIAL MODEL DEFINING NDVI AND CORN YIELDS IN SALINE-SODIC SOILS

Abstract

Geospatial tools coupled with remote sensing methods can assist in making sound natural resource management decisions. The objective of this chapter is to select appropriate models that can define or predict spatial variability of Normalized Difference Vegetation Index (NDVI) and crop yield. This experiment was conducted at Pierpont, SD [44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″W in Major Land Resource Area (MLRA) 55C]. The dominant soils in the study area were Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls. A total of 169 grid points (62 x 62 m grid) were laid out in the field in 2014. Reflectance (485-1050 nm of the reflectance bands) readings were made using crop scan [Multispectral Radiometer (MSR)] between seeding and the corn (*Zea mays*) growth stage V1. Corn yields were measured with a yield monitor at harvest. The normalized difference vegetation indices [NDVI = (NIR - Red) / (NIR + Red)] was computed from reflectance in red and near infrared (NIR) bands. Semi-variograms for the spherical, exponential, and Gaussian models were determined. The exponential semivariogram model for yield and NDVI was the optimal model with the spatial dependence (nugget/sill ratio) of 14.4 and 0 %, respectively. The spatial dependence also extends up to a range of 178 m and 105 m for NDVI and yield, respectively. Comparative analysis of spatial interpolation methods (Trend Surface Analysis, Inverse Distance Weighting, Ordinary Kriging, and Linear Regression models) using elevation as an independent variable were used to map NDVI and yield at the field scale. The Ordinary Kriging was the

optimal model for NDVI with a correlation coefficient of 0.544 (R^2=0.33) and root mean square

error (RMSE) of 0.089 when compared to other methods. For yield the Inverse Distance

Weighting (IDW) method with class of nearest neighbor (k) = 2 was found to be optimal with a

correlation coefficient of 0.413 (R^2= 0.24) and RMSE of 0.223. Therefore, the study clearly

showed that geospatial models coupled with remote sensing methods can be used as potential

tools to analyze and predict the spatial dependence of NDVI values and crop yield, and aid in the

spatial prediction of un-sampled spatial variables in salt-affected soils.

Keywords: Argiudolls, Calciaquolls, Endoaquolls, Hapludolls, interpolation, Natrudolls, radiometer, salinity, Calciudolls, Normalized Difference Vegetation Index (NDVI), semivariograms, spatial interpolation methods, sodicity.

3.1 Introduction

Worldwide saline and Na^+ affected soils are separated into at least three groups: saline (high total salts), saline/sodic (high total salts and Na^+), and sodic (high Na^+) (Halvorson and Rhoades, 1976). The classification of salt-affected soils into one of these groups is based on the soil electrical conductivity (EC) and the amount of Na^+ on the cation exchange sites expressed as ESP (exchangeable Na^+ percentage) or SAR (Na^+ adsorption ratio). Historically, sodic soils are characterized as having a Na^+ adsorption ratio (SAR) > 13, whereas in the NGP, soils are at risk when the SAR > 4 (He *et al*., 2014; Qadir *et al*., 2007). Saline soils have high salt concentrations and soil electrical conductivities, and these soils reduce yields by decreasing seed germination and slowing plant growth due to high osmotic forces. Sodic soils have high Na^+ concentrations which can result in soil dispersion, decreased water infiltration, and increased erosion.

The development of saline soils is growing problem and in the Northern Great Plains (NGP) high salinity and sodic concentrations impact productivity on over 10 million hectares of land. World-wide high salt concentrations impact growth on over 930 million hectares of land (Cook and Muller, 1997; Szabolcs, 1989). Historically, salinity and sodicity problems were most often observed on irrigated lands, whereas in the NGP salinity and sodicity problems are often observed in dryland agriculture (Cheeseman, 2015; Rengasamy, 2006).

To develop effective solutions, which may include reseeding to grasslands or installing tile drainage, the extent of the problem must be identified and the effectiveness of remediation measured assessed. Techniques for characterizing a soil's saline and sodic characteristics include measuring, pH, electrical conductivity, and ESP and/or SAR. High salt areas can be identified by conducting a visual survey of the area, conducting an apparent electrical

conductivity survey using a Geonics EM 38 (Geonics Inc., Mississauge, Ontario, Canada, 2016) or the Veris Soil EC Mapping System (Veris Technologies, Salina, Kansas, 2016), tracking changes in yield over multiple years, and collecting and analyzing soil samples for electrical conductivity (EC). Historically, saline management recommendations were based on the EC of a saturated paste extraction (ECe). Most commercial soil testing laboratories do not analyze EC from a saturated paste as part of their "normal" analysis (Owen, 2014). They generally determine the EC of a solution containing 10 mL (= 10 g) of water to 10 g of soil (1:1). The soil water extracted from a 1:1 extraction and saturated paste extraction produce different EC values.

Geospatial techniques coupled with remote sensing may overcome these barriers (Barnes *et al*., 2003). In the past, several methods have been used to identify and map salt-affected areas (Eldiery *et al*., 2005). However, spatial models that can easily determine the spatial variability of some selected attributes on salt affected soils were not investigated. Semivariograms are a graphical representation of the spatial variability in a given dataset (Cohen, 1994) and help to determining the spatial autocorrelation of spatial variables. (Lam, 1983). Comparing the different interpolation methods could also help to select the best way to map NDVI, yield, and other soil attributes.

The objectives of this study were to select appropriate models that can define or predict spatial variability of NDVI and yield and compare the efficiency of spatial interpolation methods.

3.2 Materials and Methods

The experiment was conducted in Pierpont in Day County, South Dakota (44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″W, representing Major Land Resource Area, MLRA, 55C), in April 2014. A yield interpolated map was plotted (Figure 3.1). The dominant soils in the study area were Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls (USDA-NRCS, 2016a; 2016b). Detailed soil and site characteristics of the study area are shown in Appendix II.
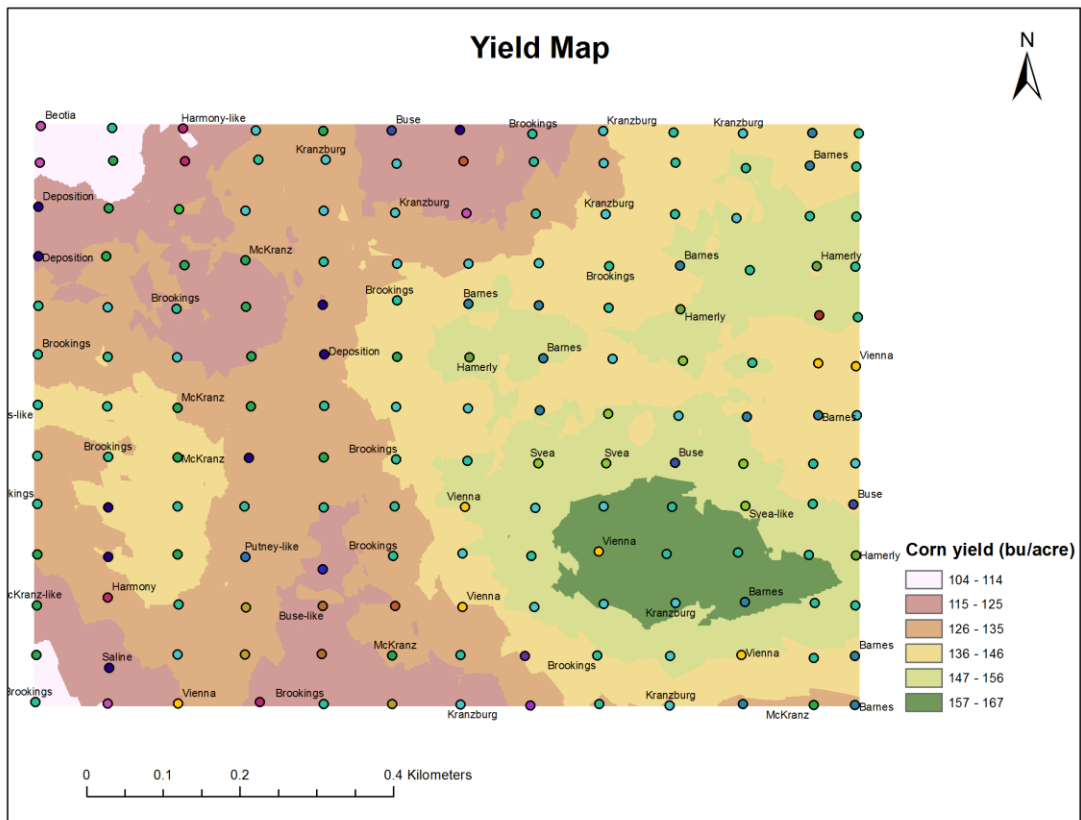
Figure 3.1 The study area plotted with 2014 corn (*Zea mays*) yield values from yield monitor at each data point

Coordinates: 44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls).

Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.

3.2.1   Data analysis

A total of 169 grid points (62 x 62 m) were laid out in the field. Multispectral Radiometer (MSR) readings was taken by holding the MSR 2 m above the surface and 1 m diameter data was collected at each grid point in corn (*Zea mays*) field in April 2014. The readings were taken between 10 am to 3 pm. Reflectance readings bands range from 485 to 1050 nm. Reflectance reading broad bands included: blue, 485 ± 2.1 nm; green, 560 ± 2.6 nm; red, 660 ±3.4 nm; NIR, 830 ± 4.3; and MIR, 1650 ± 5.5; and narrow bands included: 510 ± 2.3 nm; 566 ± 2.7 nm; 610 ± 3.0 nm; 661 ± 3.4; 710 ± 3.8 nm; 760 ± 4.0 nm; 810 ± 4.2; 840 ± 4.4 nm; 870 ± 4.5 nm; 905 ± 4.5 nm; and 1050 ± 4.9 nm.

The following equation was used to calculate percentage reflectance:

$$Reflectance\ \% = (\frac{Down\ sensor\ reading}{Up\ sensor\ reading})\ x\ 100 \tag{3.1}$$

The normalized difference vegetation indices (NDVI) were computed using the following equation:

$$NDVI = \frac{NIR\ -\ Red}{NIR\ +\ Red} \tag{3.2}$$

Grain yield was measured at the site by a combine equipped with a yield monitoring system and Global Positioning System (GPS). Standard protocols were followed to insure data accuracy. Yield data at each grid point was extracted from the yield monitor data using SMS™ Ag Leader* developed software (Ag Leader Inc., 2016).

*SMS™ is software that helps to make management decisions and is produced by Ag Leader. The use of a trade or commercial name is for educational purposes and does not imply endorsement of the product by the author, the Agronomy, Horticulture and Plant Science Department, or South Dakota State University.

Digital elevation map (DEM) of 30m x 30m was downloaded from United States Geological Survey (USGS, 2016). Landfire website and elevation points were extracted from DEM. (http://www.landfire.gov/NationalProductDescriptions7.php).

Semi-variances were calculated using Equation 3.3, where γ(h) is the semi-variance for lag distance h, N is the number of samples, A is the test value for sample i, X is the location of sample i. and $X_i + h$ represents the distance between two sample locations (Nielsen and Wendroth, 2003).

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [A_i(X_i) - A_i(X_i + h)]^2$$

(3.3)

The selected interpolation methods tested were: Trend Surface Analysis (TSA), Inverse Distance Weighting (IDW), Ordinary Kriging (OK), and Linear Regression (LR) using elevation as an independent variable. These interpolation models were tested to map NDVI and crop yield. Finally, interpolation accuracy was evaluated using Root Mean Square Error (RMSE) and correlation coefficient (Trangmar *et al.*, 1985).

The relationship between distance and the semi-variance values were determined using the spherical, exponential, and Gaussian models. Crop yield and NDVI maps were developed. Interpolation accuracy was evaluated using RMSE and correlation coefficient (r).

The RMSE was calculated:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(X_{obs,i} - X_{model,i})^2}{n}}$$
(3.4)

Where, X_{obs} is observed values and X_{model} is modelled values at time/place i.

$$(\text{Correlation Coefficient})\ r = \frac{\sum XY - n\overline{X}\overline{Y}}{\sqrt{\sum X^2 - n\overline{X}^2}\sqrt{\sum Y^2 - n\overline{Y}^2}}$$
(3.5)

3.3 Results and Discussion

The NDVI data was positively skewed with the Skewness and Kurtosis values of 0.25 and 2.28, respectively. Similarly, the yield data was positively skewed with the skewness and Kurtosis values of 2.82 and 120.2, respectively. The kurtosis for a normal distribution is 3.0. The NDVI kurtosis value indicates that there are fewer and less extreme outliers when compared to a normal distribution while for yield has more outliers and is more peaked than normal.

If the (nugget/sill)*100 is < 25% then the spatial distribution of the data has a strong relationship, while 26-75% is a moderate relationship, and > 75% is a weak spatial dependence. Whereas, 100% shows there is no spatial correlation (Di Virgilio *et al*., 2007). Accordingly, in our data the best spatial dependence of NDVI and crop yield was found by using the Exponential semivariogram models, when compared to Spherical and Gaussian due to the lower nugget to sill ratio criteria (See Figures 3.2a, 3.2b, and Tables 3.1, 3.2).
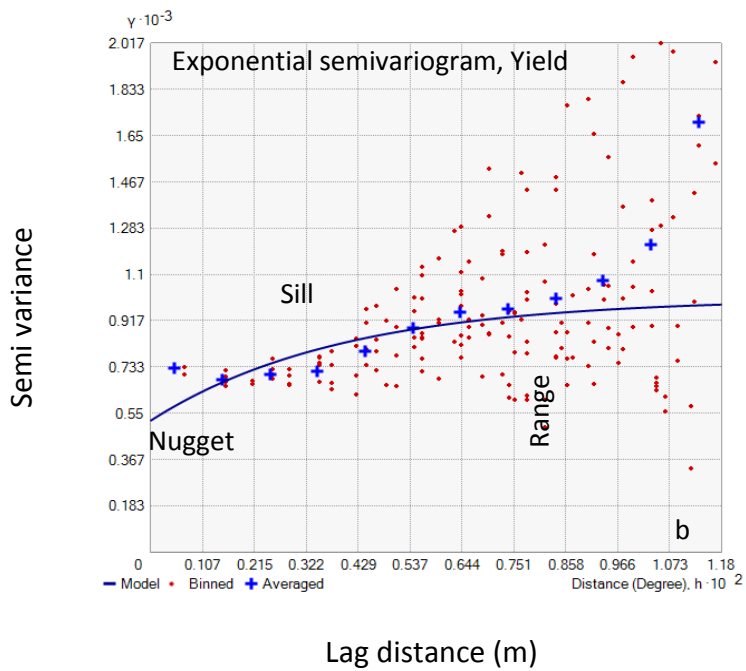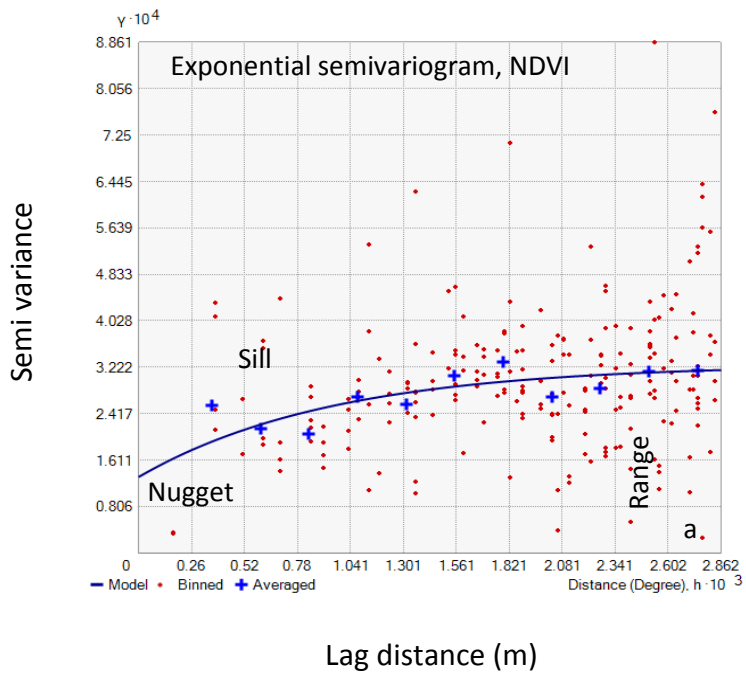
Figure 3.2 2014 Exponential semivariogram models fit for Normalized Difference Vegetation Index- NDVI (a) and corn (*Zea mays*) yield (b) at Pierpont.

Coordinates 44°55′30″ to 45°28′30″ N and 97°50′9″ to 98°28′34″ W. Dominant study site soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls [USDA-NRCS, 2016b].

Table 3.1 2014 Semivariogram models and parameters for models for Normalized Difference Vegetation Index (NDVI) at Pierpont, SD.

Parameters at Pierpont*	Semivariogram Model	Nugget (C_0)	Sill (C_0+C_1)	Nugget/Sill (%)	Range (m)
NDVI	Spherical	0.00404	0.0056	71.7	178
	Exponential	0.00125	0.0087	14.4	60
	Gaussian	0.00573	0.0040	142.1	101

*44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″W. (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls [USDA-NRCS, 2016b]).

C_0 = Nugget Semi-variance, C_1 = Partial sill semi-variance

Table 3.2 2014 Semivariogram models and parameters for models for corn (*Zea mays*) yield at Pierpont, SD.

Parameters at Pierpont*	Semivariogram Model	Nugget (C_0)	Sill (C_0+C_1)	Nugget/Sill (%)	Range (m)
Yield	Spherical	0.0241	0.025	95	105
	Exponential	0	0.051	0	33
	Gaussian	0.0088	0.040	22	34

*44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″W. (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls [USDA-NRCS, 2016b]).

C_0 = Nugget Semi-variance, C_1 = Partial sill semi-variance

Table 3.3 2014 Comparative analysis of interpolation methods and their correlation coefficient and Root Mean Square Error (RMSE) for Normalized Difference Vegetation Index (NDVI) at Pierpont, SD.

Element at Pierpont*	Interpolation Method	Correlation Coefficient	RMSE
	TSA: Linear TS	0.422	0.096
	TSA: Quadratic TS	0.429	0.096
	IDW: k = 1	0.463	0.099
NDVI	IDW: k = 2	0.478	0.094
	OK	0.544	0.089
	Linear Regression (LR)	0.460	0.094

TSA= Trend Surface Analysis, TS=Trend Surface IDW= Inverse Distance Weighting
OK= Ordinary Kriging, LR el IV= Linear regression using elevation as an independent variable
k= class of nearest neighbor
*44°55′30″ to 45°28′30″N and   97°50′9″ to 98°28′34″W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls [USDA-NRCS, 2016b]).

Spatial interpolation methods were tested for interpolating NDVI and crop yield, Tables 3.3 and 3.4, respectively. Ordinary Kriging was found to have relatively highest correlation coefficient (0.544) or R^2= 0.3 and lowest RMSE (0.089), respectively for NDVI and therefore was selected for interpolation. Whereas, Inverse Distance Weighting (IDW) with k = 2 was found to have relatively highest correlation coefficient (0.413) or R^2= 0.2 and lowest RMSE (0.223) for yield and therefore was selected for interpolation.

Table 3.4 Comparative analysis of interpolation methods and their correlation coefficient and Root Mean Square Error (RMSE) for 2014 corn (*Zea mays*) yield at Pierpont, SD.

Element at Pierpont*	Interpolation Method	Correlation Coefficient	RMSE
	TSA: Linear TS	0.262	0.235
	TSA: Quadratic TS	0.364	0.228
Yield	IDW: k = 1	0.368	0.233
	IDW: k = 2	0.413	0.223
	OK	0.396	0.235

TSA= Trend Surface Analysis, TS=Trend Surface, IDW= Inverse Distance Weighting, OK= Ordinary Kriging, k= class of nearest neighbor
*44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″N (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls [USDA-NRCS, 2016b]).

Figures 3.3, 3.4, and 3.5 demonstrate the interpolated surfaces of 2014 corn yield using different interpolation methods. The lower values of yield were obtained in areas where there were low NDVIs and that could be attributed to lower elevations, accumulation of salts, water logging, or a combination of one or more factors. Figures 3.6, 3.7, 3.8, and 3.9 shows the interpolated surfaces of NDVI using different interpolators. Previous research on yield variability on a small plots and large fields have shown similar result of variation of yield in time and space due to soil and other climatic factors (Bhatti *et al*., 1991; Di Virgilio *et al*., 2007; Vieira and Paz Gonzalez, 2003). Characterization of spatial heterogeneity of landscape vegetation cover from the modeling of the variogram of high spatial resolution NDVI data showed that land use is a major factor for variability (Garrigues *et al*., 2006). In our study differences in the NDVI values could be as result of differences in soil property (particularly, EC, and SAR) that ultimately resulted in differences in 2014 corn yield and NDVI values.

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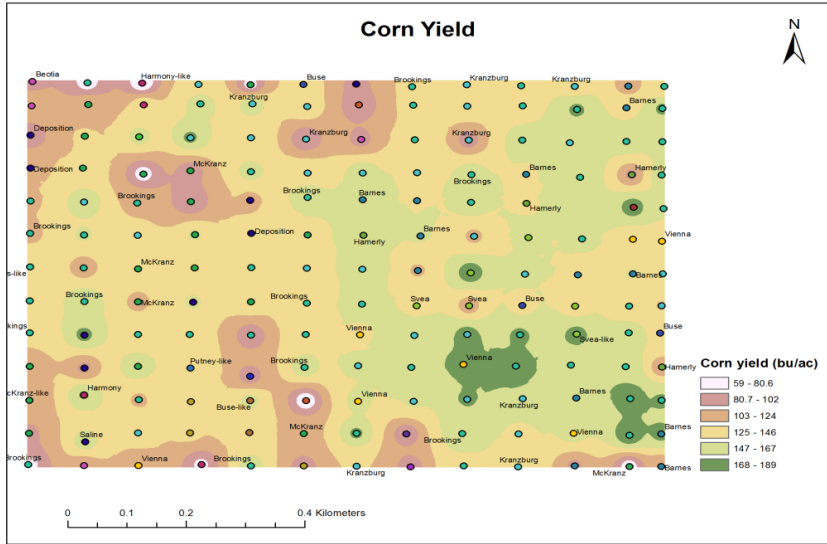
Figure 3.3 Corn (*Zea mays*) yield (2014) interpolated surface map of the study area (Pierpont, SD) using the Inverse Distance Weighting interpolation method.

Pierpont GPS: 44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls [USDA-NRCS, 2016b]).
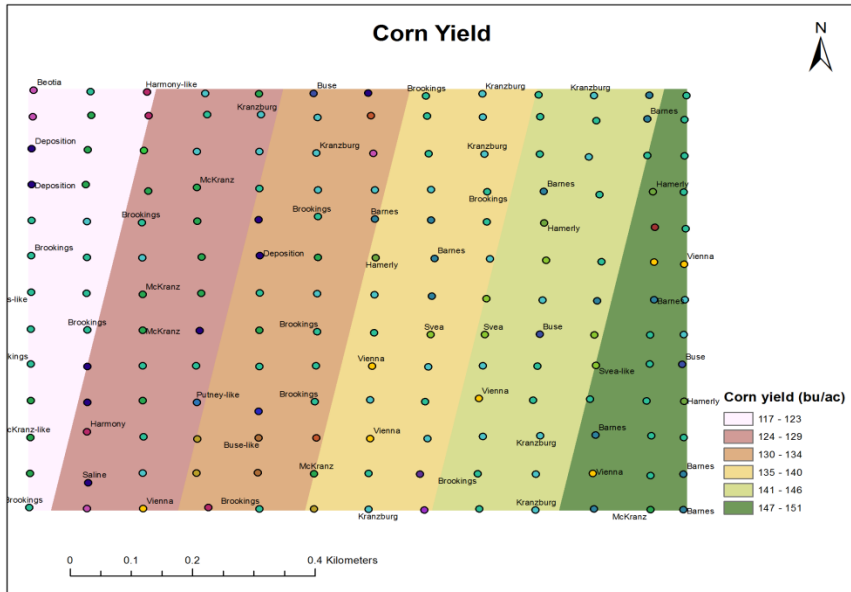
Figure 3.4 Corn (*Zea mays*) yield (2014) interpolated surface map of the study area (Pierpont, SD) using Trend Surface interpolation method.

Pierpont GPS:44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls [USDA-NRCS, 2016b]).
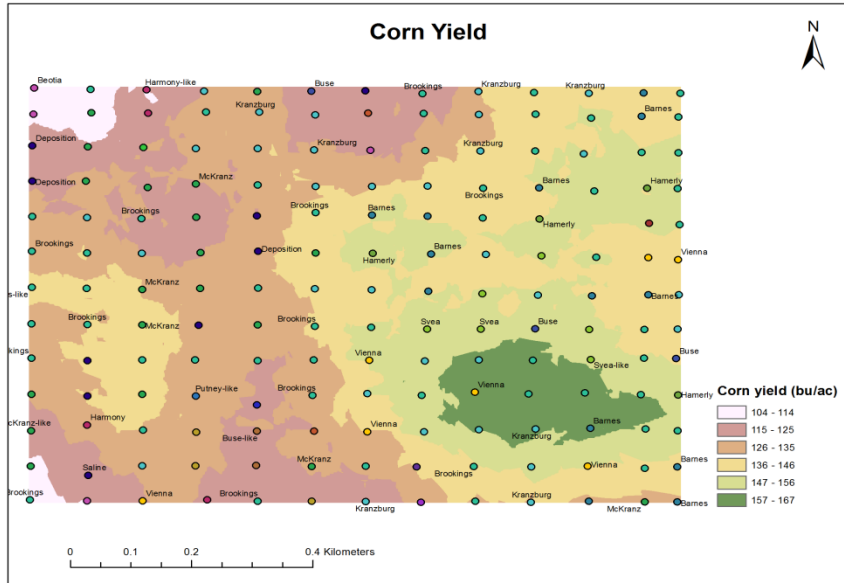
Figure 3.5 Corn (*Zea mays*) yield (2014) interpolated surface map of the study area (Pierpont, SD) using the Ordinary Kriging interpolation method.

Pierpont GPS:44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls [USDA-NRCS, 2016b]).
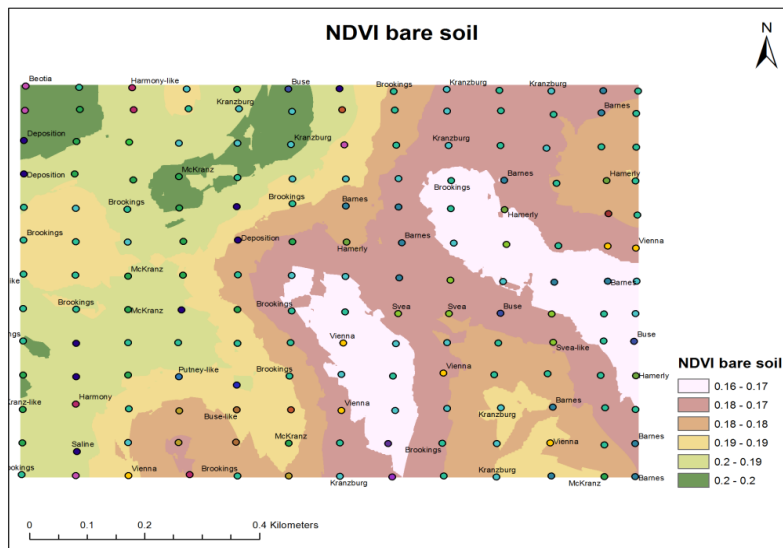
Figure 3.6 Normalized Difference Vegetation Index (NDVI bare soil) interpolated surface map (2014) of the study area (Pierpont, SD) using the Ordinary Kriging interpolation method.

Pierpont GPS:44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls [USDA-NRCS, 2016b]).

Figure 3.7 Normalized Difference Vegetation Index (NDVI V1) interpolated surface map (2014) of the study area (Pierpont, SD) using the Ordinary Kriging interpolation method.

Pierpont GPS:44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls [USDA-NRCS, 2016b]).

Figure 3.8 Normalized Difference Vegetation Index (NDVI V4) interpolated surface map (2014) of the study area (Pierpont, SD) using the Ordinary Kriging interpolation method.

Pierpont GPS:44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls [USDA-NRCS, 2016b]).

Figure 3.9 Normalized Difference Vegetation Index (NDVI V6) interpolated surface map (2014) of the study area (Pierpont, SD) using the Ordinary Kriging interpolation method.

Pierpont GPS:44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls [USDA-NRCS, 2016b]).

3.4 Conclusions

Geospatial models coupled with remote sensing methods, including MSR, were used to analyze and predict the spatial dependence of NDVI values and corn yield and gave insight about for spatial prediction of unknown spatial variables. However, detailed analysis of other soil attributes are needed to give a better understanding of spatial variability at different scales. In future studies, unmanned aircraft should be tested with their high resolution image capability. In addition, testing more and relevant interpolation methods and other geospatial approaches, including multivariable and spatial classification techniques, should be done to determine if they would be more helpful in understanding the relationship of the different attributes. The study of reflectance signatures at different crop growth stages as an indicator of plant stress and salt level could also be another area of future research.

3.5 Literature Cited

Ag Leader Inc. 2016. http://www.agleader.com/products/sms-software/ (accessed 04/09/2016).

Barnes, E. M., K. A. Sudduth, J. W. Hummel, S. M. Lesch, D. L. Corwin, C. Yang, C. S. Daughtry and W. C. Bausch. 2003: Remote-and ground-based sensor techniques to map soil properties. Photogrammetric Engineeringand Remote Sensing 69: 619-630.

Bhatti, A., D. Mulla and B. Frazier. 1991. Estimation of soil properties and wheat yields on complex eroded hills using geostatistics and thematic mapper images. Remote Sensing of Environment 37: 181-191.

Cheeseman, J. 2015. Food Security in the Face of Salinity, Drought, Climate Change, and Population Growth. Halophytes for Food Security in Dry Lands 3rd ed, M. A. Khan, M, Ozturk, B. Gul, and M. Z., Ahemed. Academic Press. p.111-120.

Cohen, W. B. 1994. GIS Applications Perspective: Current Research on Remote Sensing of Forest Structure. Forest Ecosystem Management at the Landscape Level: the Role of Remote-Sensing and Integrated GIS in Resource Management Planning, Analysis, and Decision Making. Sample, A (ed.).Remote sensing and GIS in ecosystem management, p 91-107. Island Press. Washington, D. C.

Cook, G. D. and W. J. Muller. 1997. Is exchangeable sodium content a better index of soil sodicity than exchangeable sodium percentage? A reassessment of published data. Soil Science 162: 343-349.

Di Virgilio, N., A. Monti, and G. Venturi. 2007. Spatial variability of switchgrass (Panicum virgatum L.) yield as related to soil parameters in a small field. Field Crops Research 101: 232-239.

Eldiery, A., L. A. Garcia and R. M. Reich. 2005. Estimating soil salinity from Remote Sensing data in corn fields. Hydrology Days 970: 31-42.

Garrigues, S., D. Allard, F. Baret and M. Weiss. 2006. Quantifying spatial heterogeneity at the landscape scale using variogram models. Remote Sensing of Environment 103: 81-96.

Geonics Inc. 2016. Ontario, Canada. http://www.geonics.com/ (accessed 5/27/216).

Halvorson, A. and J. Rhoades. 1976. Field mapping soil conductivity to delineate dryland saline seeps with four-electrode technique. Soil Science Society of America Journal 40: 571-575.

He, B., Y. Cai, W. Ran and H. Jiang. 2014. Spatial and seasonal variations of soil salinity following vegetation restoration in coastal saline land in eastern China. Catena 118: 147-153.

Lam, N. S.-N. 1983. Spatial interpolation methods: a review. The American Cartographer 10: 129-150.

Nielsen, D. R. and O. Wendroth. 2003. Spatial and Temporal Statistics: Sampling Field Soils and their Vegetation. Catena Verlag GMBH, Reiskirchen, Germany.

Owen R. K. 2014. Spatial Variability of Saline and Sodic Soils in the Black Glaciated Region of the Northern Great Plains, USA. MSc Thesis. Plant Science Department. South Dakota State University.

Qadir, M., J. Oster, S. Schubert, A. Noble, and K. Sahrawat. 2007. Phytoremediation of sodic and saline-sodic soils. Advances in Agronomy 96: 197-247.

Rengasamy, P. 2006. World salinization with emphasis on Australia. Journal of Experimental Botany 57: 1017-1023.

Szabolcs, I. 1989. Amelioration of soils in salt affected areas. Soil Technology 2: 331-344.

Trangmar, B. B., Yost, R. S., and Uehara, G. 1985. Application of geostatistics to spatial studies of soil properties. Advances in Agronomy 38: 45-94.

USDA-NRCS. 2016a. Major Land Resource Area Explorer. USDA-NRCS, http://apps.cei.psu.edu/mlra/ (accessed 04/07/2016).

USDA-NRCS. Soil Survey Division. 2016b. Web Soil Survey. USDA-NRCS, http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx (accessed 04/07/2016).

USGS. 2016. Land Fire. (http://www.landfire.gov/NationalProductDescriptions7.php). (accessed 3/11/216).

Veris Technologies. 2016. Salina, Kansas. http://www.veristech.com/ (accessed 5/27/216).

Vieira, S. R. and A. Paz Gonzalez. 2003. Analysis of the spatial variability of crop yield and soil properties in small agricultural plots. Bragantia 62: 127-138.

4. CHAPTER IV

WATER INFILTRATION AND SOIL DISPERSION AS AFFECTED BY

AMMENDEMENTS

Abstract

Soils with sodic properties significantly affect water infiltration by altering soil physical and chemical properties leading to runoff and loss of topsoil through erosion. Surface amendments (SA) and cropping systems (CS) are used to reduce the sodium level in the soil and improve soil physical properties. The objectives of this study were 1) compare different soil remediation strategies particularly the influence of SA (gypsum, calcium chloride, and elemental sulfur) and CS in a corn (*Zea mays*) soybean (*Glycine max*) rotation system on water infiltration by double-ring (ponded) and Cornell sprinkler infiltrometer, and 2) evaluate the effect of variable cation concentrations on the dispersion of bentonite clay and selected soil samples. A field study was conducted in three locations: White Lake (2013-2015), Redfield (2014-2015), and Pierpont (2014-2015) in Eastern South Dakota. Infiltration rates (IR) and runoff rates (ROT) were computed. A randomized complete block design with 4 replications was used. The treatments were: cover crop and surface amendments. The cover crop was a mixture of barley (*Hordeum vulgare* L.) and sugar beet (*Beta vulgaris*) seeded at the rate of 34 kg ha^{-1} and 4.5 kg ha^{-1}, respectively. There were significant differences among the chemical amendments in 2013 in White Lake and 2014 and 2015 in Redfield. Cover crop treatments significantly improved ponded infiltration at Pierpont in 2014. The infiltration rate and runoff rate measurements using Cornell infiltrometer showed no significant differences among treatments in all locations. The results of this study suggest that chemical amendments influenced double-ring water infiltration

more than the cover crop treatments in White Lake and Redfield, whereas, cover crop influenced infiltration more at Pierpont. Monitoring of the experiment in the long-term could be useful. Significantly higher turbidity was measured in NaCl solutions at different concentrations when compared with similar concentrations of $CaCl_2$ or $MgCl_2$ solutions. There was no significant difference in $CaCl_2$ and $MgCl_2$ solutions at variable concentrations. Therefore, effect of Mg^{2+} and Ca^{2+} solutions on clay dispersion demonstrates that the two ions have more flocculating effect than dispersion at the concentrations tested. Turbidity can be used as an indicator/measure of clay dispersion potential in salt-affected soils.

Keywords: Bentonite clay, Cornell sprinkler infiltrometer, dispersion, double-ring infiltration, flocculation, sodic properties, turbidity, saline, sodic, saline-sodic.

4.1 Introduction

Saline-sodic soil genesis is a major form of soil degradation resulting in the decline of agricultural productivity and environmental quality. Millions of hectares of these soils have formed worldwide. With improved management these soils could produce more food, fiber, and energy to feed the ever increasing world population (Qadir *et al*., 2007). In addition, above average precipitation and changes in land use and management in the last few decades coupled with extensive tile drainage installation have aggravated saline-sodic soil formation (Franzen, 2007).

Previous reports have identified factors that affect water infiltration into the soil including: soil structure, texture, pores (size, distribution, and orientation), slope, and organic matter content (Bronick and Lal, 2005; Tisdall and Oades, 1982); soil vegetative cover (Meek *et al*., 1992); antecedent water content and rainfall intensity (Radke and Berry, 1993); and water management (Agassi *et al*., 1986). Soils with sodic properties affect water infiltration into soil by altering soil physical properties (structure, porosity, and bulk density) that ultimately lead to increased runoff and loss of topsoil (Chi *et al*., 2012; Hulugalle *et al*., 2010; Rengasamy and Olsson, 1991). Clay-size fraction dispersion caused by high exchangeable Na^+ levels causes soil structural degradation and poor permeability (Amezketa, 1999; Sumner, 1993).

Water turbidity is a measure of water clarity and measured by nephelometric turbidity units (NTU) (Davies-Colley and Smith, 2001). Sediments from surface erosion are a major source of turbidity (Alexander *et al*., 1998; Lettenmaier *et al*., 1991; Wong *et al*., 2010). Sodic conditions can cause soil organic matter loss by increasing dispersion of aggregates and, increasing bulk density (Wong *et al*., 2010).

Reclamation of sodic soils using tillage has been found to be effective in improving water infiltration and reducing runoff (Hulugalle *et al*., 2010), however the interactive effect of different chemical amendments and cropping systems on Northern Great Plains (NGP) saline-sodic soils has not been tested. The objectives of this study were: to evaluate the effectiveness of surface chemical amendments and cover crops in improving water infiltration measured using the ponded infiltration method in saline-sodic soils; and to evaluate the effect of selected cation concentrations on the dispersion and flocculation of bentonite clay and selected NGP soils.

4.2 Materials and Methods

4.2.1   Sites description and experimental set up

A field study was conducted in three locations: White Lake (43°40′31″N, -98°45′50″W), Redfield (44°58′10″N, -98°27′52″W), and Pierpont (45°30′31″N, -97°53′50″W) in Eastern South Dakota. Sites were selected in 2013 and three years of field study (2013-2015) were conducted in White Lake and in Redfield and a two years were conducted in Pierpont. Prior to treatment application the surface soil salt level of the sites were determined (Table 4.1). The area is known to have a corn (*Zea mays*), sorghum (*Sorghum bicolor*), and soybean (*Glycine max*) crop rotation. Occasionally, spring wheat *(Triticum aestivum)* and oats (*Avena sativa*) are planted as part of a 3-year rotation with corn and soybeans.

The dominant soils at the Redfield, Spink County study site were Harmony-Aberdeen silty clay loams (0-2 % slopes), Winship-Tonka silt loams (0-1 % slopes), and Great Bend-Beotia silt loams (0-2 % slopes). Whereas, the dominant soils at the White Lake, Aurora County study site were Beadle-Dudley complex (0-3 % slopes), Delmont-Talmo complex (6-15 %

slope), Houdek and Ethan loams (2-6 % slopes) (USDA-NRCS, 2016a; 2016b). Kranzburg-Brookings silt loams and Nahon-Aberdeen-Exline silt loams with slopes of 2 to 6 and 0 to 2, respectively, were the two dominant soil series at the Pierpont (Day County) research site.

The study used a randomized complete block design with 4 replications. The treatments were soil surface amendments and cover crop (cover crop and non-cover crop). Barley (*Hordeum vulgare* L.) and sugar beet (*Beta vulgaris*) were seeded at the rate of 34 kg ha^{-1} and 4.5 kg ha^{-1}, respectively. Sugar beet and barely were mixed at their recommended rate and planted in 6 rows between the main crop (corn, soybean, and sorghum). The date of cover crop planting was based on the growth stage of the main crop and the soil conditions. For corn and sorghum the cover crop planting was done when the main crop growth stage was between V4 and V6. Whereas the cover crop planting in soybean field was conducted between V stage (unfolding of trifoliate leaves, the final number of trifoliate's depends on the soybean variety and the environmental conditions) and R1-beginning flowering - plants have at least one flower on any node (Clark, 2008; Fehr *et al*., 1971; Vaughan and Evanylo, 1998). Soil surface amendments application rates are summarized in Table 2.2.

4.2.2 Soil chemical analysis

Soil EC, pH, and soluble cation concentrations were determined from a saturated extract (Table 4.1). Electrical conductivity was determined using a conductivity probe (PC 2700, Oakton Instruments Vernon Hills, IL). Cation concentrations of Na^+, Ca^{2+}, and Mg^{2+} were measured using flame atomic adsorption spectrophotometry (200 A, Buck Scientific, Norwalk, CT) (Rhoades, 1982). Sodium adsorption ratio (SAR) was calculated using Equation 4.1.

$$SAR = \frac{[Na^+]}{\left(\frac{[Ca^{2+}] + [Mg^{2+}]}{2}\right)^{1/2}}$$ (4.1)

Table 4.1 Initial soil properties mean values by soil depth and location

Sites	Salt Composition	Electrical Conductivity (EC) (dS/m)			pH			Sodium Adsorption Ratio (SAR)		
		Depth (cm)								
		0-7.5	7.5-15	15-30	0-7.5	7.5-15	15-30	0-7.5	7.5-15	15-30
Redfield*	Saline	8.0	6.2	6.5	7.3	7.8	7.8	3.6	3.3	3.0
White Lake**	Saline-sodic	10.2	8.2	7.3	7.6	7.4	7.5	17.0	17.8	12.3
Pierpont***	Saline-sodic	20.0	19.0	18.0	7.9	7.5	7.5	19.0	23.0	16.0

*44°58′10″N, -98°27′52″W (Dominant soils: Hapludolls, Natrudolls, Argiudolls).
**43°40′31″N, -98°45′50″W (Dominant soils: Argiustolls, Natrustolls, Haplustolls, Calciustolls).
***45°30′31″N, -97°53′50″W (Dominant soils: Hapludolls, Natrudolls).
Source of soil information: USDA-NRCS, Soil Survey Division (2016b).
n= 4 (Redfield); n=5 (White Lake); n=5 (Pierpont).

4.2.3 Ponded infiltration measurements

Water infiltration was measured at 32 points at each research site location using a double-ring with a 12 cm radius inner ring water infiltrometer (Figure 1). *In situ* soil moisture measurements of the surface soil were measured with a moisture probe (Table 4.2). The ring was driven into the soil to a depth of 4 cm and the infiltration measurements were conducted for about 60 minutes (Reynolds and Elrick, 1990). Field water infiltration measurements were done 5 months after application of the treatments (October 2013) and each consecutive year after harvest (2013 to 2015). Additional field infiltration and runoff measurements were taken with a Cornell Sprinkle Infiltrometer after harvest in 2015 (Ogden *et al*., 1997). Cornell infiltration measurement showed different values compared to double-ring water infiltration measurement

due to surface structure breakdown, dispersion, and surface sealing due to water drops that occurred during field measurement.

Infiltration Rate (IR)

The infiltration rate (IR), reported in mm h^{-1}, was calculated as:

$$IR = \frac{\Delta Q}{A \ x \ \Delta t}$$

(4.1)

Where ΔQ is the volume of water collected during a given time period, Δt, and A is the cross-sectional area of the soil columns.

Figure 4.1 Infiltration measurement at White Lake, SD.

4.2.4   Bentonite clay and soil dispersion

A laboratory experiment was conducted to evaluate the effect of variable concentrations of selected cations (Ca^{2+}, Mg^{2+}, Na$^+$) on the dispersion and flocculation of bentonite clay and selected NGP soils. Bentonite clay soil material (10 g) was placed in a 250 mL Erlenmeyer flask and 200 mL of 0.1, 0.2, or 0.3 M CaCl$_2$, MgCl$_2$, or NaCl were added. The suspension was shaken for 1 hr and allowed to settle for 24 hours. A 50 mL subsample of the suspension was taken. The

level of suspended soil materials was determined by measuring absorbance at 650 nm using a colorimeter to measure turbidity.

A second part of experiment was conducted to evaluate the effect of variable cation Ca^{2+}, Mg^{2+}, Na^+) concentrations on the dispersion of selected NGP saline-sodic and normal (non-saline, non-sodic) soils. Soil samples were collected from four locations (Pierpont, Andover, and White Lake in 2014; and Brookings in 2016). Forty g of soil was placed in a 250 mL Erlenmeyer flask and a 200 mL of 0.1, 0.2, or 0.3 M $CaCl_2$, $MgCl_2$, or NaCl were added. The experiment was replicated 4 times. The suspension was shaken for 1 hr and allowed to settle for 24 hr and a 50 mL subsample of the suspension was taken. The level of suspended soil materials was determined by measuring absorbance at 650 nm using a colorimeter to measure turbidity.

4.2.5   Statistical analysis

Infiltration rates variability and turbidity differences were tested for analysis of variance (ANOVA) using SAS version, SAS Institute, Cary, NC (SAS, 2007). Statistical differences were declared significant at $\alpha = 0.05$ level.

4.3 Results and Discussion

4.3.1   Ponded Infiltration Measurements

Average precipitation and temperature of the research sites for the months of April to October and soil moisture content of the research plots are shown Table 4.2. Month by month precipitation and temperature is reported in chapter 2, Figures 2.1 to 2.5. The measured double-ring water infiltration rate was significantly different due to surface treatments in 2013 at White Lake, but treatments were not significantly different in consecutive years (2014 and 2015). The

sulfur treatment was significantly higher in 2013 when compared to the control and was numerically higher in 2014 and 2015. Cover crop did not significantly influence ponded water infiltration in all years at White Lake (Table 4.3).

Table 4.2 Mean annual precipitation, mean annual temperature, and % antecedent soil moisture at research sites.

Research Sites	Soil Moisture (%)	Average April to October Precipitation (mm)			Average April to October Temperature (^{0}C)		
		2013	2014	2015	2013	2014	2015
Redfield*	-	-	46	81	-	15	17
White Lake**	36.8	51	46	54	15	16	17
Pierpont***	29.5	66 (9 years average)			16 (9 years average)		

Source: South Dakota Climate and Weather, 2016
*44°58′10″N, -98°27′52″W (Dominant soils: Hapludolls, Natrudolls, Argiudolls).
**43°40′31″N, -98°45′50″W (Dominant soils: Argiustolls, Natrustolls, Haplustolls, Calciustolls).
***45°30′31″N, -97°53′50″W (Dominant soils: Hapludolls, Natrudolls).
Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.

Table 4.3 Saturated water infiltration rates (double-ring) of surface amended soils and cover crop treatments from 2013-2015 at White Lake, SD.

	Infiltration rate (mm h^{-1})					
Treatments at White Lake	2013	n	2014	n	2015	n
Surface Amendments (SA) †						
CaCl$_2$	236^{b†}	7	183^a	8	-	
No-treatment	182^b	3	92^a	8	119^a	8
Gypsum (CaSO$_4$·2H$_2$O)	130^b	6	135^a	8	-	
Sulfur (S)	535^a	6	137^a	4	149^a	8
Cropping System (CS) ††						
CC	302^a	12	129^a	14	127^a	8
NCC	337^a	10	145^a	14	141^a	8
ANOVA P>F						
SA	0.024		0.563		0.650	
CS	0.463		0.742		0.823	
SA*CS	0.776		0.805		0.250	

†Means with different letters within a column, treatment are significantly different at $P < 0.05$.
‡CC = cover crop (sugar beet and barley); NCC = non-cover crop.
**43°40′31″N, -98°45′50″W (Dominant soils: Argiustolls, Natrustolls, Haplustolls, Calciustolls).
Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.

The measured water infiltration rates for the treatments tested were significantly different at Redfield in 2014 at the 0.05 level. Both gypsum and sulfur significantly increased infiltration rates in 2014 with no significant difference in 2015 when compared to the control. Similar to White Lake (2013 and 2014) the cover crop treatments did not show a significant difference in Redfield plots (Table 4.4). Water infiltration measurements were also done at Pierpont in 2014 and 2015. There were no significant differences in both years for the chemical amendments. However, there was a significant difference for cover crop treatment in 2014 (Table 4.5). The results of the double-ring water infiltration study suggest that chemical amendments influenced water infiltration more than cover crop treatments in White Lake and Redfield. Whereas cover crop influenced ponded infiltration more in the Pierpont study site. Because soil and parent materials differ at the three locations more studies on different soils and parent materials are needed. The water infiltration variation could be attributed to soil differences among sites, changes in soil properties as a result of surface amendment application (mainly sulfur and gypsum), and cover crop. The influence of the treatments is site specific. The infiltration rate and runoff rate measurements using Cornell infiltrometer showed no significant difference among treatments (amendment and cover crop) in all locations (Table 4.6). The differences in results obtained from each study sites is attributed to the differences in soil properties, salinity levels, sodicity, parent materials, and precipitation. Similar results were found in previous findings on the effects of amendments and salt concentration on infiltration of sodic soils (Agassi *et al*., 1981; Robbins, 1986). However, research on the impact of cover crop in salt affected soil is very limited. The recorded values of double-ring water infiltration were much higher when compared to the Cornell infiltration due to soil dispersion (breakdown of soil structure) and surface sealing of soil pores when using Cornell infiltration process when compared to the seepage with the

double-ring water infiltration measurement (Ben-Hur *et al*., 1987; van Es, 2015). This could be part of the reason that higher infiltration rates were recorded in double-ring when compared to Cornell infiltration measurements.

Table 4.4 Saturated water infiltration rates (double-ring) of surface amended soils and cover crop treatments from 2014-2015 at Redfield, SD.

	Infiltration rate (mm h^{-1})			
Treatments at Redfield	2014	n	2015	n
Surface Amendments (SA)†				
CaCl$_2$	144[bc†]	7	-	
No-treatment	42[c]	7	213 [a]	6
Gypsum (CaSO$_4$·2H$_2$O)	362[ab]	8	-	
Sulfur (S)	535[a]	8	649 [a]	6
Cropping System (CS)††				
CC	230[a]	16	284[a]	6
NCC	311[a]	14	578[a]	6
ANOVA P>F				
SA	0.013		0.060	
CS	0.445		0.170	
SA*CS	0.861		0.232	

†Means with different letters within a column, treatment are significantly different at *P* < 0.05.
‡CC = cover crop [barley (*Hordeum vulgare* L.) and sugar beet (*Beta vulgaris*)]; NCC = non-cover crop.
*44°58′10″N, -98°27′52″W (Dominant soils: Hapludolls, Natrudolls, Argiudolls).
Source of soil information: USDA-NRCS, Soil Survey Division, 2016.

Table 4.5 Saturated water infiltration rates (double-ring) of surface amended soils and cover crop treatments from 2014-2015 at Pierpont, SD.

	Infiltration rate (mm h^{-1})			
Treatments at Pierpont	2014	n	2015	n
Surface Amendments (SA) †				
CaCl$_2$	223[a†]	7	-	
No-treatment	116[a]	7	236[a]	6
Gypsum (CaSO$_4$·2H$_2$O)	195[a]	8	-	
Sulfur (S)	163[a]	8	333[a]	6
Cropping System (CS) ††				
CC	247[a]	16	379[a]	6
NCC	101[b]	14	230[a]	6
ANOVA P>F				
SA	0.5243		0.4829	
CS	0.0114		0.3743	
SA*CS	0.3723		0.3579	

†Means with different letters within a column, treatment are significantly different at *P* < 0.05.
‡CC = cover crop [barley (*Hordeum vulgare* L.) and sugar beet (*Beta vulgaris*)]; NCC = non-cover crop.
***45°30′31″N, -97°53′50″W (Dominant soils: Hapludolls, Natrudolls).
Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.

Table 4.6 Comparison of infiltration rate and runoff rate (using Cornell sprinkle infiltrometer) two years after surface amendment and cover crop treatments.

Treatments	**White Lake			*Redfield			***Pierpont		
	Infiltration rate $mm\ h^{-1}$	Runoff rate $mm\ h^{-1}$	n	Infiltration rate $mm\ h^{-1}$	Runoff rate $mm\ h^{-1}$	n	Infiltration rate $mm\ h^{-1}$	Runoff rate $mm\ h^{-1}$	n
					2015				
Surface Amendments (SA) †									
No-treatment	5.3 [a†]	0.40 [a]	8	5.5 [a]	0.37 [a]	8	5.3 [a]	0.359 [a]	8
Sulfur (S)	5.3 [a]	0.45 [a]	8	5.7 [a]	0.32 [a]	8	5.4	0.340 [a]	8
Cropping System (CS) ‡									
CC	5.3 [a]	0.43 [a]	8	5.8 [a]	0.33 [a]	8	5.5 [a]	0.376 [a]	8
NCC	5.3 [a]	0.41 [a]	8	5.4 [a]	0.36 [a]	8	5.4 [a]	0.446 [a]	8
ANOVA P>F									
SA	0.337	0.337		0.383	0.408		0.474	0.474	
CS	0.688	0.688		0.173	0.630		0.597	0.597	
SA*CS	0.298	0.298		0.348	0.182		0.848	0.848	

†Means with different letters within a column, treatment are significantly different at $P < 0.05$.

‡CC, cover crop; NCC, non cover crop.

*44°58′10″N, -98°27′52″W (Dominant soils: Hapludolls, Natrudolls, Argiudolls);

**43°40′31″N, -98°45′50″W (Dominant soils: Argiustolls, Natrustolls, Haplustolls, Calciustolls);

***45°30′31″N, -97°53′50″W (Dominant soils: Hapludolls, Natrudolls), Soil Survey Division, 2016b.

4.3.2 Turbidity as a measure of dispersion

Table 4.7 Soil chemical properties of the tested soils.

Locations	EC (dS/m)	pH	SAR	soil type
White Lake*	13	7.6	17	Saline Sodic
Pierpont**	20	8.0	19	Saline Sodic
Andover***	18	7.7	8	Saline
Brookings***	3.9	7.8	-	None saline, none sodic
Bentonite	-	8.2	-	

*44°58′10″N, -98°27′52″W (Dominant soils: Hapludolls, Natrudolls, Argiudolls).
**43°40′31″N, -98°45′50″W (Dominant soils: Argiustolls, Natrustolls, Haplustolls, Calciustolls).
**45°30′31″N, -97°53′50″W (Dominant soils: Hapludolls, Natrudolls).
**** 44° 19' 7"N,-96° 46' 56"W (Dominant soil: Hapludolls).
Source of soil information: USDA-NRCS, Soil Survey Division (2016b).

Selected soil chemical properties of the tested soils and bentonite clay are presented in Table 4.7. Results of the lab study showed significant differences for the chemical treatments and the different salt concentrations for all selected soils and bentonite clay. There was significantly higher turbidity in NaCl solutions at different concentrations when compared to similar concentrations of $CaCl_2$ and $MgCl_2$ solutions (see Tables 4.8 and 4.9) for the saline, sodic and saline-sodic soils studied (except for 0.1 *M* on the White Lake soil). The turbidity measurements of $CaCl_2$ and $MgCl_2$ solutions at variable concentrations were not significantly different from each other (except for 0.3 *M* on the White Lake soil) and were less turbid than NaCl solutions (See Figure 4.2, Table 4.8, and Table 4.9). The highest turbidity was recorded in NaCl treated soil for saline, sodic and saline-sodic soils while the highest turbidity measurements in the bentonite clay and Brookings soils were with distilled water. This increased turbidity could be attributed to higher dissolved organic matter level in the Brookings soil and the fine clay particles of the bentonite clay. In previous studies, smaller particle sizes have contributed the higher turbidity reading (Cuker *et al.*, 1990; Cuker and Hudson Jr, 1992). In other studies similar results of dispersion of organic matter being increased with dispersion of clay was reported (Fitzpatrick *et al*., 1994; Naidu *et al.*, 1993).
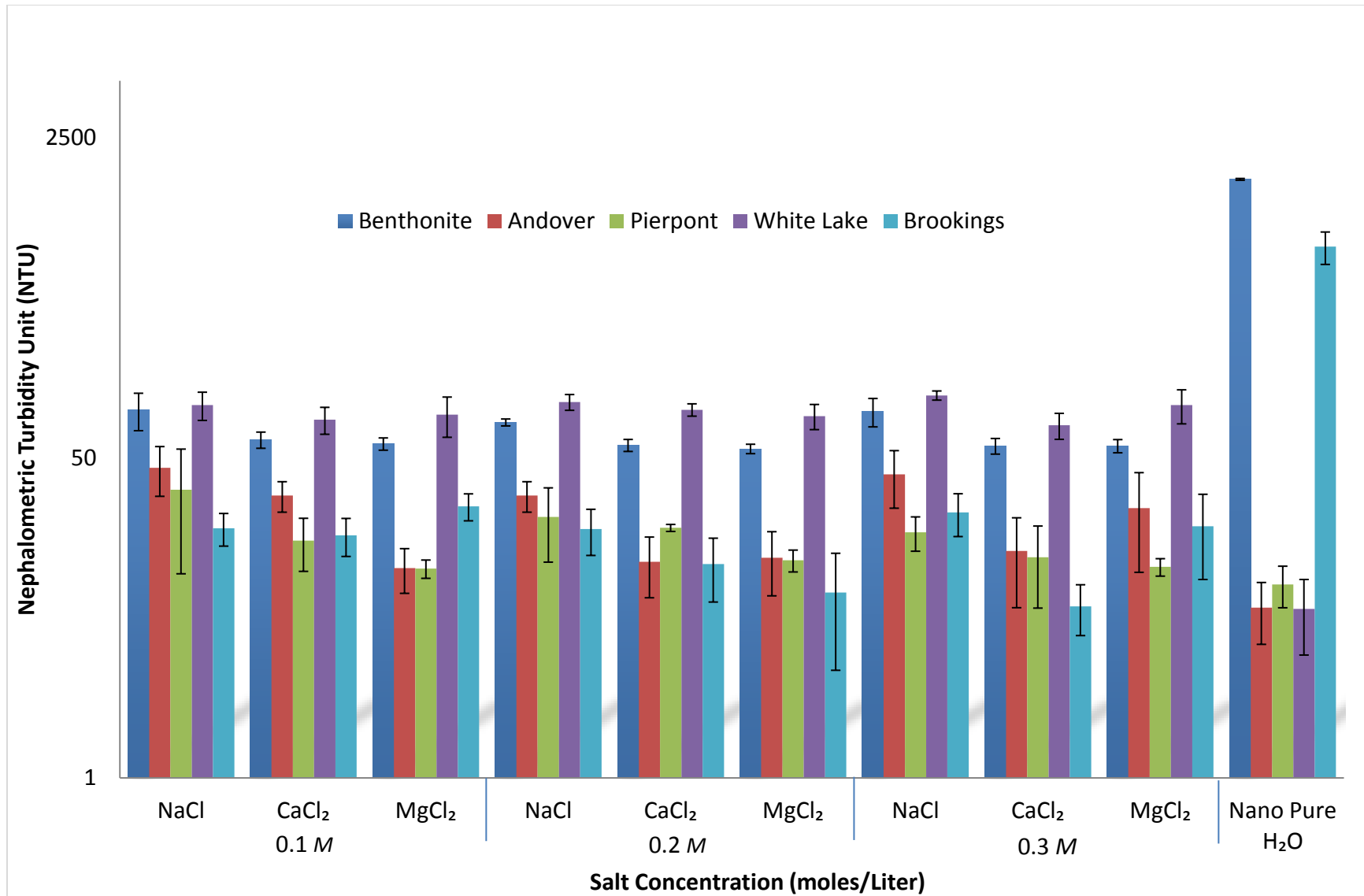
Figure 4. 2 Bentonite clay and selected soils turbidity measurement after treated with variable concentration of salts (Logarithmic scale of base 10).

Table 4.8 Effect of salt concentration on soil dispersion (turbidity as an indicator) of three different salt affected soils, a normal soil and bentonite clay.

	Soil Sampling Locations			n=12	
Treatments	**Andover (Saline)**	**Pierpont (Sodic)**	**White Lake (Saline-sodic)**	**Brookings (Normal)**	**Bentonite Clay**
Salts (S)	Turbidity in (NTU)	Turbidity in (NTU)	Turbidity in (NTU)	Turbidity in (NTU)	Turbidity in (NTU)
NaCl‡					
0.1 M	44.3 [a†]	23.3 [a]	95.0 [a]	21.0 [b]	89.8 [b]
0.2 M	31.5 [a]	24.3 [a]	98.5 [a]	20.8 [b]	77.0 [b]
0.3 M	40.8 [a]	20.3 [ab]	107.0 [a]	25.5 [b]	88.0 [b]
Distilled H_2O	7.5 [b]	10.5 [b]	7.8 [b]	659.3 [a]	1500 [a]
ANOVA P>F	0.001	0.040	<.0001	<.0001	<.0001
CaCl$_2$·2H$_2$O					
0.1 M	20.3 [a]	18.0 [a]	79.3 [ab]	19.3 [b]	62.3 [b]
0.2 M	14.0 [a]	21.0 [a]	90.0 [a]	13.5 [b]	58.3 [b]
0.3 M	18.5 [a]	15.0 [ab]	74.5 [b]	8.0 [b]	57.8 [b]
Distilled H_2O	7.5 [a]	10.5 [b]	7.8 [c]	659.3 [a]	1500 [a]
ANOVA P>F	0.312	0.047	<.0001	<.0001	<.0001
MgCl$_2$·6H$_2$O					
0.1 M	13.0 [b]	12.8 [a]	84.5 [a]	27.5 [b]	59.3 [b]
0.2 M	14.8 [ab]	14.3 [a]	83.3 [a]	9.5 [b]	55.8 [b]
0.3 M	27.0 [a]	13.0 [a]	95.0 [a]	21.5 [b]	58.8 [b]
Distilled H_2O	7.5 [b]	10.5 [a]	7.8 [b]	659.3 [a]	1500 [a]
ANOVA P>F	0.033	0.137	<.0001	<.0001	<.0001

†Means with different letters within a column, treatments are significantly different at $P < 0.05$.
‡S=Salt type; NaCl=sodium Chloride; CaCl$_2$·6H$_2$O= Calcium Chloride Hexahydrate;
MgCl$_2$·2H$_2$O= Magnesium Chloride Dehydrate;
C=Concentration in molarity; 0.1, 0.2, and 0.3 M
NTU=Nephelometric Turbidity Unit.

Table 4.9 Effect of salt type on soil dispersion (turbidity as an indicator) of three different salt affected soils, a normal soil and bentonite clay.

Treatments	Soil Sampling Locations			n=12	
	Andover (Saline)	Pierpont (Sodic)	White Lake (Saline-sodic)	Brookings (Normal)	Bentonite Clay
Salts Concentration	Turbidity in (NTU)	Turbidity in (NTU)	Turbidity in (NTU)	Turbidity in (NTU)	Turbidity in (NTU)
0.1 *M* ‡					
NaCl	44.3 ᵃ	23.3 ᵃ	95.0 ᵃ	21.0 ᵇ	89.8 ᵇ
CaCl₂·2H₂O	20.3 ᵇ	18.0 ᵃᵇ	79.3 ᵃ	19.3 ᵇ	62.3 ᶜ
MgCl₂·6H₂O	13.0 ᵇ	12..8 ᵇᶜ	84.5 ᵃ	27.5 ᵇ	59.3 ᶜ
Distilled H₂O	7.5 ᵇ	10.5 ᶜ	7.8 ᵇ	659.3 ᵃ	1500 ᵃ
ANOVA P>F	0.003	0.007	<.0001	<.0001	<.0001
0.2 *M* ‡					
NaCl	31.5 ᵃ	24.3 ᵃ	98.5 ᵃ	20.8 ᵇ	77.0 ᵇ
CaCl₂·2H₂O	14.0 ᵇ	21.0 ᵃᵇ	90.0 ᵃᵇ	13.5 ᵇ	58.3 ᶜ
MgCl₂·6H₂O	14.8 ᵇ	14.3 ᵇᶜ	83.3 ᵇ	9.5 ᵇ	55.8 ᶜ
Distilled H₂O	7.5 ᵇ	10.5 ᶜ	7.8 ᶜ	659.3 ᵃ	1500 ᵃ
ANOVA P>F	<.0001	0.015	<.0001	<.0001	<.0001
0.3 *M* ‡					
NaCl	40.8 ᵃ	20.3 ᵃ	107.0 ᵃ	25.5 ᵇ	88.0 ᵇ
CaCl₂·2H₂O	18.5 ᵇᶜ	15.0 ᵃᵇ	74.5 ᵇ	8.0 ᵇ	57.8 ᶜ
MgCl₂·6H₂O	27.0 ᵃᵇ	13.0 ᵇ	95.0 ᵃ	21.5 ᵇ	58.8 ᶜ
Distilled H₂O	7.5 ᶜ	10.5 ᵇ	7.8 ᶜ	659.3 ᵃ	1500 ᵃ
ANOVA P>F	0.007	0.049	<.0001	<.0001	<.0001

†Means with different letters within a column, treatments are significantly different at *P* < 0.05.

‡S=Salt type; NaCl=sodium Chloride; CaCl₂·6H₂O= Calcium Chloride Hexahydrate;

MgCl₂·2H₂O= Magnesium Chloride Dehydrate;

C=Concentration in molarity; 0.1, 0.2, and 0.3 *M*

NTU=Nephelometric Turbidity Unit.

4.4 Conclusions

Sulfur appeared to improve double-ring water infiltration in all years and locations (although values were not always statistically significant). However, significant differences among the chemical amendments were observed in year 2013 in White Lake and 2014 in Redfield. A cover crop treatment seems to have a positive effect at Pierpont soil in terms of improving double-ring water infiltration. The infiltration rate and runoff rate measurements using Cornell infiltrometer showed no significant differences among the treatments in all locations. The experiment needs to be monitored longer (5 years or more) as a permanent plot trial since soil physical property change often requires time to obtain the anticipated result.

The effect of Mg^{2+} and Ca^{2+} solutions on clay dispersion suggest that the two ions have more flocculating effect than dispersion for the concentrations studied on the soils tested. Na^+ had more dispersion effect (increased turbidity) as seen in many previous studies. However, additional experiments are needed to be conducted at higher ion concentrations on a wider variety of salinity and sodicity levels in various parent materials soils under field conditions. Turbidity can be used as an indicator of clay dispersion in salt affected soils.

4.5 Literature Cited

Agassi, M., I. Shainberg, and J. Morin. 1986. Effect of powdered phosphogypsum on the infiltration rate of sodic soils: Irrigation Science 7: 53-61.

Agassi, M., I. Shainberg, and J. Morin. 1981. Effect of electrolyte concentration and soil sodicity on infiltration rate and crust formation: Soil Science Society of America Journal 45: 848-851.

Alexander, R. B., J. R. Slack, A. S. Ludtke, K. K. Fitzgerald, and T. L. Schertz. 1998. Data from selected US Geological Survey national stream water quality monitoring networks: Water Resources Research 34: 2401-2405.

Amezketa, E. 1999. Soil aggregate stability: a review. Journal of Sustainable Agriculture, 14: 83-151.

Ben-Hur, M., Shainberg, I., and Morin, J. 1987. Variability of infiltration in a field with surface-sealed soil. Soil Science Society of America Journal 51: 1299-1302.

Bronick, C. J., and R. Lal. 2005. Soil structure and management: a review: Geoderma 124: 3-22.

Chi, C., C. Zhao, X. Sun, and Z. Wang. 2012. Reclamation of saline-sodic soil properties and improvement of rice (Oriza sativa L.) growth and yield using desulfurized gypsum in the west of Songnen Plain, northeast China. Geoderma 187: 24-30.

Clark, A. 2008. Managing cover crops profitably 3rd ed. Handbook Series Book 9. Sustainable Agriculture Network. Beltsville, MD.

Cuker, B. E., P. T. Gama, and J. M. Burkholder. 1990. Type of suspended clay influences lake productivity and phytoplankton community response to phosphorus loading. Limnology and Oceanography 35: 830-839.

Cuker, B. E., and L. Hudson Jr. 1992. Type of suspended clay influences zooplankton response to phosphorus loading: Limnology and Oceanography 37: 566-576.

Davies-Colley, R., and d. Smith. 2001. turbidity suspened sediment, and water clarity: A review. JAWRA Journal of the American Water Resources Association 37:1085–1101.

Fehr, W., Caviness, C., Burmood, D., Pennington, J. 1971. Stage of development descriptions for soybeans, Glycine max (L.) Merrill. Crop Science 11: 929-931.

Fitzpatrick, R. W., S. Boucher, R. Naidu, and E. Fritsch. 1994. Environmental consequences of soil sodicity. Soil Research 32: 1069-1093.

Franzen, D. 2007. Managing Saline Soils in North Dakota. NDSU Extension Service. https://www.ndsu.edu/soilhealth/wp-content/uploads/2013/03/Managing-saline-sodic-soils_2003.pdf (accessed 6/1/2016).

Hulugalle, N., T. Weaver, and L. Finlay. 2010. Soil water storage and drainage under cotton-based cropping systems in a furrow-irrigated Vertisol. Agricultural Water Management 97: 1703-1710.

Lettenmaier, D. P., E. R. Hooper, C. Wagoner, and K. B. Faris. 1991. Trends in stream quality in the continental United States, 1978–1987. Water Resources Research 27: 327-339.

Meek, B. D., E. Rechel, L. M. Carter, W. R. DeTar, and A. Urie. 1992. Infiltration rate of a sandy loam soil: effects of traffic, tillage, and plant roots. Soil Science Society of America Journal. 56: 908-913.

Naidu, R., D. Williamson, R. Fitzpatrick, and I. Hollingsworth. 1993. Effect of landuse on the composition of throughflow water immediately above clayey B horizons in the Warren Catchment, South Australia. Animal Production Science 33: 239-244.

Ogden, C., H. Van Es, and R. Schindelbeck. 1997. Miniature rain simulator for field measurement of soil infiltration. Soil Science Society of America Journal 61: 1041-1043.

Qadir, M., J. Oster, S. Schubert, A. Noble, and K. Sahrawat. 2007. Phytoremediation of sodic and saline-sodic soils. Advances in Agronomy 96: 197-247.

Radke, J., and E. Berry. 1993. Infiltration as a tool for detecting soil changes due to cropping, tillage, and grazing livestock. American Journal of Alternative Agriculture 8: 164-174.

Rengasamy, P., and K. Olsson. 1991. Sodicity and soil structure. Soil Research 29: 935-952.

Reynolds, W., and D. Elrick. 1990. Ponded infiltration from a single ring: I. Analysis of steady flow. Soil Science Society of America Journal. 54: 1233-1241.

Rhoades, J.1982. "Soluble salts." Methods of soil analysis. Part 2. Chemical and microbiological properties. ASA-SSSA. Madison. WI.

Robbins, C. 1986. Sodic calcareous soil reclamation as affected by different amendments and crops. Agronomy Journal 78: 916-920.

SAS. 2007. SAS user's guide: Statistics. SAS Inst., Cary, NC

South Dakota Climate and Weather. http://climate.sdstate.edu/climate_site/archive_data.htm (accessed 5/12/2016).

Sumner, M. E. 1993. Sodic soils-New perspectives. Soil Research 31: 683-750.

Tisdall, J., and J. M. Oades. 1982. Organic matter and water-stable aggregates in soils. Journal of Soil Science 33: 141-163.

USDA-NRCS. 2016a. Major Land Resource Area Explorer. USDA-NRCS,

http://apps.cei.psu.edu/mlra/ (accessed 04/07/2016).

USDA-NRCS. 2016b. Web Soil Survey. USDA-NRCS,

http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx (accessed 04/07/2016).

van Es., H. 2015. Field Procedures and Data Analysis for the Cornell Sprinkle Infiltrometer.

Department of Crop and Soil Science, Cornell University, Ithaca, NY.

Vaughan, J.D. and Evanylo, G.K. 1998. Corn response to cover crop species, spring desiccation

time, and residue management. Agronomy Journal 90: 536-544.

Wong, V. N., R. Greene, R. Dalal, and B. W. Murphy. 2010. Soil carbon dynamics in saline and

sodic soils: a review. Soil Use and Management 26: 2-11.

5. CHAPTER V

SPATIAL VARIABILITY ANALYSIS OF SELECTED SOIL ATTRIBUTES IN

SALINE-SODIC SOIL

Abstract

Soil spatial variability in the northern Great Plains of USA is related to natural (topographic, vegetation, time, parent material, and climate) and anthropogenic (management and landuse change) factors. The objective of this study was to describe the spatial variability of selected soil properties at a landscape scale and define spatial class. The study was conducted at Pierpont, SD with dominant soils of Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls. A total of 169 grid points (62 x 62 m grid) were laid out in the field in 2014. The field was planted with corn (*Zea mays*). Soil pH, electrical conductivity (EC) and sodium adsorption ratio (SAR) were analyzed. Mollic depth and lime depth were measured at each grid points. Semivariograms fit for exponential, spherical, and Gaussian models were tested. Spatial class was developed using nugget to sill ratio. Analysis of variance for soil attributes were made to test if there is variation due to differences in soil series. Global *Moran's I* and local *Moran's I* statistics were performed. The exponential model was the optimum fit for mollic depth, lime depth, pH, EC, and SAR with nugget to sill ratio of 0, 0, 45, 17, and 49, respectively. EC and SAR showed moderate spatial dependence whereas the other parameters showed strong spatial dependence. At the V1, V4, and V6 growth stages the exponential model was the optimum fit for NDVI with a value of nugget to sill ratio of 23, 0, and 25, respectively. At all plant growth stages the NDVI had showed strong spatial dependence. Analyses of variance of all the parameters measured were significantly different at $P < 0.05$.

Mollic depth, lime depth, and EC showed slight positive spatial autocorrelation with *Moran's* statistic value of 0.193, 0.106, and 0.337 and significantly small p-values at alpha 0.05. So the null hypothesis of random distribution was rejected for these variables. Whereas the Global Moran's I statistics value and the z-score of SAR was very small and p-value was insignificant. SAR showed random distribution. Patterns of local spatial autocorrelation were assessed from a generated map using Local *Moran's I*. Semivariogram modelling *and Moran's I* of soil attributes and NDVI data can help to quantify spatial heterogeneity in saline-sodic soils.

Key words: Semivariogram, clustering, dispersion, soil spatial variability, northern Great Plains, NDVI, saline-sodic soil, Argiudolls, Calciaquolls, Endoaquolls, Hapludolls, interpolation, Natrudolls, Calciudolls, mollic depth, lime depth, EC, SAR, and soil moisture.

5.1 Introduction

Soil properties distribution in a field or landscape are variable in terms of time and space (Corwin *et al*., 2003). In-depth understanding of the spatial and temporal distribution of these properties at all levels (field, landscape, or watershed) is useful to make sound management decisions in natural resource conservation and agriculture (Cambardella *et al*., 1994).

Several methods have been used to estimate spatial variability of soil physical and chemical properties (Cambardella *et al*., 1994; Goovaerts, 1998), soil apparent electrical conductivity (Corwin and Lesch, 2005), soil moisture (Vinnikov *et al*., 1996), infiltration (Sharma *et al*., 1980), and several other properties. Several attempts were also made to estimate variability at various scales (Cambardella *et al*., 1994; Nielsen *et al*., 1973).

Semivariogram models are used to characterize the spatial variability of soil attributes. (Goovaerts, 1998). Spatial dependence can be expressed as a percentage ratio of nugget semivariance to the sill semivariance with a value < 25 % (strong spatial dependence), 26-75 % (moderate spatial dependence), and > 75 % (weak spatial dependence) (Schlesinger *et al*., 1996). However, soil spatial variability studies in saline sodic soils of the Northern Great Plains have not been well studied in the past and there is very little information available as to the spatial variability of properties in saline-sodic soils.

Therefore, this study was conducted to describe the spatial variability of selected soil properties at a landscape scale and define spatial class for measured soil variables in selected Northern Great Plains (NGP) soils.

Objectives

i.   To assess the global and local spatial autocorrelation and variability of selected soil attributes

ii. Evaluate the differences in soil properties due to soil series.

5.2 Materials and Methods

A field measurement was conducted in Pierpont in Day County, South Dakota ($44°55′30″$ to $45°28′30″$N and $97°50′9″$ to $98°28′34″$W in April 2014. The dominant soils in the study area were Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls (USDA-NRCS, 2016a; 2016b).

A total of 169 grid points (62 x 62 m) were laid out in the field. Multispectral Radiometer (MSR) readings were taken by holding the MSR 2 m above the surface and 1 m diameter data was collected at each grid point in corn (*Zea mays*) field in April 2014. The readings were taken between 10 am to 3 pm.

Soil samples were taken from each grid point. Mollic depth, till depth (glacial till parent materials), and lime depth were measured at each grid point after sampling soil using soil sampling probe. Soil samples from 0-7.5 cm consisted of 10 subsamples collected with a 1.9 cm diameter soil probe. Each sample was dried at 40°C, ground, sieved (<2 mm), stored in plastic bags and analyzed for pH, electrical conductivity (EC), water soluble cations, sodium adsorption ratio (SAR) (Page, 1982).

Water soluble cation concentrations (Na^+, Ca^{2+}, and Mg^{2+}), EC, and pH and were determined from a saturated extract. One hundred and fifty grams of air-dry soil was weighed and mixed with distilled water until saturated. The mixture was covered and allowed to

equilibrate for 24 hours. After 24 hours, the soil solution was extracted using a Büchner funnel apparatus and vacuum. All extracts were stored at 4°C until they were analyzed for pH, EC, Ca, Mg, and Na (Rhoades, 1982). Sodium adsorption ratio (SAR) was calculated using the following equation.

$$SAR = \frac{[Na^+]}{\left(\frac{[Ca^{2+}] + [Mg^{2+}]}{2}\right)^{1/2}}$$

Data exploration was made to evaluate the normality of the data. Exponential, spherical, and gaussian semivariograms were fitted for the selected variables (see Appendix V and Figures 5.1 to 5.5). The details (nugget, sill, and range) of the models were determined.. Spatial class was developed for selected soil variables using the nugget to sill ratio as an indicator. Generally, semivariograms with higher range indicates spatial autocorrelation, whereas, higher sill values indicates more variation between neighbors samples.

The normalized difference vegetation indices (NDVI) were computed using the following equation:

$$NDVI = \frac{NIR - Red}{NIR + Red}$$

Semi-variances were calculated using equation below, where $\gamma(h)$ is the semi-variance for lag distance h, N is the number of samples, A is the test value for sample i, X is the location of sample i. and $X_i + h$ represents the distance between two sample locations (Nielsen and Wendroth, 2003).

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [A_i(X_i) - A_i(X_i + h)]^2$$

Analysis of variance (ANOVA) was performed for selected soil attributes (EC, SAR, lime depth, mollic depth, till depth and soil moisture) and NDVI was computed for the crop growth stage (V1, V4, and V6) of corn (Z*ea mays*). Spatial autocorrelation was tested for selected soil attributes using Global Moran's I statistics and clsutering and dispersion was detected using local local Moran's I statistics (Anselin, 1995). The test was applied for selected soil attributes including mollic depth, lime depth, electrical conductivity, and sodium adsorption ratio.

5.3 Results and Discussion

5.3.1   Correlation of soil properties

The soil properties selected at each grid point were correlated with each parameter. The raw correlation matrix is based on Appendix V, Table 3. A summary of the significant correlations from this matrix is given in Table 5.1.

Yield was positively correlated with elevation and lime depth content while negatively correlations were seen with salinity, sodicity and soil moisture properties. Elevation was positively correlated with yield and chlorophyll negatively correlated with salinity, sodicity, moisture level, mollic depth, redox depth and depth to till. This demonstrates how erosion and water interact on the landscape to affect yield and soil properties studied

Table 5.1 Summary of significant correlation relationship for selected soil properties.

Soil Property (n=169)	Significantly positively correlated*	Significantly negatively correlated*
Soil moisture E (SME)	SMV1, ECV1, EC, SAR, MD	Yld, Elev
Soil moisture V1 (SMV1)	EC V1, EC, SAR, MD, SME	Yld, Elev
EC V1 (EC V1)	EC, SAR, MD, RD, TD, SME,SMV1	Yld, Elev
Chlorophyll V4 (CV4)	Elev, pH	MD
Yield (Yld)	Elev, LD	EC, pH, SAR, SME, SMV1, ECV1
Elevation (Elev)	CV4, Yld	EC, SAR, MD, RD, TD, SME, SMV1, ECV1
EC 0-3 inch depth	SAR, MD, RD, SME, SMV1,ECV1	Yld, Elev
pH 0-3 inch depth	RD, CV4	LD, Yld
SAR 0-3 inch depth	MD, RD, SME, SMV1,ECV1, EC	Yld, Elev
Lime depth (LD)	MD, RD, TD, Yld	pH
Mollic depth	RD, TD, SME, SMV1, ECV1, EC, SAR, , LD	Elev, CV4
Redox depth (RD)	TD, ECV1, EC, pH, SAR, LD, MD	Elev
Till depth (TD)	ECV1, LD, RD, MD	Elev

Pierpont coordinate: (44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls). Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.

E= Emergence (crop), EC = electrical conductivity, SAR = sodium adsorption ratio, V1=one leaf with collar visible, V4= four leaves with collar visible

*significant at 0.05 alpha level.

5.3.2   Data Exploration

Detailed statistics of the data exploration are summarized in Table 5.2. All the measured soil data (mollic depth, lime depth, EC, and SAR) have showed a distribution of positive skewness. Whereas, all the calculated NDVI value were negatively skewed. The transformed data was not improved when compared to the raw data (original).

Table 5.2 Descriptive statistics showing data distribution for the variables measured at Pierpont.

Parameter	n	Min	Max	Mean	Std. Dev.	Skewness	Median	Pr>F
Mollic Depth	168	0.00	49.0	21	10.88	0.61	18.00	<.0001
Lime Depth	168	0.00	40.0	17	9.18	0.08	16.00	<.0001
EC	168	0.00	25.8	2.0	3.84	3.79	0.07	0.0140
SAR	168	0.00	21.3	1.5	2.67	3.74	0.58	0.0008
NDVI E	168	0.14	0.23	0.2	0.02	0.25	0.18	0.0012
NDVI V1	168	0.00	0.27	0.8	0.06	-2.35	0.19	0.1125
NDVI V4	168	0.00	0.31	0.1	0.11	-2.58	0.20	0.2553
NDVI V6	168	0.09	0.79	0.5	0.16	-0.81	0.55	0.0077

Pierpont coordinate: (44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls). Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.
E= Emergence (crop), EC = electrical conductivity, SAR = sodium adsorption ratio, NDVI=normalized difference vegetation indices, V1=one leaf with collar visible, V4= four leaves with collar visible, V6=six leaves with collar visible.

5.3.3 Semivariogram model fitting

Spatial variability of the different soil attributes measured is summarized in Table 5.3. Mollic depth had a strong spatial dependence and fitted well all the models tested (with the exponential model being the optimum fit with 0 nugget to sill ratio and RMS=10.15).

Similarly, the exponential model was the optimal fit for lime depth, pH, EC, and SAR with nugget to sill ratio of 0, 45, 17, and 49, respectively. EC and SAR showed moderate dependence whereas the other parameters showed strong spatial dependence. Spatial variability of the NDVI values are summarized in Table 5.4. The exponential model was the optimum fit for NDVI at V1, V4, and V6 stage with a value of nugget to sill ratio of 23, 0, and 25, respectively. At all stages the NDVI showed a strong spatial dependence. Similar results of spatial variability and model fitting were reported in earlier research (Burrough, 1983; Gessler *et al*., 1995; Goovaerts, 1998). Semivariogram fit for all other soil properties and NDVI values are presented in Appendix V (Figures 3 to 12).

Table 5.3 Variogram models for selected soil paameters.

Parameter	Model	Nugget	Sill	Range	Nugget/Sill Ratio	Root-Mean-Square	Spatial Class
Mollic depth	Exponential	0.0000	133.5	0.001	0	10.15	S
	Spherical	0.0000	121.0	0.001	0	10.03	S
	Gaussian	0.1228	122.9	0.001	0.1	10.06	S
Lime depth	Exponential	0.0000	91.7	0.001	0	9.64	S
	Spherical	4.0179	87.0	0.001	5	9.67	S
	Gaussian	34.3257	88.6	0.001	39	9.66	M
EC	Exponential	8.0082	17.9	0.010	45	3.54	M
	Spherical	9.1545	17.3	0.008	53	3.50	M
	Gaussian	10.5491	17.6	0.007	60	3.47	M
pH	Exponential	1.4332	8.4	0.001	17	2.87	S
	Spherical	6.0567	8.4	0.001	72	2.89	M
	Gaussian	6.4498	8.4	0.001	77	2.84	W
SAR	Exponential	4.1089	8.4	0.009	49	2.55	M
	Spherical	4.5440	8.0	0.007	57	2.53	M
	Gaussian	5.1224	8.1	0.006	63	2.50	M

Pierpont coordinate: (44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls). Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.
S= strong, M=moderate, W=weak, EC= electrical conductivity, SAR=sodium adsorption ratio.

Table5.4 Variogram models for NDVI at different crop growth stage.

Parameter	Model	Nugget	Sill	Range	Nugget/Sill Ratio	Root-Mean-Square	Spatial Class
NDVI V1	Exponential	0.0010	0.004	0.012	23	0.04	S
	Spherical	0.0014	0.004	0.012	33	0.04	M
	Gaussian	0.0016	0.005	0.012	30	0.04	M
NDVI V4	Exponential	0.0000	0.018	0.012	0	0.03	S
	Spherical	0.0000	0.022	0.012	0	0.03	S
	Gaussian	0.0015	0.031	0.012	5	0.04	S
NDVIV6	Exponential	0.0074	0.030	0.007	25	0.11	S
	Spherical	0.0116	0.029	0.007	40	0.12	M
	Gaussian	0.0141	0.029	0.005	49	0.12	M

Pierpont coordinate: (44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls). Source of soil information: USDA-NRCS, Soil Survey Division, 2016b. S= strong, M=moderate, W=weak NDVI=normalized difference vegetation indices, V1=one leaf with collar visible, V4= four leaves with collar visible, V6=six leaves with collar visible.

Table 5.5 Analysis of Variance for selected soil parameters as affected by soil series.

Soil Series†	Mollic Depth (inches)	n	Lime Depth (inches)	n	EC (dS/m)	n	SAR	n	Till depth(inches)	n	SM (%)	n
Brookings	26 ± 6.1bc	55	24 ± 6ab	55	3.0 ± 2.9b	37	2 ± 2.1b	37	36 ± 8.6abc	53	30 ± 4.7abc	29
McKranz	15 ± 10.5d	19	8 ± 5.7d	19	6.0 ± 7.0b	15	4 ± 4.0b	15	32 ± 11.4bcd	19	30 ± 3.6ab	18
Deposition	41 ± 3.9a	7	25 ± 4.4ab	4	4.0 ± 3.2b	5	3 ± 2.5b	5	43 ± 4.2abc	4	34 ± 3.9ab	7
Beotia	35 ± 7.5a	4	24 ± 23.3ab	2	5.0 ± 1.8b	2	3 ± 1.4b	2	42 ± 6.9abc	4	32 ± 2.4ab	4
Kranzburg	14 ± 2.3d	32	15 ± 3.2bcd	32	2 ± 3.5b	28	1 ± 2.0b	28	29 ± 6.0cd	32	28 ± 4.2abc	18
Harmony	42 ± 4.8a	4	25 ± 7.6ab	4	2.0 ± 0.8b	2	1 ± 0.6b	2	50 ± 5.5a	3	31 ± 1.3ab	4
Buse	9 ± 5.8d	5	6 ± 7.8de	5	2.0 ± 0.0b	1	1 ± 0.0b	1	19 ± 0.0de	1	30 ± 2.6abc	3
Vienna	10 ± 2.2d	7	14 ± 3.1bcd	7	1.0 ± 0.6b	5	1 ± 0.2b	5	16 ± 2.6e	7	28 ± 6.5abc	3
Barnes	11 ± 2.6d	13	13 ± 5.0cd	13	1.0 ± 0.8b	9	1 ± 0.6b	9	12 ± 0.0e	1	23 ± 2.6cd	4
Hamerly	13 ± 2.1d	4	0 ± 0.0e	4	1.0 ± 0.0b	1	1 ± 0.0b	1	nd	-	27 ± 0.0abc	1
Svea.like	29 ± 6.9abc	6	29 ± 6.9a	6	1.0 ± 0.1b	3	1 ± 0.3b	3	36 ± 0.0abcd	1	14 ± 0.0d	1
Aastad	18 ± 0bcd	1	18 ± 0.0bcd	1	0.4 ± 0.0b	1	1 ± 0.0b	1	nd	-	nd	-
Aberdeen	33 ± 0ab	1	21 ± 0.0abc	1	2 ± 0.0b	1	3 ± 0.0b	1	36 ± 0.0abcd	1	32 ± 0.0ab	1
Bearden	17 ± 3.1bcd	3	12 ± 3.8cd	3	1.0 ± 0.4b	3	2 ± 1.5b	3	45 ± 3.8	3	28 ± 1.1abc	3
Putney	42 ± 0a	1	15 ± 0.0bcd	1	nd		Nd	-	48 ± 0.0ab	1	30 ± 0.0abc	1
Nahon	42± 0a	1	16 ± 0.7bcd	2	3.0 ± 1.3b	2	3 ± 0.2b	2	48 ± 0.0ab	1	34 ± 2.0ab	2
Huffton	30 ± 0abc	1	13 ± 0.0bcd	1	1.0 ± 0.0b	1	1 ± 0.0b	1	42 ± 0.0abc	1	25 ± 0.0bcd	1
Heil	29 ± 0abc	1	21 ± 0.0abc	1	0.3 ± 0.0b	1	1 ± 0.0b	1	nd	-	37 ± 0.0a	1
Badger	32 ± 0ab	1	15 ± 0.0bcd	1	4.0 ± 0.0b	1	7 ± 0.0ab	1	nd	-	24 ± 0.0bcd	1
Saline	40 ± 5.7a	2	14 ± 8.5bcd	2	14 ± 16.5a	2	12 ± 13.6a	2	44 ± 0.0abc	1	36 ± 2.3a	2
ANOVA P>F	<.0001		<.0001		0.0314		0.0018		<.0001		0.0002	

†Means with different letters within a column, treatments are significantly different at *P* < 0.05.
Pierpont coordinate: (44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls). Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.
EC= electrical conductivity, SAR=sodium adsorption ratio, SM= soil moisture, dS/m= deciSiemens per meter, n=number of samples, nd= not determined

5.3.4 Analysis of variance and Moran's I statistics

Analysis of variance was performed to test if there is variation in soil series for selected soil attributes. Accordingly, all the parameters (mollic depth, lime depth, till depth, EC, SAR, and SM) measured were significantly different at $P < 0.05$. The selected soil properties are used in South Dakota to classify and organize soils into management groups. The thickest mollic depths were recorded for the following series, Beotia, Putney, Nahon, Harmony Deposition (unidentified), and saline (unidentified) soil series (see Table 5.5).

Svea soil series had the greatest lime depth whereas; the Hamerly series had lime at soil surface. Saline (unidentified) had the highest EC (14 dS/m). Aastad and Heil had the lowest EC value of 0.3 and 0.4 dS/m, respectively. Harmony had the highest till depth (50). Heil and Saline (unidentified) soil series had the highest moisture content (37 and 36%, respectively). Svea like soil series had the lowest (14%).

Moran's I statistics measure of the degree of spatial correlation present in a spatial data set. In *Moran's I* statistics, a value closer to one indicates presence of positive spatial autocorrelation. Any value close to zero indicates the absence of spatial auto correlation (Anselin, 1995). Results of the Global Moran's I test are presented in Table 5.6. Maps of the local Moran's I are shown in Figures 5.1 to 5.5. Mollic depth, lime depth, and EC showed slight positive spatial autocorrelation with Moran's statistic value of 0.193, 0.106, and 0.337, respectively, and significantly small p-values at alpha 0.05 (Table 5.6). So the null hypothesis of random distribution was rejected for these variables. Whereas the Moran's I statistics value and the z-score of SAR and pH were very small the p-values were insignificant and showed random distribution. Patterns of local spatial autocorrelation were assessed from a generated map using Local Moran's I.

Mollic depth shows a pattern of high-high and low-low correlation. That means areas of high mollic depth values are surrounded by areas of high mollic depth and vice versa (see Figure 5.1). Similar results were found for lime depth and EC (see Figures 5.2 and 5.3, respectively).

Table 5.6 Summary of spatial autocorrelation of selected soil attributes using Global Moran's I.

Variable	Moran's Index	Expected Index	Variance	z-score	p-value	Pattern
Mollic depth	0.193	-0.00595	0.0042	3.0637	0.0022	Clustered
Lime Depth	0.106	-0.00595	0.0042	1.7286	0.0839	Clustered
EC	0.337	-0.00595	0.0040	5.4154	0.0001	Clustered
SAR	0.088	-0.00595	0.0037	1.5390	0.1238	Random
pH	0.094	-0.00595	0.0041	1.5533	0.1203	Random

Pierpont coordinate: (44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls).
Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.
EC= electrical conductivity, SAR=sodium adsorption ratio.
A significance level of 0.05, a z score would have to be less than -1.96 or greater than 1.96 to be statistically significant. Global Moran's I evaluates whether the pattern expressed is clustered, dispersed, or random. When the Z score indicates statistical significance, a Moran's I value near $+1.0$ indicates clustering while a value near -1.0 indicates dispersion.
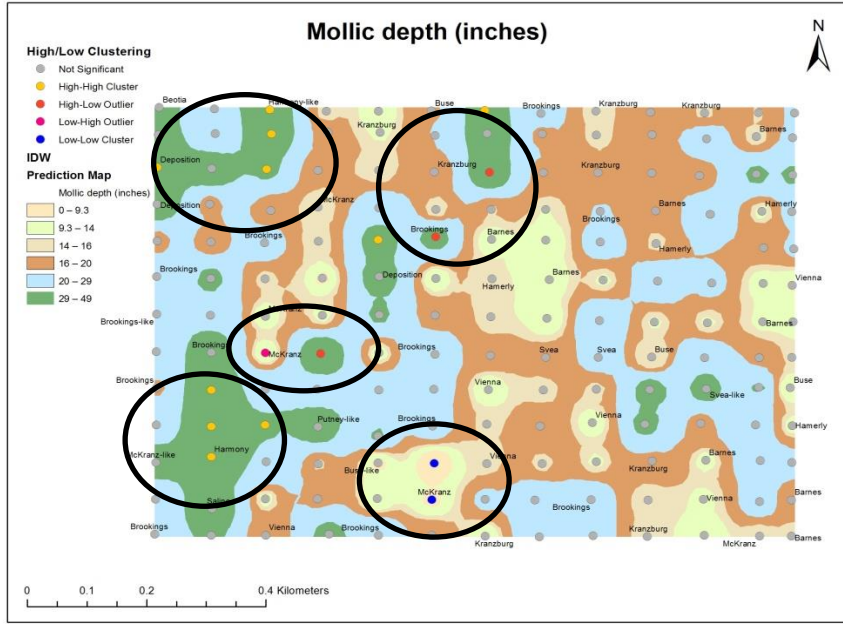
Figure 5.1 Interpolated map showing the clustering of mollic depth using local Moran's I test.

Pierpont, SD coordinates: (44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls). Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.
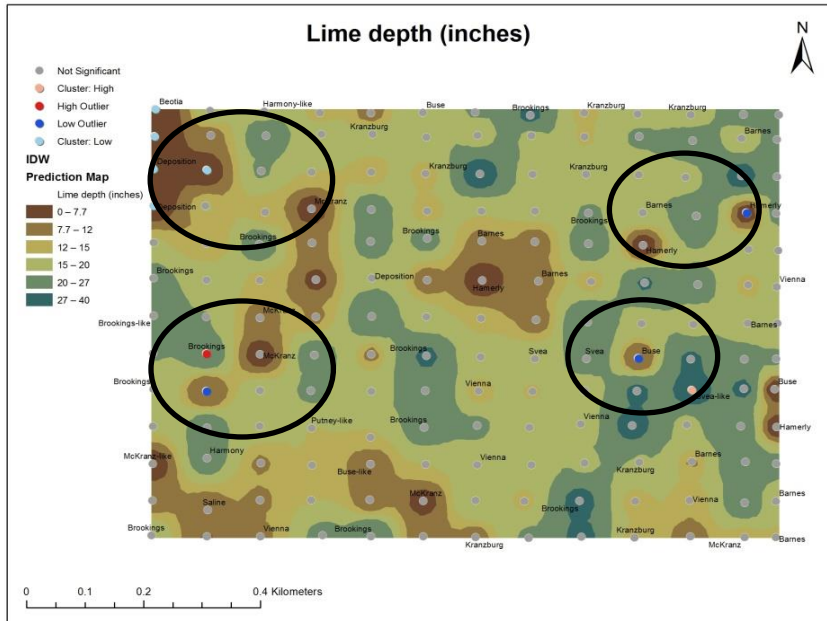

Figure 5.2 Interpolated map showing the clustering of lime depth using local Moran's I test.

Pierpont, SD coordinates: (44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls). Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.

Figure5.3 Interpolated map showing the clustering of EC using local Moran's I test.

Pierpont, SD coordinates: (44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls). Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.
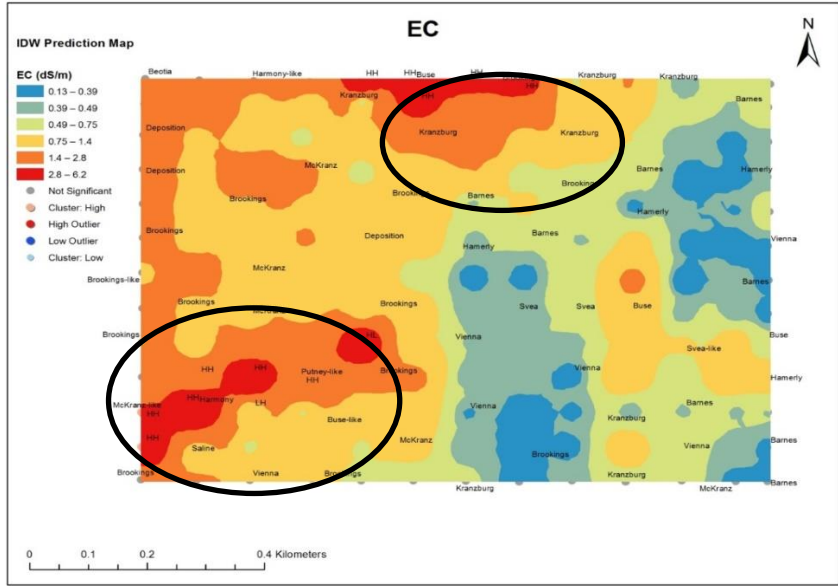

Figure 5.4 Interpolated map showing the clustering of SAR using local Moran's I test.

Pierpont, SD coordinates: (44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls). Source of soil information: USDA-NRCS, Soil Survey Division, 2016.
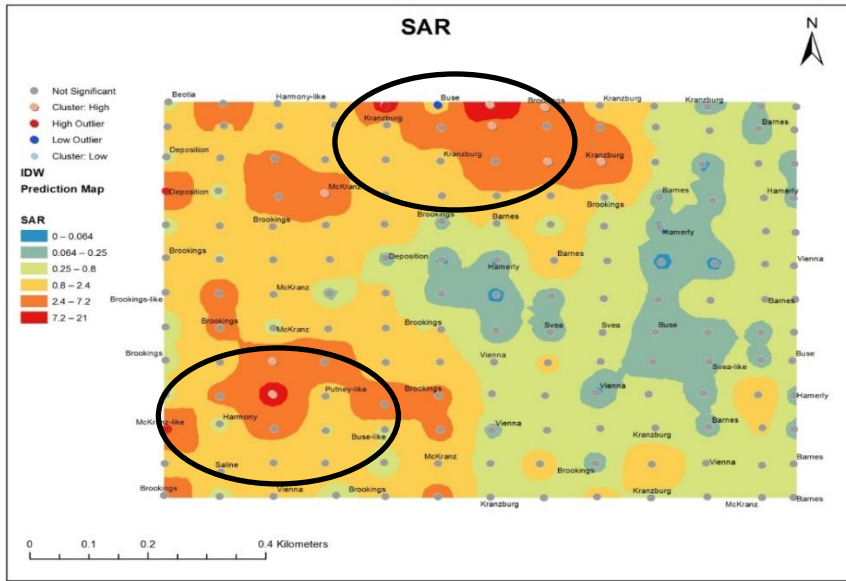
Figure 5.5 Interpolated map showing the clustering of pH using local Moran's I test.

Pierpont, SD coordinates: (44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls). Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.
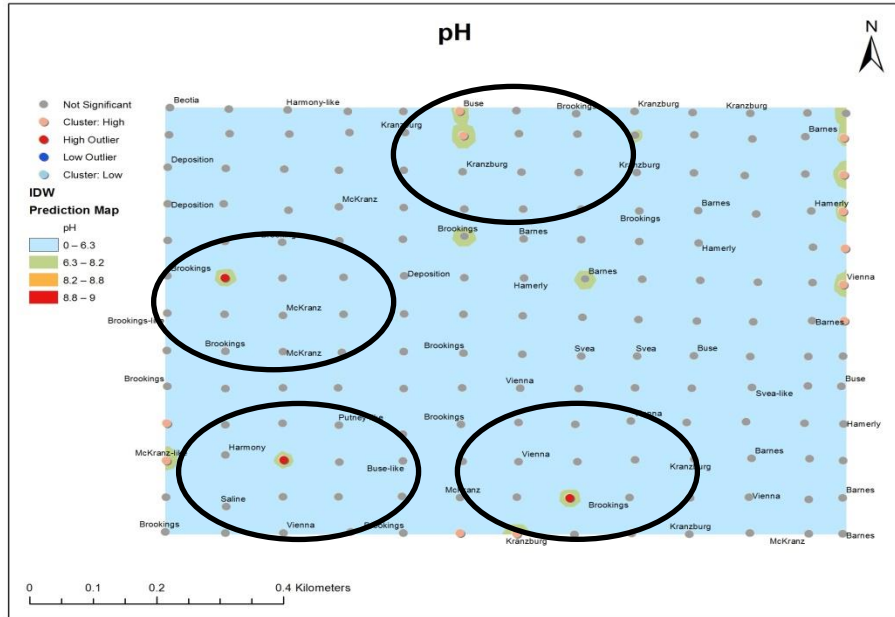
5.4 Conclusions

This study clearly showed using geospatial statistics particularly, local Moran's I, semivatiogram modelling of soil attributes, and NDVI data, could help to quantify spatial heterogeneity in saline-sodic soils. Thus, a better understanding of the spatial pattern of the measured soil variables in saline sodic soils can easily be captured. It also showed soil series variation for all the measured soil attributes and demonstrates the need to further explore and examine other soil attributes not covered in this study. Integrating high resolution imagery for NDVI and other indices could be an area of future research in saline-sodic soil.

5.5 Literature Cited

Anselin, L. 1995. Local indicators of spatial association—LISA. *Geographical analysis* **27**: 93-115.

Burrough, P. 1983. Multiscale sources of spatial variation in soil. II. A non-Brownian fractal model and its application in soil survey. J Soil Sci 34: 599-620.

Cambardella, C., T. Moorman, T. Parkin, D. Karlen, J. Novak, R. Turco and A. Konopka. 1994. Field-scale variability of soil properties in central Iowa soils. Soil Sci Soc Am J 58: 1501-1511.

Corwin, D., S. Kaffka, J. Hopmans, Y. Mori, J. Van Groenigen, C. Van Kessel, S. Lesch and J. Oster. 2003: Assessment and field-scale mapping of soil quality properties of a saline-sodic soil. Geoderma 114: 231-259.

Corwin, D. and S. Lesch. 2005. Characterizing soil spatial variability with apparent soil electrical conductivity: I. Survey protocols. Comput Electron Agr 46: 103-133.

Gessler, P.E., Moore, I., McKenzie, N., Ryan, P. 1995. Soil-landscape modelling and spatial prediction of soil attributes. International Journal of Geographical Information Systems 9: 421-432.

Goovaerts, P. 1998. Geostatistical tools for characterizing the spatial variability of microbiological and physico-chemical soil properties. Biol Fert Soils 27: 315-334.

Nielsen, D. R., J. W. Biggar, and K. T. Erh. 1973. Spatial variability of field-measured soil-water properties. University of California, Division of Agricultural Sciences.

Nielsen, D. R. and O. Wendroth. 2003. Spatial and Temporal Statistics: Sampling Field Soils and their Vegetation. Catena Verlag GMBH, Reiskirchen, Germany.

Page, A. L. 1982. Methods of soil analysis. Part 2. Chemical and microbiological properties, American Society of Agronomy, Soil Science Society of America.Madison, WI.

Rhoades, J. 1982. Cation exchange capacity: Methods of soil analysis. Part 2. Chemical and microbiological properties. ASA-SSSA. Madison. WI.

Schlesinger, W. H., Raikes, J. A., Hartley, A. E., and Cross, A. F. 1996. On the spatial pattern of soil nutrients in desert ecosystems. 77: 364-374.

Sharma, M., G. Gander and C. Hunt. 1980. Spatial variability of infiltration in a watershed. J Hydrol 45: 101-122.

Vinnikov, K. Y., A. Robock, N. A. Speranskaya and C. A. Schlosser. 1996. Scales of temporal and spatial variability of midlatitude soil moisture. Journal of Geophysical Research: Atmospheres 101: 7163-7174.

USDA-NRCS. 2016a. Major Land Resource Area Explorer. USDA-NRCS, http://apps.cei.psu.edu/mlra/ (accessed 04/07/2016).

USDA-NRCS. Soil Survry division. 2016b. Web Soil Survey. USDA-NRCS, http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx (accessed 04/07/2016).

APPENDICES

Appendix I: SAS and R codes

SAS Code for ANOVA
```
data one;
input CCT$ SA$ Rep VAR1;
cards;
;
Run;
proc glimmix;
class CCT SA Rep;
model VAR1 = CCT SA CCT*SA ;
random Rep;
lsmeans SA CCT*SA / diff;
lsmeans CCT / bylevel lines;
lsmeans SA/ bylevel lines;
run;
proc sort data=one out=one1;
by CCT;
run;
proc means data=one1 n mean std;
var VAR1;
by CCT;
run;
proc sort data=one out=one2;
by SA;
run;
proc means data=one2 n mean std;
var VAR1;
by SA;
run;
```

SAS codes used for ANOVA
```
Data;
Input TRT$    REP    NDVI;
Cards;
;
proc glm;
class TRT REP ;
model  NDVI  = TRT REP*TRT ;
test h=TRT e=REP*TRT;
means TRT/duncan alpha=0.01 e=REP*TRT;
PROC PRINT;
RUN;
```

R Code used for spatial analysis

Pierpont data - semivariograms and kriging
Before starting, we need to have both the gstat package loaded
load libraries
library(rgdal)
library(sp)
library(gstat)
library(lattice)
library(RColorBrewer)
library(raster)
#library(tiff)
install.packages (tiff)

setwd("C:/Users/Girma/Desktop/girma")
ppt <- read.csv("data.csv")

dem.grid <- readGDAL("dem2.tif")
names(dem.grid) <- "elevation"
image(dem.grid)

# Generate an empty grid for spatial interpolation
library(sp)
# Specify the min and max coordinates and cell size in the E-W direction
xcoords <- seq(586050, 586900, 10)
# Specify the min and max coordinates and cell size in the N-S direction
ycoords <- seq(5040000, 5040800, 10)
# Expand to all possible combinations of these coordinates
gridcoords.sp <- expand.grid(xcoords, ycoords)
# Use same coordinate names as in your point file
names(gridcoords.sp) <- c("x", "y")
# Make into a spatial points object
coordinates(gridcoords.sp) <- ~ x + y
Make gridded
gridded(gridcoords.sp) <- TRUE
# Look at the grid
plot(gridcoords.sp)
write.csv(gridcoords.sp, "datagrid.csv")

# Read in two datasets – the sample points and the prediction grid
# These are two gstat sample datasets – can be accessed by typing data(meuse)
# and data(meuse.grid). Here, we read them from text files as an example
data.sdf <- read.csv("data.csv")
data.grid <- read.csv("datagrid.csv")
data <- read.csv("data.csv")
class(data.sdf)
names(data.sdf)

```
# Make the data frame into a spatial data object for use with gstat
coordinates(data.sdf) <- c("x", "y")
class(data.sdf)
summary(data.sdf)

# We can access spatial locations directly with the coordinates() function
coordinates(data.sdf)[1:5,]

# Plot the spatial pattern of ACSA concentrations
bubble(data.sdf, zcol="E")

# Examine the distribution of E concentrations
attach(data.sdf@data)
hist(E)
qqnorm(E)
hist(sqrt(E))
qqnorm(sqrt(E))
hist(log(E))
qqnorm(log(E))

# Plot the semivariogram cloud
E.cl1 <- variogram(log(E) ~ 1, data=data.sdf, cloud=TRUE)
plot(E.cl1)

# Generate an empirical semivariogram for the sqrt of E concentrations
E.vgm <- variogram(log(E) ~ 1, data=data.sdf, width = 70, cutoff=350)
plot(E.vgm)
E.vgm

# Explicitly specify the width of the "bins"
E.vgm2 <- variogram(log(E) ~ 1, data=data.sdf, width = 70, cutoff=350)
plot(E.vgm2)
E.vgm2

# Explicitly specify width of bins and maximum lag distance
E.vgm3 <- variogram(log(E) ~ 1, data=data.sdf, width = 70, cutoff=350)
plot(E.vgm3)
E.vgm3

# Generate an anisotropic semivariogram with four direction classes
E.vgma <- variogram(log(E) ~ 1, data=data.sdf, alpha=c(0, 45, 90, 135))
plot(E.vgma)
E.vgma

# Fit a spherical semivariogram function
```

```
# Need to specify starting values for the fit
plot(E.vgm3)
E.fit <- fit.variogram(E.vgm3, model=vgm(psill=0.0005, model="Sph", range=350,
nugget=0.0001))
E.fit
plot(E.vgm3, E.fit)

# Fit an exponential semivariogram function
E.fit2 <- fit.variogram(E.vgm3, model=vgm(psill=0.0005, model="Exp", range=350,
nugget=0.0001))
E.fit2
plot(E.vgm3, E.fit2)

# Fit a Gaussian semivariogram function
E.fit3 <- fit.variogram(E.vgm3, model=vgm(psill=0.0005, model="Gau", range=350,
nugget=0.0001))
E.fit3
plot(E.vgm3, E.fit3)

# Examine the prediction grid
class(data.grid)
names(data.grid)
coordinates(data.grid) <- c("x", "y")
class(data.grid)
gridded(data.grid) = TRUE
class(data.grid)
summary(data.grid)

 # Fit first- and second-order trend surface models
# Specify trend-surface modeling using the degree argument
predict.tr1 <- krige(log(E) ~ 1, locations=data.sdf, newdata=data.grid, degree=1)
predict.tr2 <- krige(log(E) ~ 1, locations=data.sdf, newdata=data.grid, degree=2)

# Set blue-pink-yellow as default color ramp for trellis graphics (including spplot)
trellis.par.set(sp.theme())

# Generate maps of trend-surface predictions
spplot(predict.tr1, zcol="var1.pred")
spplot(predict.tr2, zcol="var1.pred")

# Cross-validate the trend surface models
crossval.tr1 <- krige.cv(log(E) ~ 1, locations=data.sdf, degree=1)
crossval.tr2 <- krige.cv(log(E) ~ 1, locations=data.sdf, degree=2)
# Mean absolute error
mean(crossval.tr1$residual)
mean(crossval.tr2$residual)
```

```r
# Root mean squared error
sqrt(mean(crossval.tr1$residual^2))
sqrt(mean(crossval.tr2$residual^2))
# Correlation between predicted/observed
cor(crossval.tr1$observed, crossval.tr1$var1.pred)
cor(crossval.tr2$observed, crossval.tr2$var1.pred)
# Visually assess predicted versus observed
plot(crossval.tr1$observed, crossval.tr1$var1.pred)
# add the 1:1 line
abline(0, 1, lty=2)
plot(crossval.tr2$observed, crossval.tr2$var1.pred)
abline(0, 1, lty=2)

# Generate inverse distance weighting prediction for k=1
# Call the idw function and specify the idp parameter
predict.idw1 <- idw(log(E) ~ 1, locations=data.sdf, newdata=data.grid, idp=1)
# Generate inverse distance weighting prediction for k=2
predict.idw2 <- idw(log(E) ~ 1, locations=data.sdf, newdata=data.grid, idp=2)

# Generate maps of inverse distance weighting predictions
spplot(predict.idw1, zcol="var1.pred")
spplot(predict.idw2, zcol="var1.pred")

# Assess prediction accuracy using cross-validation
# Supply idp as a list element to the set argument
crossval.idw1 <- krige.cv(log(E) ~ 1, set=list(idp=1), data.sdf)
crossval.idw2 <- krige.cv(log(E) ~ 1, set=list(idp=2), data.sdf)
cor(crossval.idw1$observed, crossval.idw1$var1.pred)
cor(crossval.idw2$observed, crossval.idw2$var1.pred)
sqrt(mean(crossval.idw1$residual^2))
sqrt(mean(crossval.idw2$residual^2))
plot(crossval.idw1$observed, crossval.idw1$var1.pred)
abline(0, 1, lty=2)
plot(crossval.idw2$observed, crossval.idw2$var1.pred)
abline(0, 1, lty=2)

# Ordinary kriging
# Include a fitted semivariogram as the model argument
E.krige <- krige(log(E) ~ 1, locations=data.sdf, newdata=data.grid, model=E.fit)
spplot(E.krige, zcol="var1.pred")
names(E.krige)
spplot(E.krige, zcol="var1.var")

crossval.krige <- krige.cv(log(E) ~ 1, locations=data.sdf, model=E.fit)
cor(crossval.krige$observed, crossval.krige$var1.pred)
sqrt(mean(crossval.krige$residual^2))
```

```
plot(crossval.krige$observed, crossval.krige$var1.pred)
abline(0, 1, lty=2)

# Linear regression using elevation as an independent variable
predict.iv <- krige(log(E) ~ elevation, locations=data.sdf, newdata=dem.grid)
spplot(predict.iv, zcol="var1.pred")
# Root mean squared error
sqrt(mean(crossval.iv$residual^2))
# Correlation between predicted/observed
cor(crossval.iv$observed, crossval.iv$var1.pred)

# Kriging with external drift using elevation as an independent variable
E.vgm2 <- variogram(log(E) ~ elevation, data=data.sdf)
E.fit2 <- fit.variogram(E.vgm, model=vgm(psill=0.0005, model="Sph", range=350,
nugget=0.0001))
predict.ed <- krige(log(E) ~ elevation, locations=data.sdf, newdata=dem.grid, model=E.fit2)
spplot(predict.ed, zcol="var1.pred")
crossval.ed <- krige.cv(log(E) ~ elevation, locations=data.sdf, model=E.fit2)
accuracy.ed <- accstats(crossval.ed$observed, crossval.ed$var1.pred, "ED")

# Kriging with external drift using elevation as an independent variable
E.vgm2 <- variogram(log(E) ~ elevation, data=data.sdf)
E.fit2 <- fit.variogram(E.vgm, model=vgm(psill=0.0005, model="Sph", range=350,
nugget=0.0001))
predict.ed <- krige(log(E) ~ elevation, locations=data.sdf, newdata=dem.grid, model=E.fit2)
spplot(predict.ed, zcol="var1.pred")
crossval.ed <- krige.cv(log(E) ~ elevation, locations=data.sdf, model=E.fit2)
accuracy.ed <- accstats(crossval.ed$observed, crossval.ed$var1.pred, "ED")
```

```
#Extract eleveation points from DEM
file<- list.files("C:\\Users\\Girma\\Desktop\\girma", "*.tif")
a<-raster(file[1])
plot(a)
elevation<-extract(a, data.sdf)
elevation

cbind(data.sdf@data,elevation)
projection(data.sdf) <- "+proj=utm +zone=14 +datum=WGS84 +units=m +no_defs
+ellps=WGS84 +towgs84=0,0,0"
proj4string(data.sdf)<-"+proj=utm +zone=14 +datum=WGS84 +units=m +no_defs
+ellps=WGS84 +towgs84=0,0,0"
```

```
install.packages("plotKML")
library(plotKML)
plotKML(data.sdf["yield"])
```

Appendix II: Soils of the study sites

Table 1 Soil of the research site with area of coverage.

| Study Site	Dominant soils	Soil Classification	US Soil Mapping units containing named soil (ac)
Redfield*, SD	Harmony	Fine, smectitic, frigid Pachic Argiudolls	1,189,440
	Aberdeen	Fine, smectitic, frigid Glossic Argiudolls	2,062,270
	Winship	Fine-silty, mixed, superactive, frigid Pachic Argiudolls	202,190
	Tonka	Fine, smectitic, frigid Argiaquic Argiudolls	13,902,240
	Bend	Fine-silty, mixed, superactive, mesic Typic Haplustolls	44,600
	Beotia	Fine-silty, mixed, superactive, frigid Pachic Hapludolls	1,448,060
White Lake** SD	Beadle	Fine, smectitic, mesic Typic Argiustolls	1,869,900
	Dudley	Fine, smectitic, mesic Typic Natrustolls	2,754,850
	Delmont	Fine-loamy over sandy or sandy-skeletal, mixed, superactive, mesic Typic Haplustolls	1,029,770
	Talmo	Sand skeletal, mixed, mesic, udorthentic Hapludolls	472,420
	Houdek	Fine-loamy, mixed, superactive, mesic Typic Argiustolls	6,9483,40
	Ethan	Fine-loamy, mixed, superactive, mesic Typic Calciustolls	5,517,300
Pierpont*** SD	Kranzburg	Fine-silty, mixed, superactive, frigid Calcic Hapludolls	2,665,320
	Brookings	Fine-silty, mixed, superactive, frigid Pachic Hapludolls	1,752,790
	Nahon	Fine, smectitic, frigid Calcic Natrudolls	1,000,250
	Aberdeen	Fine, smectitic, frigid Glossic Natrudolls	2,062,270
	Exline	Fine, smectitic, frigid Leptic Natrudolls	1,095,090
Brookings****SD	Brookings	Fine-silty, mixed, superactive,frigid Calcic Hapludolls	1752790
	Vienna	Fine-loamy, mixed, superactive,frigid Calcic Hapludolls	1721590

*44°58′10″N, -98°27′52″W, **43°40′31″N, -98°45′50″W, ***45°30′31″N, -97°53′50″W, **** 44° 19' 7"N,-96° 46' 56"W

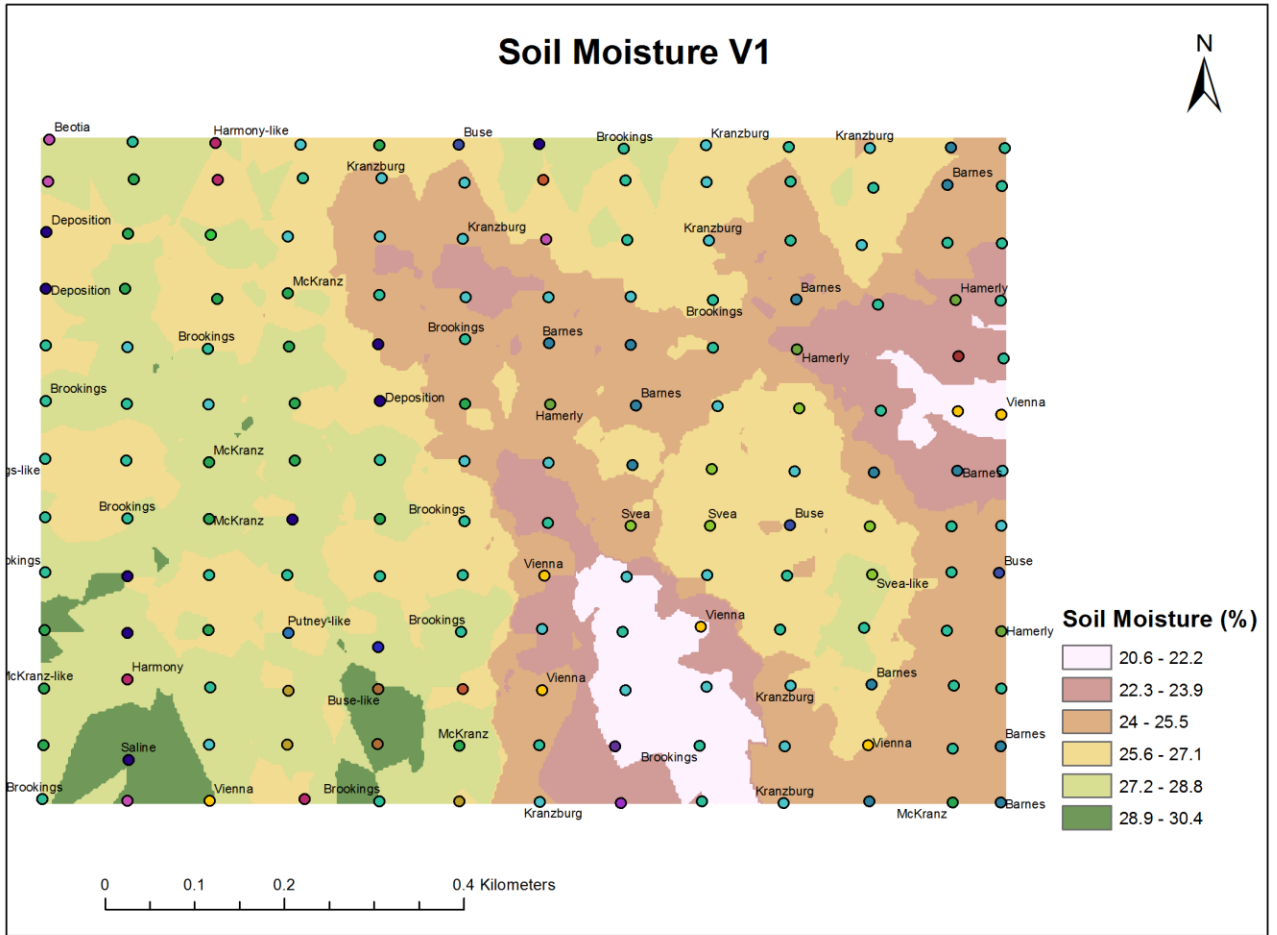Source of soil information: USDA-NRCS, Soil Survey Division (2016b).

Appendix III: Interpolated maps of selected soil attributes using different interpolation methods.

Figure 1 Interpolated electrical conductivity (EC) measured at V1 (first leaf) stage of corn (*Zea mays*) overlaid on soil series at Pierpont , SD saline sodic soils
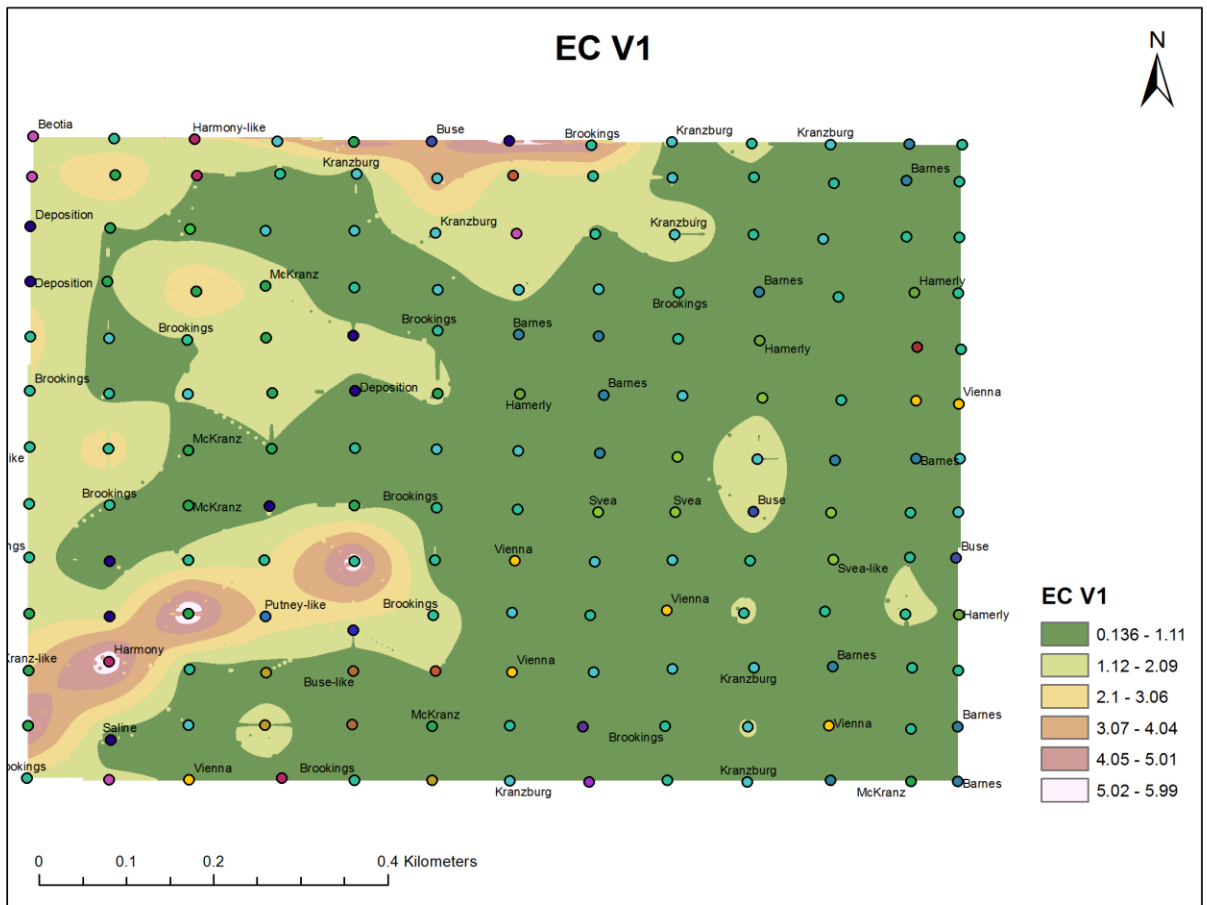
Pierpont, SD coordinates: (44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls).
Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.

Figure 2 Interpolated soil moisture measured at V1 (first leaf) stage of corn (*Zea mays*) overlaid on soil series at Pierpont , SD saline sodic soils

Pierpont, SD coordinates: (44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls). Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.

Appendix IV: ANOVA tables

Table 2 ANOVA summary of soil attributes and NDVI values, soil series as independent variable at Pierpont.

NDVI E	0.0012**	156
NDVI V1	0.1125	142
NDVI V4	0.2553	88
NDVI V6	<.0001***	156
Soil Moisture E	0.0055**	91
Soil Moisture V1	0.2353	155
Soil Moisture V4	0.1262	156
Soil Moisture V6	0.4364	156
EC V1	<.0001***	156
EC V4	0.0012**	156
EC V6	<.0001***	156
Chlorophyll V4	0.5424	139
Chlorophyll V6	0.0077**	156
EC 0-3	0.0140*	112
pH 0-3	0.6894	24
SAR 0-3	0.0008***	112
Lime depth	<.0001***	154
Mollic depth	<.0001***	155
Redox depth	<.0001***	79
Till depth	<.0001***	125
Yield	<.0001***	156

Pierpont coordinate**:** 45°30′31″N, -97°53′50″W (Dominant soils: Hapludolls, Natrudolls).
Source of soil information: USDA-NRCS, Soil Survey Division (2016b).
NDVI= Normalized Difference Vegetation Index, E=emergence, V1= first leaf, V4=four leaves, V6=six leaves, EC= electrical conductivity, SAR=sodium adsorption ratio.
*Significant at $P < 0.05$.
** Significant at $P < 0.01$.
*** Significant at $P < 0.001$.
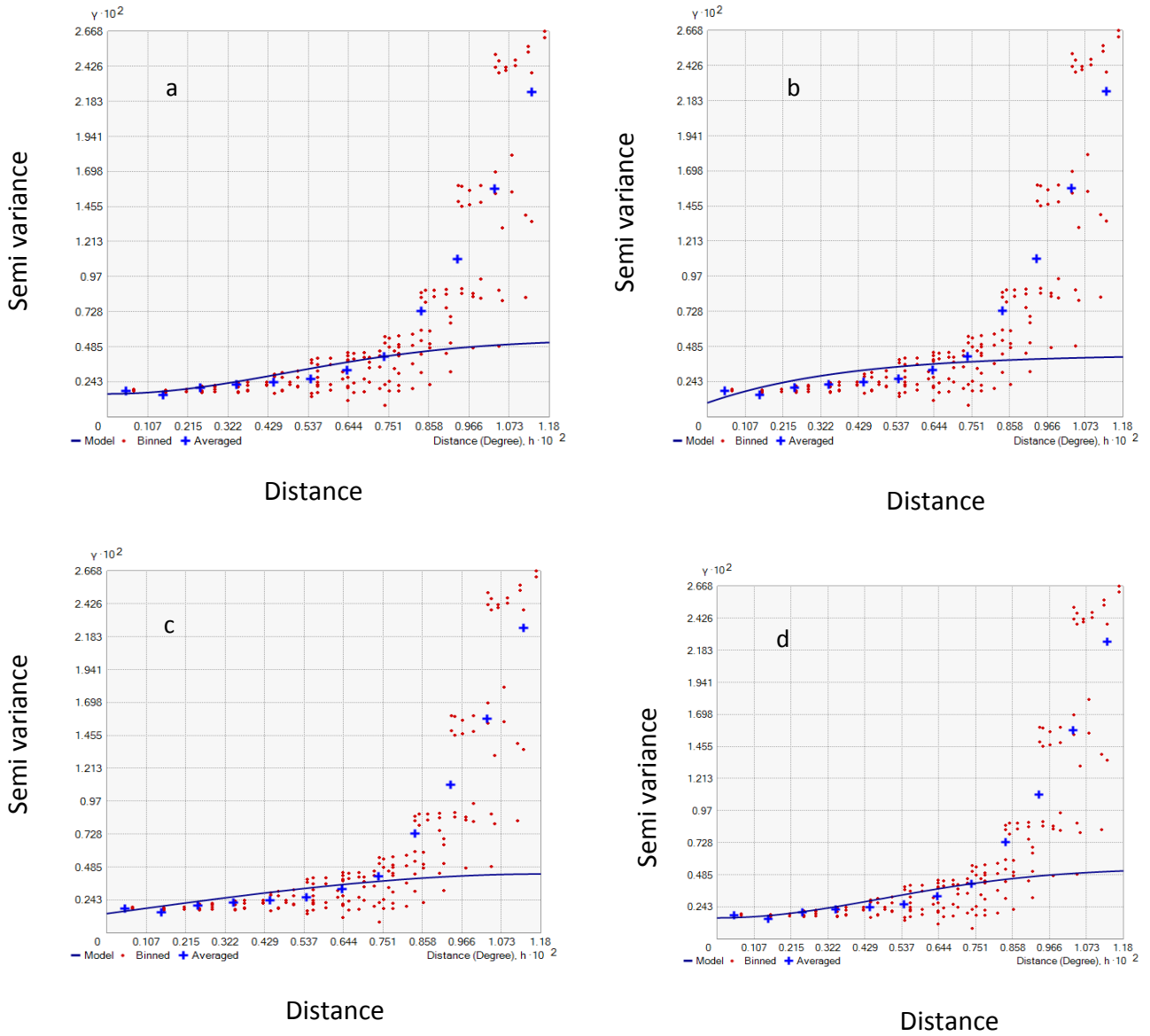
Appendix V: Soil variability

Figure 3 Semivariograms fit for NDVI at V1 stage of corn (*Zea mays*) at Pierpont, SD field: stable (a), exponential (b), Spherical (c) and Guassian (d)models.

Pierpont coordinate: (44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls).
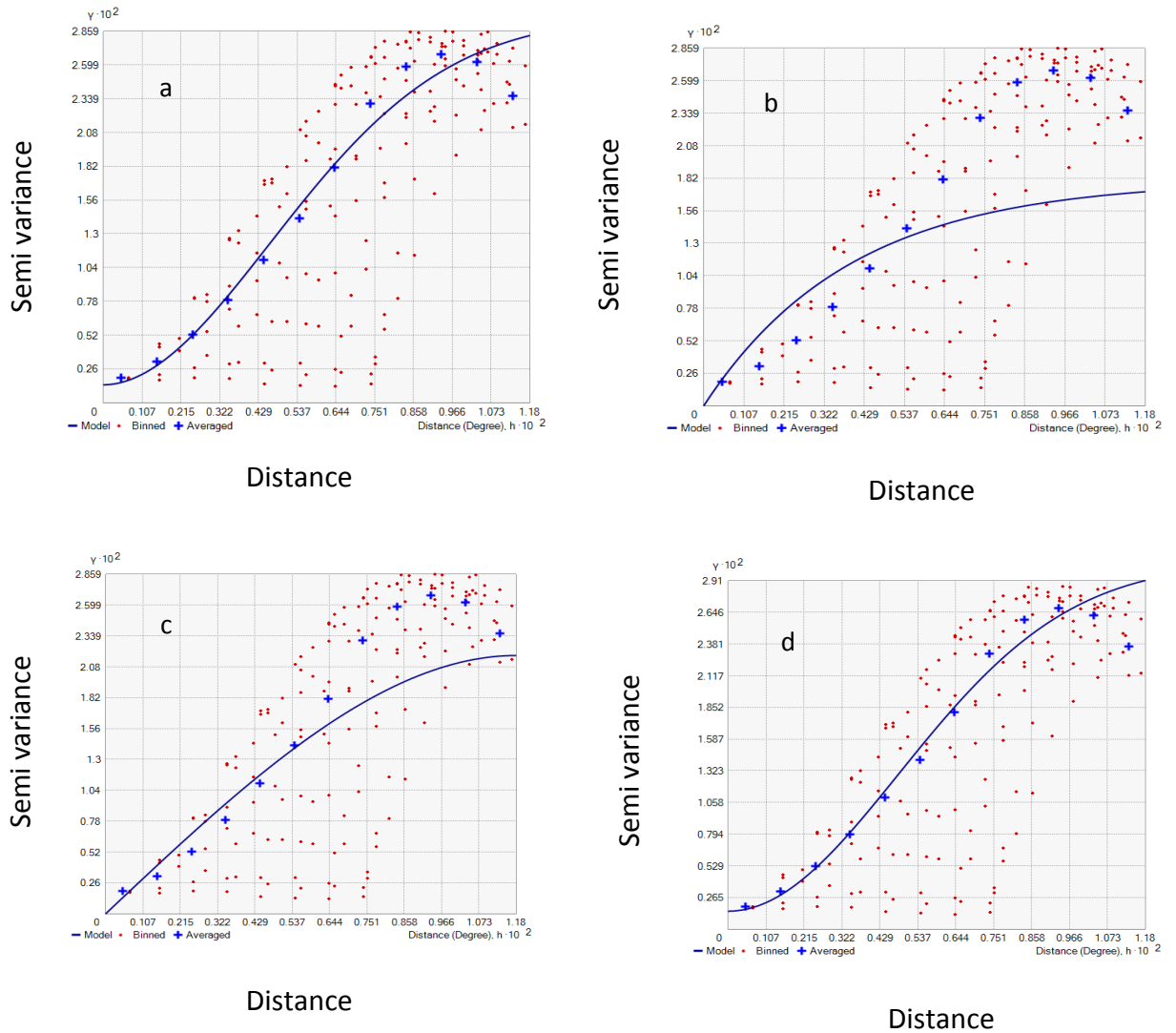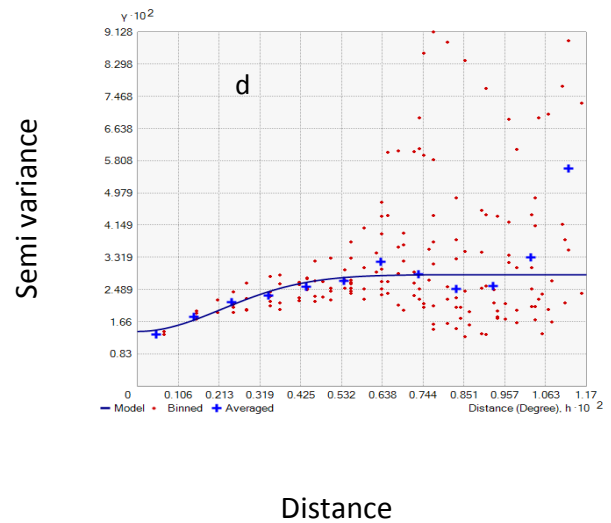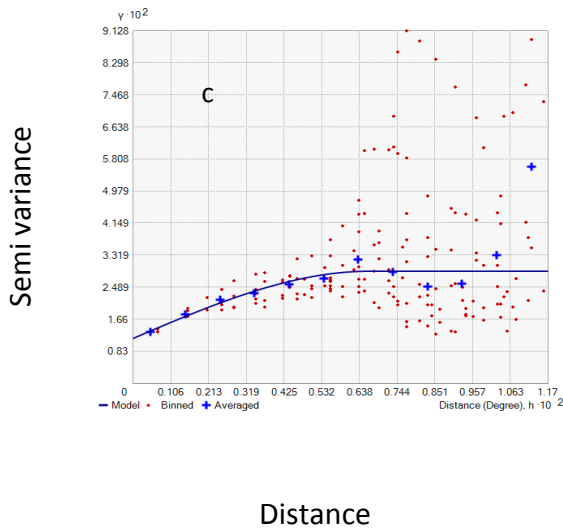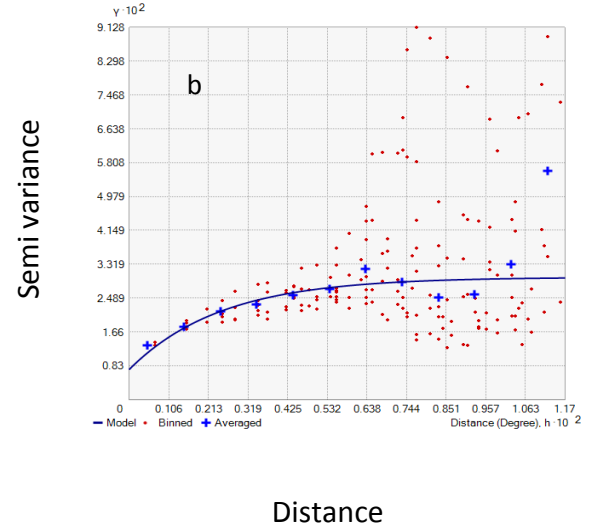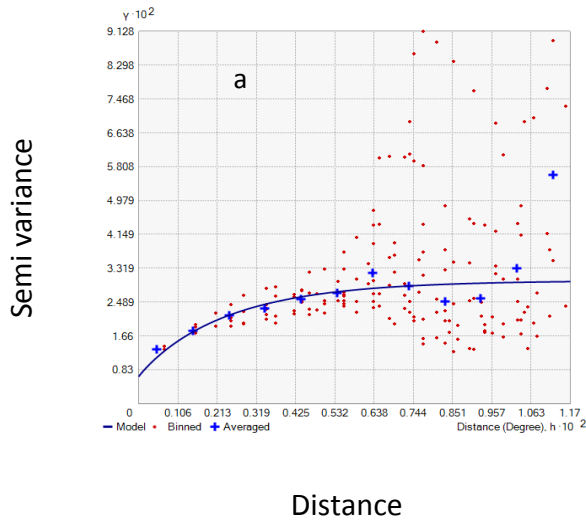Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.

Figure 4 Semivariograms for NDVI at V4 stage of corn (Z*ea mays*) at Pierpont, SD field: (a) stable, (b) exponential), Spherical (c) and Guassian (d) models.

Pierpont coordinate: (44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls).
Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.

Figure 5 Semivariograms for NDVI at V6 stage of corn (*Zea mays*) at Pierpont, SD field: (a) stable, (b) exponential), Spherical (c) and Guassian (d) models.

Pierpont coordinate: (44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls).
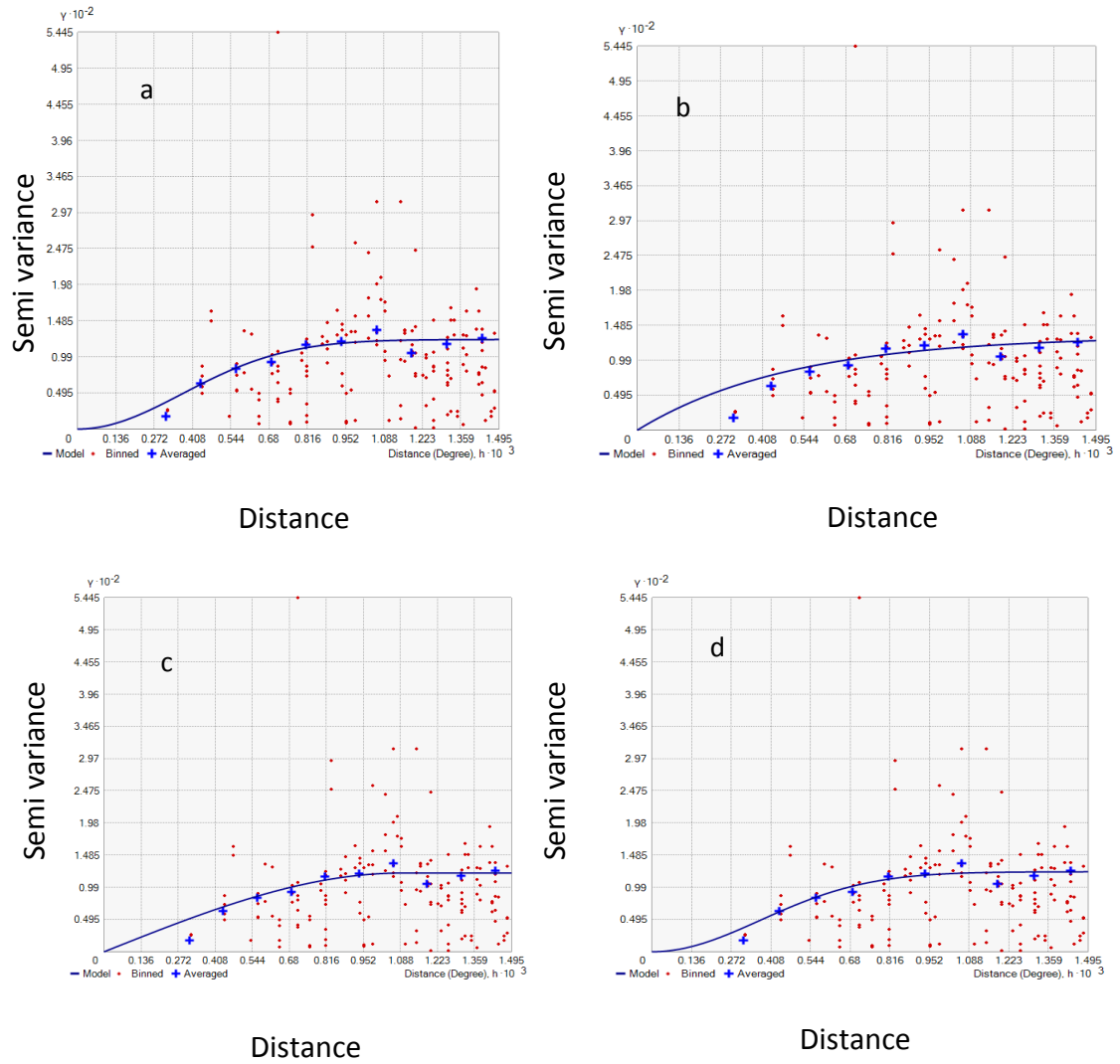Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.

Figure 6 Semivariograms for mollic depth at Pierpont, SD field: (a) stable, (b) exponential),
Spherical (c) and Guassian (d) models.

Pierpont coordinate: (44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″W (Dominant soils:
Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls).
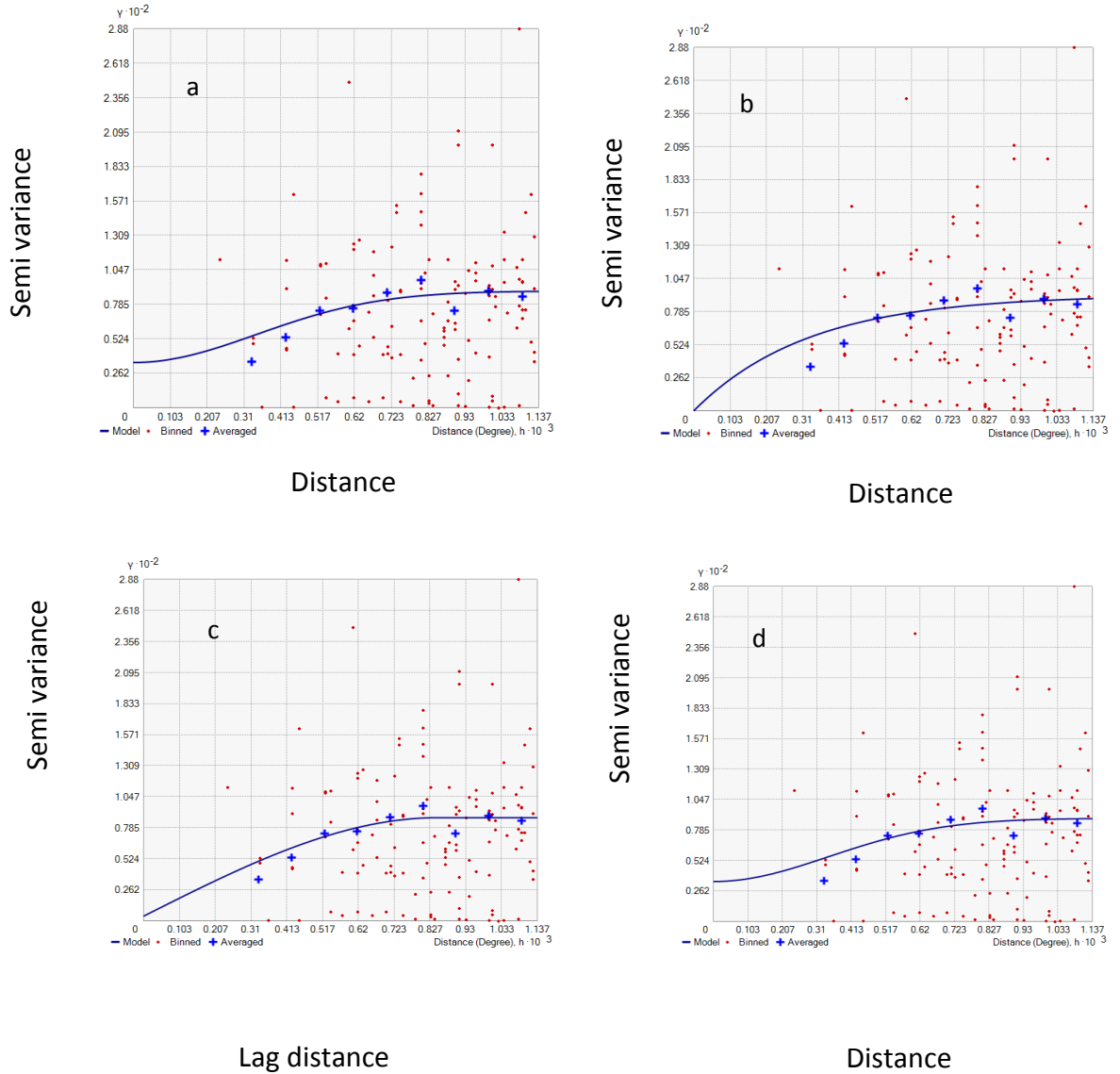Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.

Figure 7 Semivariograms for lime depth at Pierpont, SD field: (a) stable, (b) exponential), Spherical (c) and Guassian (d) models.

Pierpont coordinate: (44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls).
Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.

Figure 8 Semivariograms for pH at Pierpont field: (a) stable, (b) exponential), Spherical (c) and Guassian (d) models.

Pierpont coordinate: (44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls).
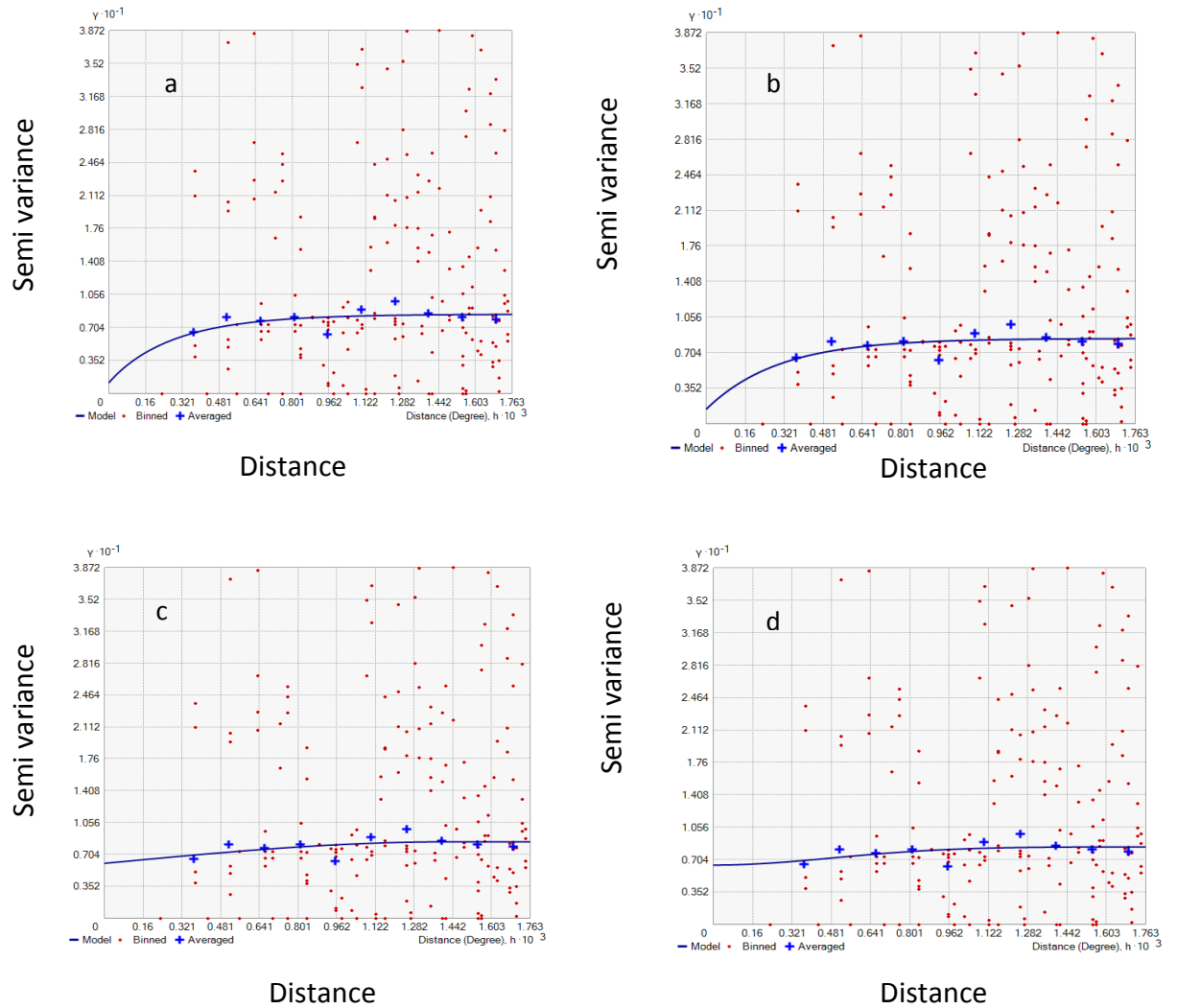Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.

Figure 9 Semivariograms for EC at Pierpont field: stable, exponential), Spherical and Guassian models.

Pierpont coordinate: (44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls).
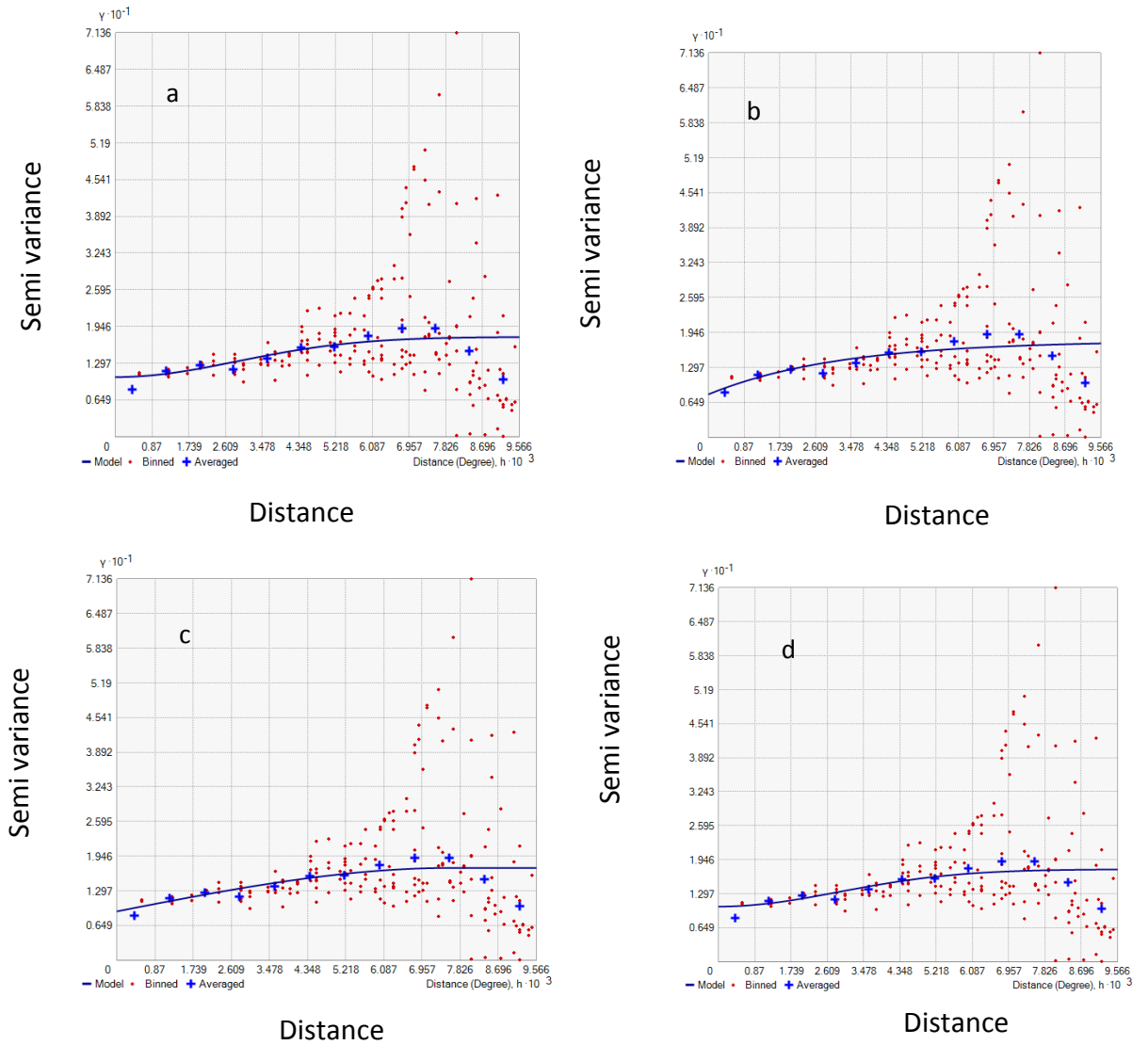Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.

Figure 10 Semivariograms for SAR at Pierpont field: (a) stable, (b) exponential), Spherical (c) and Guassian (d) models.

Pierpont coordinate: (44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls).
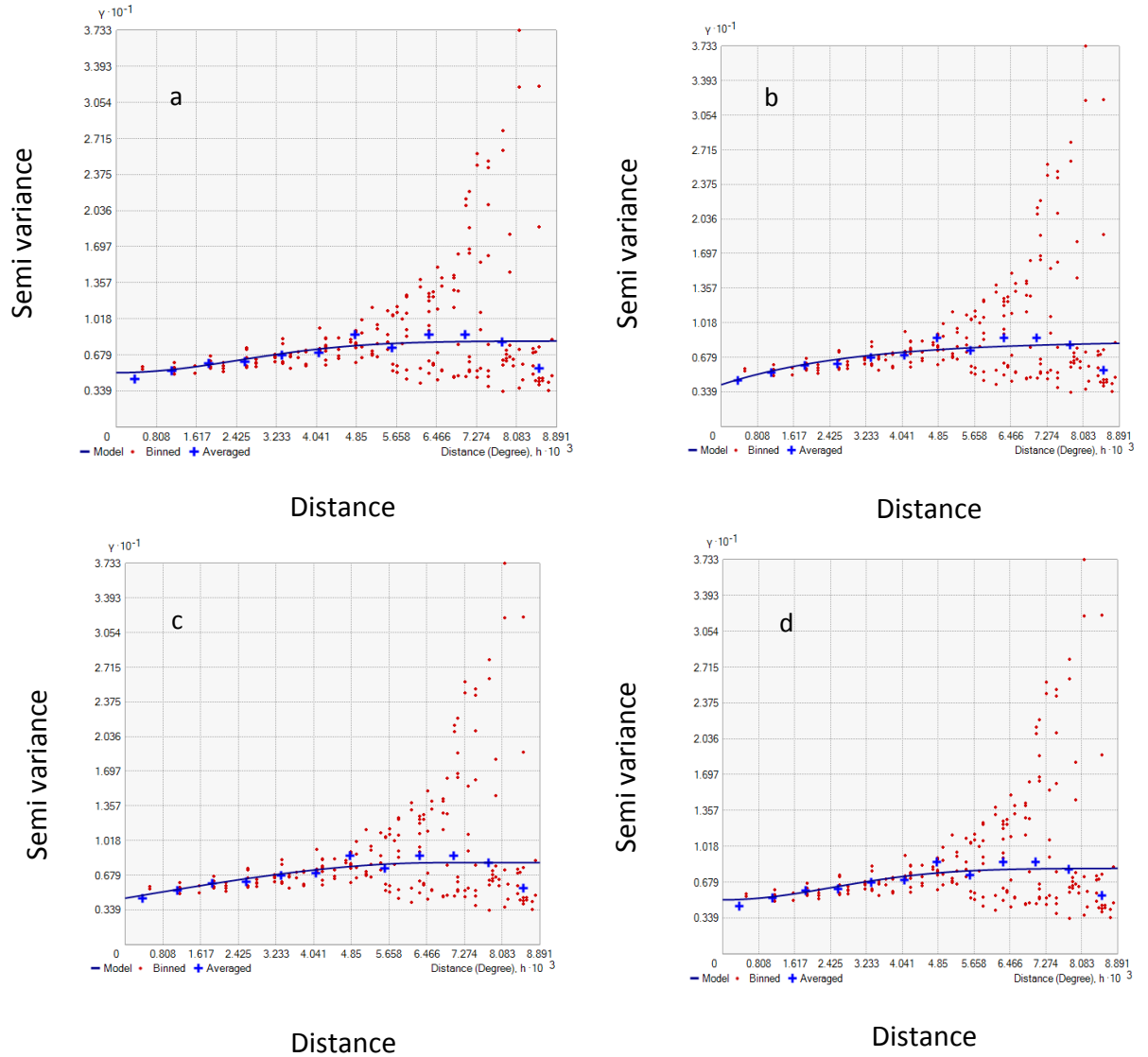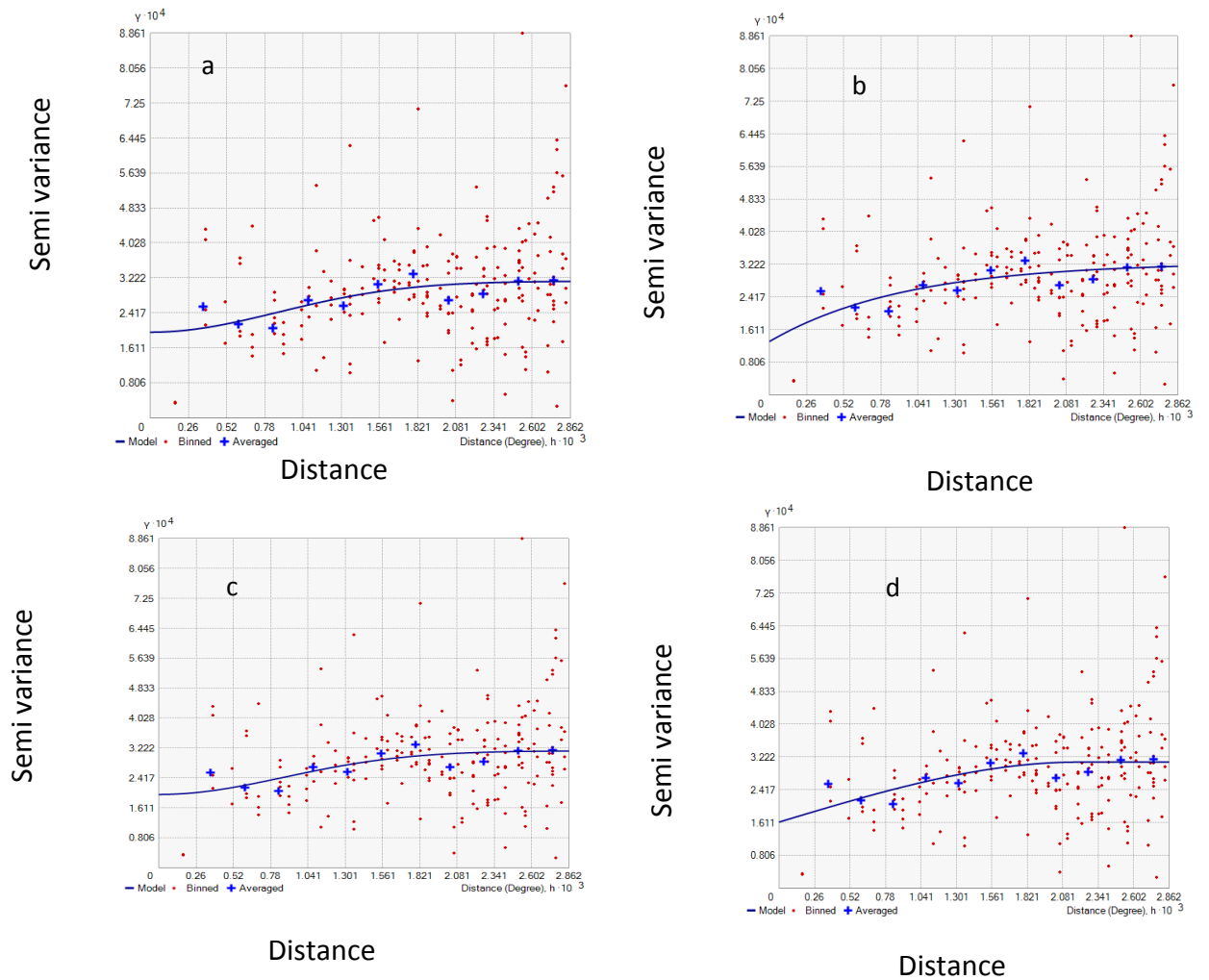Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.

Figure 11 Semivariograms fit for NDVI at bare soil/emergence stage of corn (*Zea mays*) at Pierpont field: stable, (b) exponential), Spherical and Guassian models.

Pierpont coordinate: (44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls).
Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.
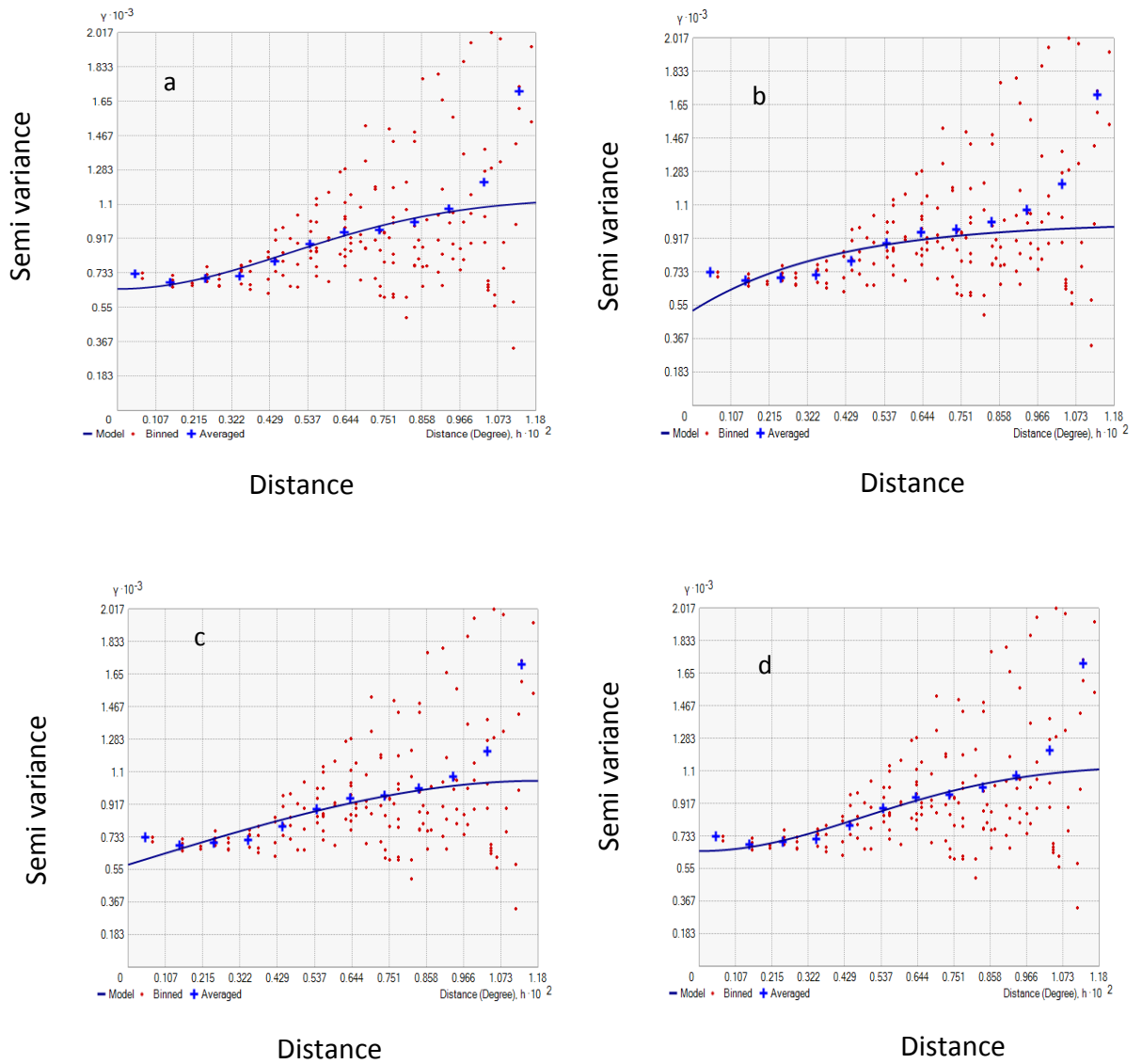
Figure 12 Semivariograms fit for corn (*Zea mays*) yield at Pierpont, SD field: stable, (b) exponential), Spherical and Guassian models.

Pierpont coordinate: (44°55′30″ to 45°28′30″N and 97°50′9″ to 98°28′34″W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, and Natrudolls).
Source of soil information: USDA-NRCS, Soil Survey Division, 2016b.

Table 3 Correlation matrix of soil attributes

Properties	SM E	SM V1	EC V1	Chlorophyll V4	Yield	Elevation	EC 0-3 inch depth	pH 0-3 inch depth	SAR 0-3 inch depth	Lime_ depth	Mollic depth	Redox depth	Till depth
Soil moisture E	1.00	0.17**	0.24**	-0.02	-0.31**	-0.50**	0.20**	0.01	0.24**	0.06	0.35**	0.12	0.05
Soil moisture V1		1.00	0.45**	-0.02	-0.16*	-0.24**	0.36**	-0.06	0.34**	0.05	0.15*	-0.01	0.03
EC V1			1.00	-0.09	-0.30**	-0.38**	0.91**	-0.11	0.77**	-0.01	0.18**	0.25*	0.16*
Chlorophyll V4				1.00	-0.03	0.27**	-0.05	0.40**	-.010	-0.10	-0.15**	-0.13	-0.05
Yield					1.00	0.34**	-0.24**	-0.37**	-0.37**	0.30**	0.02	0.02	0.00
Elevation						1.00	-0.28**	-0.10	-0.31**	0.11	-0.36**	-0.35**	-0.30**
EC 0-7.5 cm depth							1.00	-0.08	0.81**	-0.03	0.17**	0.17**	0.09
pH 0-3 inch depth								1.00	-0.06	-0.33**	-0.01	0.15*	-0.12
SAR 0-7.5 cm depth									1.00	-0.07	0.22**	0.21**	0.12
Lime depth										1.00	0.63**	0.45**	0.32**
Mollic depth											1.00	0.52**	0.66**
Redox depth												1.00	0.73**
Till depth													1.00

Pierpont coordinate**:** 45°30′31″N, -97°53′50″W (Dominant soils: Hapludolls, Natrudolls).

Source of soil information: USDA-NRCS, Soil Survey Division (2016b).

NDVI= Normalized Difference Vegetation Index, E=emergence, V1= first leaf, V4=four leaves, V6=six leaves, EC= electrical conductivity, SAR=sodium adsorption ratio.* Significant at 0.05, **significant at 0.01

VITA

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