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Evaluating the Effects of Topographic Position on Soil Carbon Content in Prairie Pothole Agricultural Landscapes

by

Grace Uchytil

A Thesis Submitted in Partial Fulfillment of the
Requirements for the Degree of
Master of Science
In
Geography

Minnesota State University, Mankato
Mankato, Minnesota
May 2024

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Evaluating the Effects of Topographic Position on Soil Carbon Content in Prairie Pothole Agricultural Landscapes

Grace Uchytil

This thesis has been examined and approved by the following members of the student's committee.

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Table of Contents

Abstract .... *v*

Chapter 1 Introduction *1*

Chapter 2 Literature Review *6*

2.1 Prairie Pothole Formation and Distribution 6
2.1.1 Formation 6
2.1.2 Distribution 8

2.2 Prairie Pothole Stratigraphy, Morphology, and Hydrology 10
2.2.1 Stratigraphy 10
2.2.2 Morphology 11
2.2.3 Hydrology 12

2.3 Prairie Pothole Ecological Function and Environmental Benefits 14
2.3.1 Water Storage/Flooding 14
2.3.2 Carbon Sequestration 15

2.4 Impacts to Prairie Potholes 17
2.4.1 Conversion to Cultivated Croplands 17
2.4.2 Wetland Drainage 19
2.4.3 Climate Change 22

2.5 Land Uses/Land Covers 26
2.5.1 Conventional Agriculture 26
2.5.2 Conservation Agriculture 28
2.5.3 Conservation Reserve Program 32

2.6 Carbon Dynamics 34
2.6.1 Carbon Cycle 34
2.6.2 Carbon Sequestration by Landscape Type 37
2.6.3 Carbon Dynamics by Land Covers and Topographic Position 41

Chapter 3 Study Area *44*

3.1 Physiography and Topography 47

3.2 Climate and Weather 53

3.3 Surface and Groundwater Hydrology 55

3.4 Land Use and Land Cover 56

3.5 Geology 58

3.6 Soils 60

Chapter 4 Methods *65*

4.1 Site Selection Methods 65

4.2 Field-Based Methods ... 66

4.3 Laboratory-Based Methods ... 67
4.3.1 Bulk Density ... 67
4.3.2 Particle Size Analysis ... 68
4.3.3 Carbon Content ... 68

4.4 Statistical Analysis ... 69

Chapter 5 Results ... 70

5.1 Influence of Topographic Position on Soil Physical Properties ... 71
5.1.1 Total Carbon Based on Topographic Position ... 71
5.1.2 Bulk Density Based on Topographic Position ... 74
5.1.3 Particle Size Based on Topographic Position ... 76

5.2 Influence of Land Use on Soil Physical Properties ... 79
5.2.1 Total Carbon Based on Land Use ... 79
5.2.2 Bulk Density Based on Land Use ... 82
5.2.3 Particle Size Based on Land Use ... 84

5.3 Interactions Among Topographic Position, Land Use, Depth and Soil Properties 85

Chapter 6 Discussion ... 90

6.1 Influence of Topographic Position on Soil Carbon ... 91
6.1.1 Role of Geomorphic and Pedogenic Processes ... 91
6.1.2 Role of Particle Size ... 93

6.2 Influence of Land Use on Soil Carbon ... 95
6.2.1 Total Carbon Based on Land Use ... 95

6.3 Carbon Stock ... 99
6.3.1 Influence of Topographic Position on Carbon Stock ... 99
6.3.2 Influence of Land Use on Carbon Stock ... 101

Chapter 7 Conclusion ... 105

References Cited ... 109

Abstract

Prairie potholes are depressional wetland features found throughout the northern Great Plains region of the United States and Canada. These wetlands have high potential to store large quantities of carbon, but many have been altered for conventional agricultural practices. Recently, conservation practices (e.g., no-till and cover crops) and federal conservation programs (e.g., Conservation Reserve Program (CRP)) are contributing to these landscapes returning to their more natural state. The restoration of prairie pothole soils has the potential to increase their carbon storage abilities, which would help decrease CO_2 in the atmosphere and aid in mitigating climate change.

The purpose of this study is to evaluate the effects that topographic position has on soil carbon content in agricultural landscapes with prairie potholes. Methods include: 1) collecting soil cores along a toposequence from four different land uses (native grassland, CRP lands, conservation agriculture, and conventional agriculture); 2) quantifying soil carbon content; 3) characterizing prairie pothole soil physical properties (i.e., bulk density and particle size); and 4) performing statistical analyses to evaluate relationships among total carbon, bulk density, and particle size for topographic position, land use, and the interaction between them at 0-15 cm and 15-30 cm depths.

Total carbon based on topographic position followed the predicted model, carbon increased and bulk density decreased progressing from the upland position to the pothole. Clay and silt content also increased down the hillslope while sand content decreased. Total carbon based on land use was more complex, with the native site storing the most carbon followed by conventional sites, then conservation sites, and CRP sites had the lowest total carbon though differences were not statistically significant. This was probably due to small sample sizes, wide ranges of total carbon, multiple landscape positions not being accessible, and land use history not being well established. This research highlights the importance of topographic position on soil carbon sequestration and storage, an often-overlooked variable, and that land use impacts on carbon are complicated and can be overshadowed by other factors such as pothole morphology and hydrology.

Chapter 1 Introduction

Climate change, which is primarily attributed to anthropogenic contributions of greenhouse gases (i.e., predominantly carbon dioxide, CO_2) to the atmosphere (Poiani and Johnson 1991), has become an increasingly prevalent issue around the world. CO_2 levels in the atmosphere have increased drastically since the beginning of the Industrial Revolution in the early 1800s. Atmospheric CO_2 levels have been recorded at the Mauna Loa Observatory in Hawai'i since 1958 (Hofmann et al. 2009), providing one of the most important environmental records in history. Since the Industrial Revolution, CO_2 in the atmosphere has been increasing by ~2 ppm yr^{-1} with a doubling time of ~30 years (Hofmann et al. 2009). According to the Global Monitoring Laboratory, the global monthly mean CO_2 concentration in October 2023 was 418.64 ppm which increased from a global monthly mean of 416.14 ppm the previous year (NOAA 2023).

Due to the burning of fossil fuels, humans have altered the global carbon cycle, and greenhouse gas emissions, such as CO_2, are increasing in the atmosphere at a rapid pace. Increases in greenhouse gas emissions, such as CO_2, have resulted in a global average temperature increase of approximately 0.06°C (Lindsey and Dahlman 2024), with temperature increases in Minnesota of ~3°C over the past century (University of Minnesota Climate Adaptation Partnership 2024). Warmer temperatures can have many negative effects on the natural environment such as more intense wildfires, prolonged droughts, melting glaciers, and warming oceans (Goudie 2018). Hazards such as these and other interrelated environmental problems will continue to increase and negatively affect humans, animals, and the natural environment if atmospheric greenhouse gas concentrations are not reduced. Reducing atmospheric CO_2 concentrations could help to lessen the impacts of climate change and is considered one of the most viable approaches to mitigating climate change. Transitioning to renewable energy sources, such as wind, solar, geothermal, and hydropower can reduce greenhouse gas emissions and decrease the environmental impacts of climate change (Owusu and Asumadu-Sarkodie 2016). Another way to reduce atmospheric greenhouse gases and mitigate climate change is by removing carbon from the air and storing it in soil organic matter. Organic matter is ~58% carbon and a portion of this carbon can be sequestered in soil as plant material and soil organisms die and decompose (Lal 2014).

Wetland soils are particularly important for carbon storage due to their high plant productivity, and prolonged anoxic conditions (i.e., lacking oxygen) allow them to store more organic matter and carbon than typical well-aerated soils (Chapman et al. 2019). Prairie potholes are depressional wetlands that are ubiquitous throughout the northern Great Plains of the United States and Canada, specifically in the Prairie Pothole Region (Figure 1), representing a potential major resource for carbon sequestration. Many prairie potholes have been modified for conventional agricultural production, which typically inhibits their ability to sequester carbon and can cause them to become a source of atmospheric CO_2 through increased organic matter decomposition due to drainage and tillage (Lal 2004). Conventional agriculture (i.e., intensive tillage, monoculture crops, and prolonged periods of exposed soil) contributes to nonpoint source water pollution, degrades soil aggregation and water holding capacity, leads to runoff and erosion, and reduces carbon sequestration capacities of the soil (Średnicka-Tober et al. 2016).

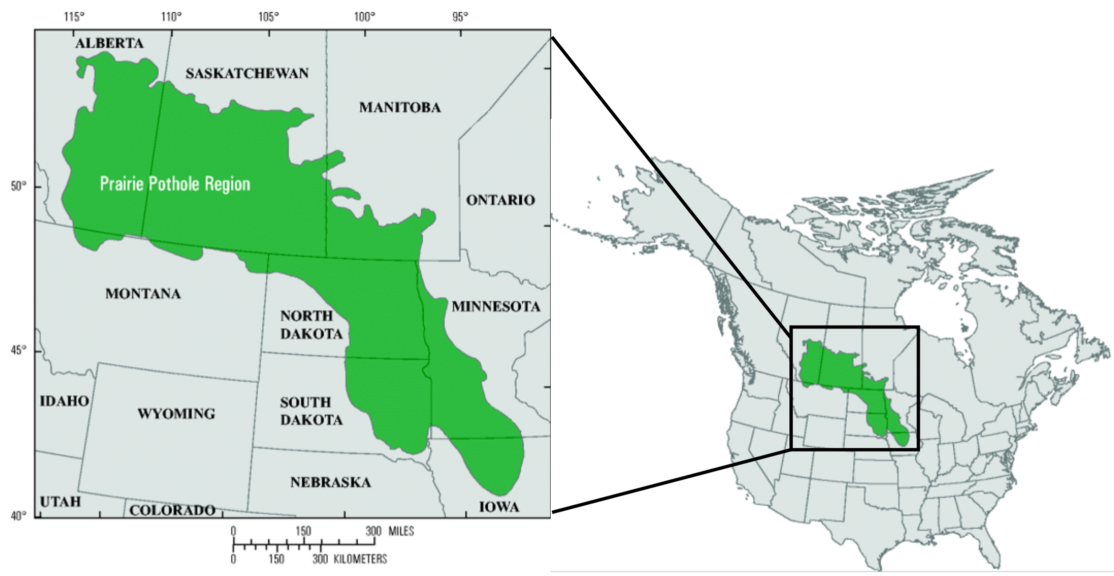

Figure 1: Prairie Pothole Region of the northern Great Plains of the United States and Canada (Renton et al. 2015).

Alternative approaches to agriculture have become increasingly popular as a way to reduce soil degradation and improve soil health. These alternative approaches include no-till or reduced tillage, planting cover crops, and crop diversification, and are generally referred to as conservation agriculture (Palm et al. 2014). There are a range of specific conservation agriculture practices that can be adopted, but they all contribute to minimum soil disturbance, reducing greenhouse gas emissions, and increasing carbon sequestration potential in their soils (Jat et al. 2020).

Recently, on the northern Great Plains restoration efforts have focused on returning prairie potholes to their native state. One program that has been influential in wetland (and grassland) restoration is the Conservation Reserve Program (CRP). The CRP is a federal conservation program that is helping to protect environmentally sensitive land in the United States. This voluntary program compensates farmers to convert environmentally sensitive cropland to native vegetation to reduce erosion and improve overall environmental health (Phillips et al. 2015). While carbon sequestration is not a primary goal of the CRP, restoring native vegetation, particularly within previously drained wetlands, has the potential to greatly increase carbon sequestration rates on CRP land.

Since prairie potholes are depressional features, many have formed at the base of hillslopes. Topography has a major impact on geomorphic and pedogenic processes along a hillslope because it is one of the five main soil forming factors (Jenny 1941). Different positions along a hillslope have different soil attributes because of this, making topography a crucial factor to consider when studying soil properties, including carbon sequestration. Sites for this study have relatively low relief and cover short distances. From the uppermost (i.e., shoulder) to lowermost (i.e., pothole) positions, relief ranges from 1.5 m to 13.1 m, distance ranges from 45 m to 245 m, and percent slope ranges from 1.24% to 5.57%. These are gentle slopes, which is important to note because even relatively minor changes in elevation can influence soil properties along a hillslope.

The purpose of this project is to evaluate the effects of topographic position on the carbon content of soils in agricultural landscapes with prairie potholes. This project involves examining soils from a range of topographic positions (i.e., within prairie potholes, adjacent to potholes, and on surrounding uplands) and agricultural practices (i.e., conventional, and different conservation approaches) at two depths (i.e., 0-15 cm and 15-30 cm). Objectives for this project include: (1) quantify carbon content of prairie potholes based on their topographic position (i.e., shoulder, backslope, toeslope, edge, half, and center); (2) quantify carbon content of prairie pothole soils in native grassland, CRP lands, conservation agriculture (e.g., no-till with single and multi-species cover crops and ridge tillage), and conventional agriculture (e.g., intensive cultivation with no cover crops); (3) characterize prairie pothole soil physical properties (i.e., bulk density and particle size); and 4) perform statistical analyses to evaluate relationships among total carbon, bulk density, and particle size for topographic position, land use, and the interaction between them at 0-15 cm and 15-30 cm depths.

I hypothesize that topographic position influences carbon sequestration rates such that the prairie pothole (i.e., center and half-radius) position will have the highest soil carbon contents followed by the lowland (i.e., pothole edge and toeslope) position and the upland (i.e., backslope and shoulder) position will have the lowest soil carbon contents. Additionally, I hypothesize that land use will influence carbon sequestration rates such that native prairie potholes will have the highest soil carbon content, potholes enrolled in CRP will have the next highest content, followed by conservation agriculture, and conventional agriculture soils will have the lowest carbon content. Lastly, I hypothesize that bulk density will have an inverse relationship with carbon content and that clay-rich soils will store the most carbon and sand-rich soils will hold the least carbon.

Chapter 2 Literature Review

2.1 Prairie Pothole Formation and Distribution

2.1.1 Formation

The Prairie Pothole Region (PPR) of North America encompasses an area of ~700,000 km^2 in the upper Midwest of the United States and central Canada (Smith et al. 1964). The PPR includes five U.S. states (Montana, North Dakota, South Dakota, Minnesota, and Iowa) and three Canadian provinces (Alberta, Saskatchewan, and Manitoba). The PPR is one of the largest wetland complexes in North America with approximately 5 to 8 million wetlands (Dahl 2014).

The PPR was once covered in glaciers, which influenced how the current landscape was formed. The Pleistocene epoch was a geologic time period that lasted from ~2.48 ma to 11.8 ka (Bagstad 2022). The most recent glaciation during the Pleistocene was the Wisconsin glaciation, beginning ~100,000 to 70,000 years before present (YBP), and maximum glaciation occurred at 20,000 to 18,000 YBP (Andrews 1987). During the Wisconsin glaciation, two large ice caps dominated northern North America, the Laurentide Ice Sheet (LIS) in the east and central regions and the Cordilleran Ice Sheet in the west (Southern Forest Resource Assessment 2013). The LIS advanced and retreated across the PPR region several times, with the Des Moines Lobe representing the furthest southern extent of the LIS during the Wisconsin glaciation (Prior 1991). Due to the advance and retreat of the Des Moines Lobe, the PPR is characterized by subtle topography, with expansive plains and gently rolling hills. This region is almost entirely covered by glacial till and outwash (NRCS 2006). Following the Younger Dryas stadial (circa 12.9 to 11.8 ka), the Des Moines Lobe progressively retreated and had retreated entirely from the PPR region of Iowa and southern Minnesota by ~12 ka (Prior 1991) and from central Canada by ~8 ka (Ullman 2022) (Figure 2).

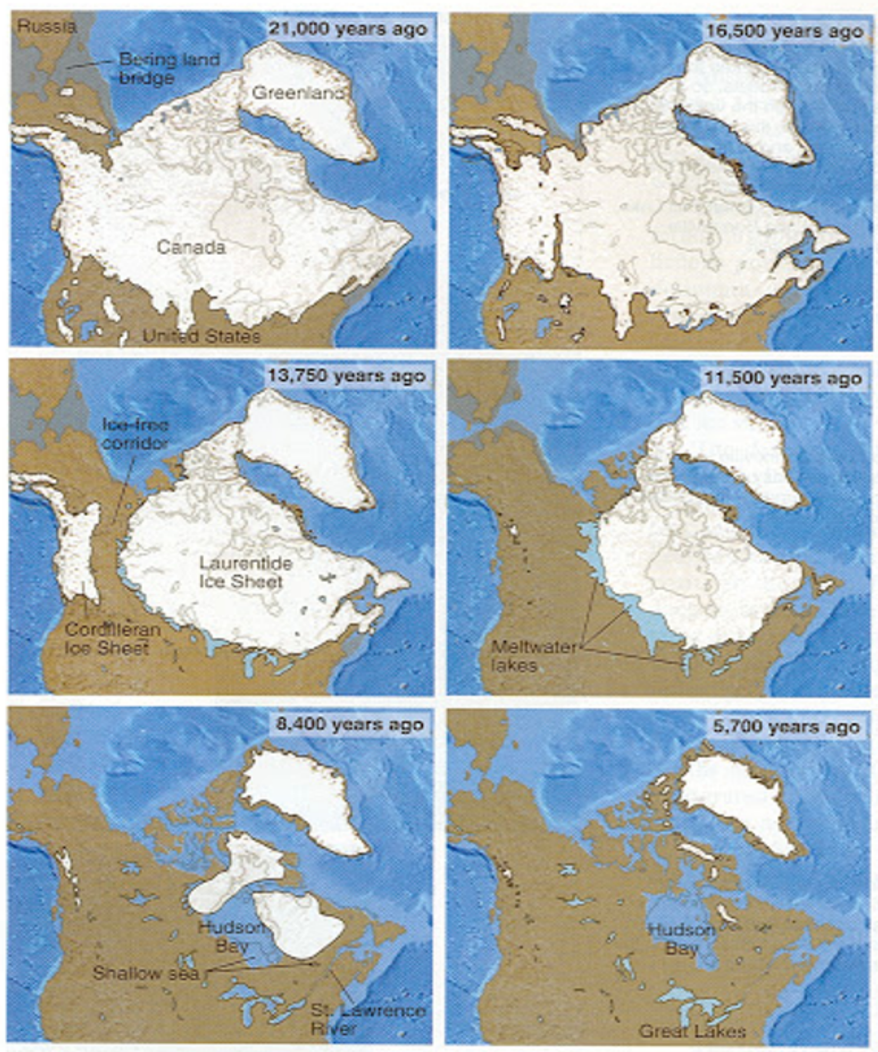

Figure 2: The retreat of the Laurentide Ice Sheet (Hartley 2014).

The effects of glaciation varied depending on local and regional environments. In the PPR, retreat of the LIS resulted in widespread deposition of till in ground moraines and the formation of thousands of depressional features known as prairie potholes

(Johnson et al. 2005). Prairie potholes formed when blocks of ice separated from the glacier and became wholly or partially buried by sediment. Over time the blocks of ice slowly melted, leaving behind a depression on the landscape that filled with meltwater and runoff to form these upland-embedded depressional wetlands (Figure 3).

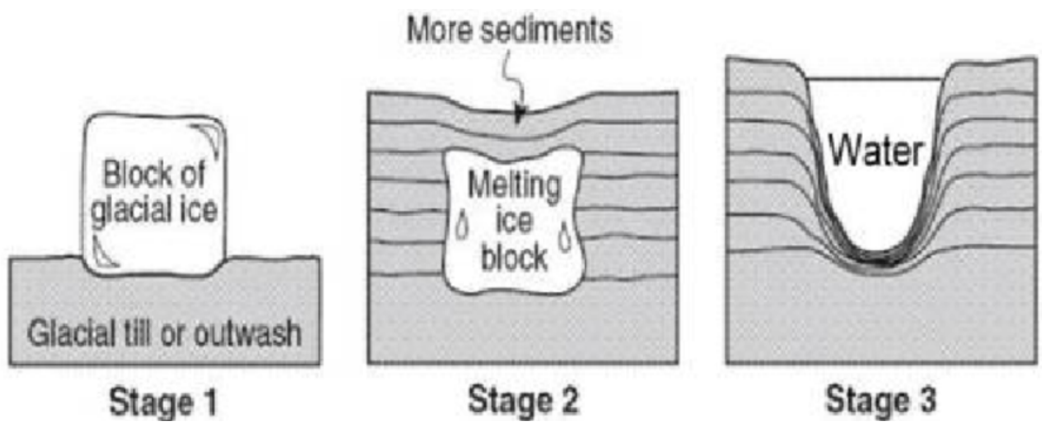

Figure 3: How a prairie pothole is formed (Hillewaert 2013).

2.1.2 Distribution

Historically, ~16-18% of the PPR was covered by wetlands, with the remaining landscape dominated by grassland ecosystems (Dahl 1990). About two-thirds of the PPR is located in south central Canada with the remaining approximately one-third in North Dakota, South Dakota, Minnesota, Iowa, and a small portion in Montana (NatureServe Explore 2022) (Figure 1). The U.S. section of the PPR contains ~1,688,000 ha of wetlands (Prairie Pothole Joint Venture Concept Plan 2021). In wetter years, the Canadian portion of the PPR can have over 30 million ha of potholes on the landscape (Ducks Unlimited 2022). About 40% of the PPR has hummocky topography, which results in areas covered by depressions of various sizes storing water (Ducks Unlimited

2022). Pothole density varies from 0 to ~74 potholes/km^2. Flatter areas in the PPR (~60% of the region) have predominantly fluvial and lacustrine materials and in some areas wetland density can exceed 40/km^2 (Doherty et al. 2018).

Since the mid-1800s, the landscape has been drastically altered and numerous depressional wetlands such as prairie potholes have been artificially/intentionally drained for agricultural production (Dahl 1990). Agriculture production and pothole drainage have intensified since the 1980s, reducing the amount of wetlands in the PPR by ~65% (Dahl 1990). Cultivated cropland, mainly soybeans and corn, is now the dominant land use in the U.S. portion of the PPR with pastureland for cattle grazing as the second most common land use (NRCS 2006).

Lack of clear criteria to define prairie potholes makes it difficult to differentiate potholes from other wetland types and waterbodies, so the precise number of prairie potholes in the PPR is unknown. For example, large, semi-permanent potholes may be classified as lakes, while small temporary potholes may not be classified as wetlands at all. Some literature argues that the variability of pond areas and vegetation composition of prairie potholes make them difficult to identify and classify (van der Kamp et al. 2016). Wetlands, including prairie potholes, are typically identified by the presence of hydric soils, hydrophytic vegetation, or ponded water. Given the high degree of variability in pothole hydroperiods and vegetation composition, hydric soils are the primary criteria for identifying and delineating prairie pothole boundaries (van der Kamp et al. 2016). However, hydric soil inventories do not typically indicate the type of wetlands they are associated with, complicating the ability to accurately distinguish prairie potholes from other wetland types.

2.2 Prairie Pothole Stratigraphy, Morphology, and Hydrology

2.2.1 Stratigraphy

Bedrock in the PPR mainly formed during the Cretaceous Period (Zanko et al. 2019) and primarily consists of sandstone, siltstone, shale, and mudstone (Jones and MacKevett 1969). Paleozoic bedrock is also common, containing shale and limestone, underlying widespread glacial and alluvial deposits (NRCS 2006). However, bedrock in the study area for this project is deeply buried by glacial till and other deposits.

The dominant soil orders in the PPR are Mollisols, Alfisols, and Entisols (NRCS 2006). Soils have frigid to mesic soil temperature regimes and ustic, udic, and aquic soil moisture regimes (NRCS 2006). The Montana section of the PPR primarily consists of very deep, well drained, loamy, or clayey soils formed in till-on-till plains, hills, or in alluvium on alluvial fans and stream terraces (NRCS 2006). Soils in the North Dakota and South Dakota sections of the PPR are very deep, range from well drained to very poorly drained, have a loamy or clayey texture that formed in glacial till on till plains, moraines, in sandy sediments on lake plains, and outwash plains, in alluvium on till plains, and in lacustrine sediments on glaciolacustrine plains (NRCS 2006). Soils in the Minnesota and Iowa section of the PPR are very deep, well drained, or moderately well drained, with silty or loamy texture, and formed in loamy till, loess, or silty drift over till, eolian deposits, glacial outwash on till plains, and moraines, colluvial and alluvial sediment in swales and depressions, and alluvial sediments on flood plains (NRCS 2006).

2.2.2 Morphology

Prairie potholes are mineral and organic soil wetlands that collect runoff, stormwater, and snowmelt from the surrounding watershed, and hydroperiod (i.e., the length of time they store water) ranges from temporary to seasonal to semi-permanent (Shaw et al. 2013). Prairie pothole surface area ranges from <0.5 ha to >10 ha with a maximum depth typically <2 m, while average depth is <1 m (Van der Valk and Pederson 2003). However, conversion of the landscape from grassland to cropland has dramatically altered prairie pothole morphology. Johnston and McIntyre (2019) determined that from 2001 to 2011, the density of the prairie potholes in the Dakotas section of the PPR decreased by 16%, and average size decreased from 2.41 to 2.16 ha. Their study attributed the loss of wetland size to farming activities eroding the edges of the wetlands and noted that many wetlands in the PPR decreased in size due to tile drainage or infilling with sediment. Sloan (1970) emphasizes that the maximum depth of prairie potholes is <2 m, but most are <1 m deep while seasonal water level fluctuations cause the depth during most of the growing season to be much lower. Prairie pothole shape is also dependent on water levels (Figure 4). Prairie potholes are more circular when they have less water and become more convoluted, or horseshoe-shaped as water levels increase (Johnston and McIntyre 2019).

Figure 4: Prairie potholes scattered across a farm field with different sizes and shapes (Ducks Unlimited Inc. 2022).

2.2.3 Hydrology

Prairie pothole hydroperiods are classified as temporary, seasonal, or semi-permanent, and cycling between flooding and drying is one of the primary natural influences on prairie potholes. These wet-dry cycles help to rejuvenate pothole functions because when potholes are dry they expose organic matter to decay, which can make nutrients more available during the next wet period (Ducks Unlimited 2022). Prairie pothole hydrology and morphology are interrelated with pothole size, depth, and shape dependent on and influencing hydroperiod. Temporary potholes are wet for a few weeks after heavy rainfall or snowmelt and are typically very small in size and shallow because they are only wet for a short time (Renton et al. 2015). Dahl (2014) found that the mean size of temporary prairie potholes is about 0.40 ha. Seasonal potholes typically dry out in midsummer and are medium in size at ~1 ha (Dahl 2014) and deeper because they receive more precipitation. Semi-permanent potholes often have water for the entire growing season and are typically the largest (Dahl 2014), but they may be dry during drought years (Renton et al.2015).

During wetter periods, short-term connections can be made between wetlands that are normally isolated from each other, this can cause species to spread and can affect water chemistry (Leibowitz and Vining 2003). Throughout the year water levels fluctuate, which results in flood patterns changing for certain areas in the pothole. The wettest parts of some prairie potholes can be flooded almost all year while the outer edges may only be saturated for the growing season (NatureServe Explore 2022).

Since the PPR extends over a wide area, hydrology is also dependent on location. One of the largest variables affecting the hydrology of prairie potholes is precipitation. Precipitation varies across the region, with drier conditions in the west and wetter conditions in the east, and precipitation patterns have changed over time. For the PPR, southwestern Minnesota received about 20% more precipitation at the end of the twentieth century compared to the start (National Climate Data Center 2011), and northeastern Montana received almost 10% less (National Climate Data Center 2011). With more precipitation, more prairie potholes fill with water, making them larger with longer hydroperiods. Conversely, during drought conditions, entire wetland communities can dry out. Wetland densities for the PPR can fluctuate from 0.8 potholes/km^2 during a drought to 4.4 potholes/km^2 during more average precipitation conditions (Cowardin et al. 1987).

2.3 Prairie Pothole Ecological Function and Environmental Benefits

2.3.1 Water Storage/Flooding

Water storage is highly variable within prairie pothole landscapes due to considerable spatial and temporal variability in climate (i.e., precipitation and temperature), runoff, infiltration, and lateral redistribution of water. As snow melts in the spring, water flows over the frozen soil restricting infiltration and most of the snowmelt water reaches prairie potholes, and they become saturated or ponded in early spring. How fast a pothole dries out depends on the weather conditions and pothole size. Temporary prairie potholes are typically smaller, so they store less water and dry out more quickly (Dahl 2014). Seasonal prairie potholes are typically much larger and dry out due to a lack of snowmelt and/or precipitation coupled with high summer temperatures. Semi-permanent prairie potholes are most often the largest potholes and can often store water throughout the growing season (Dahl 2014).

Soil properties and topography also have major controls on water storage in prairie potholes. Soil texture influences infiltration rates and the transmission of water through the soil profile (Biswas et al. 2012). Thickness of the A and C horizons, bulk density, and the absence or presence of a $CaCO_3$ layer in the soil also influence transmission of water through soil and thus water storage (Biswas et al. 2012). Topographic properties such as the wetness index (i.e., a numerical index corresponding to the ratio of the runoff from a basin each year to the annual average runoff), slope, convergence index (i.e., the relief patterns of terrain based on channels and ridges), and flow connectivity are associated with water storage (Biswas et al. 2012).

Water storage in wetlands can attenuate and delay downstream flood peaks, thus drainage or restoration of a wetland can affect downstream flood levels. A study conducted by the USGS examined data from 141 wetlands from the PPR in North Dakota and found a significant increase in wetland size from 1930 to 2010 (USGS 2015). They determined that most of the increase in surface water was because of small wetlands being drained and used for agricultural production. Drainage moves more surface water to fewer, larger wetlands, which diminishes the overall ability of the landscape to reduce regional flooding due to increased spillover (USGS 2015). Whereas less drained areas with multiple small wetlands help store more water from precipitation or snowmelt. Additionally, small wetlands in the PPR help with local and regional groundwater recharge making them environmentally and economically important.

2.3.2 Carbon Sequestration

Concerns over human-induced climate change have drastically increased over the past few decades, with a heightened focus on reducing the concentration of greenhouse gases in the atmosphere. Wetland soils are an important facet being investigated to mitigate climate change because of their potential to store large quantities of carbon. Wetlands are responsible for ~20-30% of total carbon storage in soils despite only covering ~5-8% of the total land surface (Mitsch et al. 2013). Due to their anoxic conditions organic matter decomposition rates are low, so wetlands have a favorable environment for carbon sequestration. Wetlands sequester carbon from the atmosphere through plant photosynthesis and storage of organic-rich sediment derived from runoff (Board of Soil and Water Resources 2019). Since carbon sequestration potential is high in wetlands, prairie pothole restoration could contribute to lowering CO_2 concentration in the atmosphere. Wetland restoration has become increasingly popular as a tool to help mitigate the impacts of climate change, but there is still debate on whether wetland restoration has been successful in restoring carbon sequestration potential.

A study on the potential that prairie wetlands in the PPR have in storing organic carbon during a 10-year restoration period determined that farmed wetlands had lost ~10 Mg organic carbon (OC) ha^{-1} in the top 15 cm of soil and restored semi-permanent wetlands have a replenishment rate of ~3 Mg OC ha^{-1} $year^{-1}$ in the top 15 cm (Euliss et al. 2006). Thus, according to this study, it would take approximately 3.3 years for carbon loss to be replenished in the top layer of soil after restoration from cultivated cropland. They also noted that sequestration rates are much higher in restored wetlands versus restored grasslands because grasslands store carbon at a much slower rate due to higher organic matter decomposition rates; however, carbon storage in grasslands has a much higher potential in overall carbon storage because grasslands cover much more land area than prairie potholes (Euliss et al. 2006).

Research by Streeter and Schilling (2017) compared native, reconstructed, and farmed prairie pothole soil properties in Iowa for organic and mineral prairie potholes in different stages of land use. Reconstructed prairie potholes were in three different stages of restoration from <10 years, 10-20 years, and 20-30 years. Results indicate that organic and mineral wetlands have similar morphologic restoration trends, but soil profiles are different among wetland groups and restoration ages. One of the most important findings in this study was that soil organic matter (SOM) increases significantly during the beginning years of restoration and then after 15-20 years SOM continues to increase but at a much lower rate. SOM is important in wetland restoration because it can have an impact on other soil properties such as bulk density (Streeter and Schilling 2017).

Badiou et al. (2011) investigated native, recently restored (<5 years), and long-term restored (>5 years) wetlands in the Canadian PPR. This study focused on soil organic carbon (SOC) concentration along with methane and nitrous oxide emissions. They determined that SOC was overall higher in wetland landscapes than in upland positions, and SOC content in native wetlands was higher compared to newly and long-term restored wetlands (Badiou 2011). SOC contents were estimated to be 121 Mg ha^{-1} for newly restored, 165 Mg ha^{-1} for long-term restored, and 205 Mg ha^{-1} for native wetlands (Badiou 2011). Thus, research shows that restoring wetlands has the potential to rapidly increase carbon sequestration in their soils, which could help reduce greenhouse gases in the atmosphere and be a viable mitigation strategy for climate change.

2.4 Impacts to Prairie Potholes

2.4.1 Conversion to Cultivated Croplands

The total number of prairie potholes throughout the PPR prior to European settlement has been estimated to be around 12.6 million (Van der Valk 2005). Starting in the late 1800s, potholes were drained and converted to cultivated cropland. Minnesota, Iowa, and South Dakota's main crops are soybeans and corn, while North Dakota is dominated by hard red spring wheat, durum, and barley and Montana primarily produces wheat. Recently, the highest number of potholes converted to croplands have been in Iowa at the southern end of the region, at ~90% loss, Minnesota with the second most loss at ~80%, and then less-severe losses in North Dakota, at 50%, and South Dakota, at 32% (Dahl 1990). Drainage in some areas, especially the southern part of the PPR has resulted in regional lowering of the groundwater table (Van der Valk 2005). This in turn has altered the hydrology of the remaining wetlands. The conversion of most of the uplands around prairie potholes to cultivated cropland or pastures has significantly degraded the quality of water entering these wetlands (Van der Valk 2005). Removal of eroded topsoil from croplands reduces the depth and storage volume of wetlands, which can shorten their hydroperiods and diminish groundwater recharge and water storage (Gleason et al. 2011).

Land cover has changed across the region as farmers have introduced more intensive cropping systems as well as expanded into areas once considered unfit for crop production. Between 1997 and 2009, grassland in the PPR declined overall by about 229,980 ha, and 95% of grassland loss was due to conversion to cropland (Dahl 2014). Biofuel demands are adding additional pressure to the conversion of PPR land from grassland to cropland because America is trying to reduce dependence on foreign oil (Prairie Pothole Joint Venture 2021). One of the most popular biofuels, ethanol, is derived from corn, which is one of the main crops grown in the PPR. Oil and gas development along with wind energy is expanding rapidly across the PPR, which has the potential to negatively affect the landscape even further (Prairie Pothole Joint Venture 2021).

2.4.2 Wetland Drainage

Lack of understanding of the importance of wetlands such as prairie potholes has resulted in filling, drainage, or manipulations for agricultural purposes (Renton et al. 2015). Since the late 1880s to early 1900s, prairie potholes have been drained to make the landscape more suitable for cultivated cropland. Artificial subsurface draining of wetlands is primarily accomplished through installation of tile drainage (i.e., “tiling”) (Figure 5). Tiling of prairie potholes means that drain tile is installed about 1.2 meters below the soil surface to remove water from excessively wet or poorly drained areas (Singh et al. 2006). This makes the soil environment more conducive for crop growth and field operations. There are many reasons why farmers drain wetlands such as to increase property access, crop yield, and cultivated area, to diversify crop options, and to extend the growing season (Van der Gulik et al. 2000; Blann et al. 2009). Tile drainage can have positive effects on the physical properties of soils and the landscape. When excess water is removed from the soil, it can have better aeration, porosity improves, and soil structure can become stronger (Gardner et al. 1994).

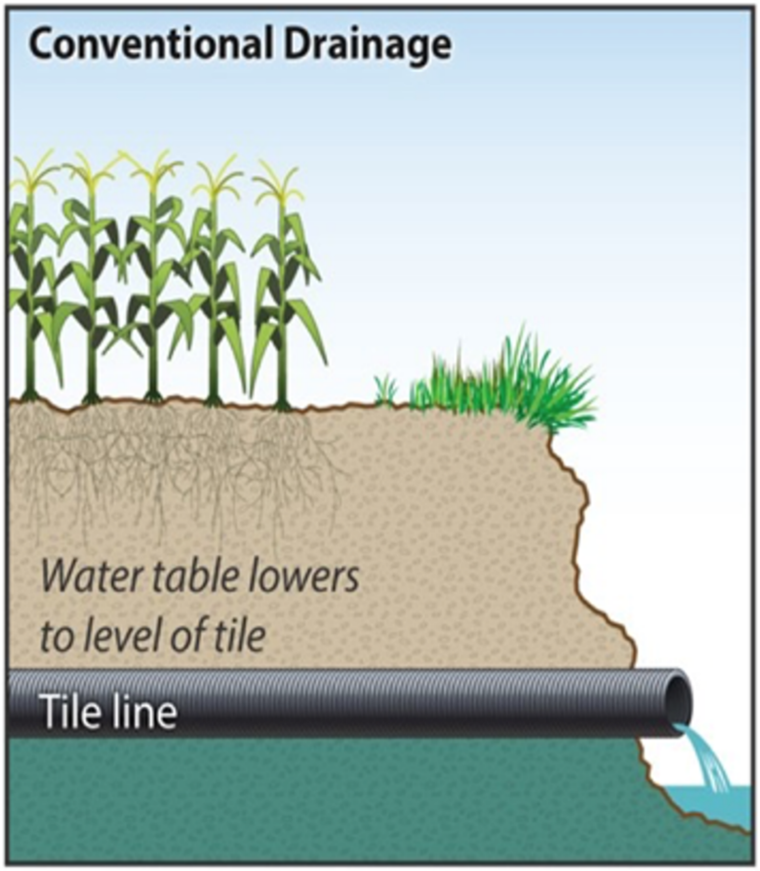

Figure 5: Example of how agricultural fields are tile drained (Agricultural Drainage Management Coalition 2019).

While draining prairie pothole wetlands can be beneficial to farmers and their agricultural activities, the negative effects on native plants, wildlife, the hydrosphere, and the atmosphere can be catastrophic. Draining prairie potholes degrades or eliminates crucial aquatic habitats and landscapes. Excess nitrogen and phosphorus can be transported to downstream waters when prairie potholes are drained due to lack of surface water storage (Skopec and Evelsizer, 2018). Neonicotinoids and herbicides have also been found in potholes with excessive drainage, which can be harmful to wetlands ecosystems (Skopec and Evelsizer, 2018).

Drainage to increase agricultural production has been one of the main causes of wetland loss, with losses of ~89% in Iowa, 49% in North Dakota, 42% in Minnesota, 35% in South Dakota, and 27% in Montana (Dahl 1990) (Figure 6). Overall, PPR wetland area has decreased by ~50% (Werkmeister et al. 2018) to 65% (Dahl 1990) due to artificial drainage. This is a problem because prairie potholes have an important role in runoff water retention, groundwater recharge, sediment entrapment, flood control, water-quality improvement, and recreation (Leitch 1996; Gleason et al. 2008; Werner et al. 2013). As of 2022, the percent share of cropland harvested under subsurface tile drainage was 46% in Iowa, 35% in Minnesota, 2% in South Dakota, and 1% in North Dakota, with a total of ~22.4 million acres reported as tile drained for these states (Ghane 2024). The proportion of harvested cropland with tile drainage has been steadily increasing and is likely to continue, showing how impactful subsurface drainage is in the PPR (Ghane 2024).

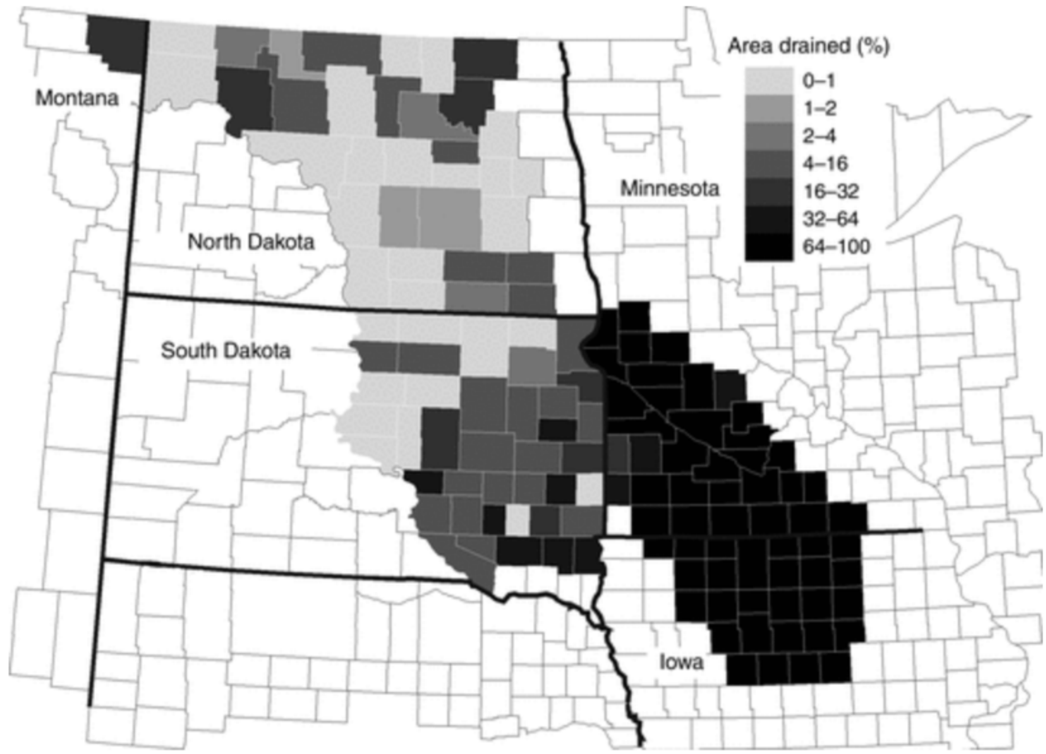

Figure 6: Percentage of total wetland area drained in counties of the PPR of the United States (Gleason et al. 2011).

2.4.3 Climate Change

The PPR spans a large area of north-central North America and climate varies considerably across the region. Overall, it is a cold-dry climate with evaporation rates exceeding precipitation, so water that has collected in wetlands is mostly lost to evapotranspiration (van der Kamp et al. 2016). There is a west-to-east precipitation gradient across the PPR, with drier conditions in the west and wetter in the east (Figure 7), and a north-south temperature gradient with temperatures increasing from north to south (Renton et al. 2015). Average annual precipitation ranges from the lowest in Montana at 25-43 cm to the greatest in Iowa at 66-104 cm (NRCS 2006). Average annual temperature is lowest in northern Montana at 3-7 degrees C and highest in Iowa at 7-13 degrees C (NRCS 2006).

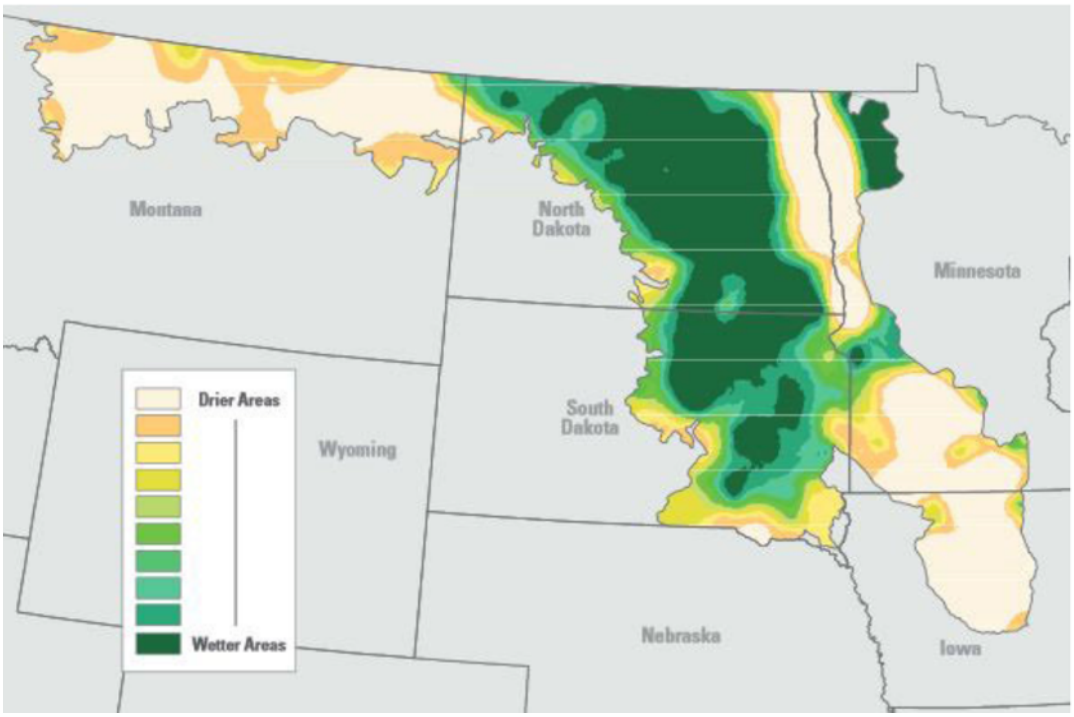

Figure 7: Map of climate in the Prairie Pothole Region (Dahl 2014).

Climate change is affecting landscapes across the world, and the PPR is no exception. According to the Intergovernmental Panel on Climate Change (2013), by the end of the century, PPR temperatures could increase between 3.7 and 6.1 degrees °C, and while precipitation is harder to predict, estimates range from an increase of 10% to a decrease of 5% from current conditions. Since wetlands in the PPR have a delicate water balance and complex nature, the PPR may be more vulnerable to drying out because of increased temperatures caused by climate change (Johnson and Poiani 2016). Climate change is expected to decrease the amount and duration of water storage, resulting in prolonged dry conditions within potholes (Renton et al. 2015). This will likely have a dramatic impact on the water depth and hydroperiod of wetlands, which will affect vegetation cover and productivity of semi-permanent wetlands (Rashford et al. 2016). Wildlife, such as waterfowl, in the PPR that are dependent on potholes, will also be affected by climate change because dried wetlands will not be able to provide valuable ecosystem services for birds that utilize prairie potholes for breeding grounds.

Climate also has an effect on land use and crop choice in adjacent uplands, which affects wetland water budgets indirectly. A warmer and drier climate may force farmers to change farming practices and shift crops because increased temperatures can affect the length of growing seasons and quicken crop maturity (Rashford et al. 2016). Farmers would in turn want to plant crops that can thrive in warmer drier conditions. These changes could negatively affect groundwater recharge and runoff, which are important aspects of wetland water budgets (Rashford et al. 2016).

Rashford et al. (2016) studied semi-permanent prairie potholes in North and South Dakota and used a climate simulator to model the effects of climate change on land use and wetland productivity. This research combined an ecological model of dynamics in wetlands with an economic model of land use change in agricultural fields. Results from the study show that climate change could have extreme consequences on land use in the PPR regions of North Dakota and South Dakota, with wheat displacing pastures and other major crops (Rashford et al. 2016). Their models indicate wetland productivity would be significantly reduced because of the pressure caused by land use and climate change. Results from this study also indicate that if temperatures increased by 4 °C, then this region of the PPR would not have the wetland productivity to support wetland-dependent species, like waterfowl (Rashford et al. 2016).

Johnson and Poiani (2016) used four phases of climate simulations to investigate how climate change would affect the hydrologic function and vegetation structure of wetlands located in the PPR over a 25-year period. They used the WETSIM (WETland SIMulator) 1 model to examine how climate change would alter water and vegetation patterns in prairie potholes and determine if these changes would affect waterfowl. Their results indicate that over four years, open water in wetlands will decrease from 50% to 38%, and after 11 years, open water will occupy only 27% of what was once covered (Johnson and Poiani 2016).

The second phase of this study used the WETSIM 3 model to determine the location of productive wetlands in sub-regional PPR climates and how they will grow, shrink, or move in the future based on three climate change scenarios: 1) and no change to precipitation, 2) 3°C temperature increase and 20% precipitation increase, and 3) 3°C temperature increase and 20% decrease in precipitation (Johnson and Poiani 2016). Results indicated that if temperatures increased by 3°C then the most productive wetlands would shift eastward toward Minnesota and cover a smaller area. If temperatures increased by 3°C and precipitation increased by 20%, then there would be less of a shift toward the east and a bigger area of wetlands productivity. Lastly, if temperatures increased by 3°C and precipitation decreased by 20%, then high-productivity wetlands would almost disappear throughout the PPR. (Johnson and Poiani 2016).

Phase three of this study used the WETLANDSCAPE-WLS Model simulation to show that each water permanence level (i.e., temporary, seasonal, semi-permanent) in the wetland complex would experience a decline in hydroperiod and water depth under increased climate warming scenarios without a precipitation increase (Johnson and Poiani 2016). Results indicate that based on the 18-year timescale used for the experiment under a 4°C temperature increase, water depth frequency for semi-permanent wetlands that exceeds 50 cm would decrease from 50% to 20% (Johnson and Poiani 2016). There would also be a decline in the water depth for seasonal wetlands that exceed 25 cm from a frequency of 30% to 15%. Finally, temporary wetlands that exceeded 25 cm of water depth would drop in frequency from 10% to 7% over the 18-year timescale (Johnson and Poiani 2016).

2.5 Land Uses/Land Covers

2.5.1 Conventional Agriculture

Agricultural practices have drastically changed over the centuries, and even in the past few decades. The Industrial Revolution, ending in the late 19th century, was the catalyst for many advancements during this time such as a major increase in population growth, rural-to-urban migration, the development of regulated agricultural markets, and the emergence of capitalist farmers (Hudson 2014). The Green Revolution, also known as the Third Agricultural Revolution, started in the 1940s and lasted until the 1970s (Patel 2013). This was a time when developed countries, especially the United States, made advancements to agricultural systems such as improving irrigation, creating hybrid seeding, and using more fertilizers to increase crop yields (Patel 2013). Another major advancement made during this time was the implementation of heavy machinery (Lal 2015). These advancements eventually made their way to developing countries where many people were struggling with starvation, and the results of these new agricultural techniques helped to reduce poverty in Asian countries and accelerate economic growth (Hazell 2010). Conventional agriculture today has been a result of the advancements made during the Industrial and Green Revolutions. Conventional agriculture uses mechanized equipment powered mostly by fossil fuels. Conventional farmers often depend on large financial investments, large-scale farms, monocultures, and extensive use of pesticides and fertilizers to increase their commodities (Fisher 2023). Conventional agriculture has helped to produce higher yields on less land, and it can be cheaper to produce products using these methods.

Tillage of agricultural fields is a common practice worldwide. There have been negative ecological effects as a result of conventional tillage, including increased erosion, non-point source pollution, and atmospheric greenhouse gas concentrations (Reicosky 2008). Intensive tillage systems have also been found to have negative effects on SOC concentrations (Lal 2013). Lal (2013) found that 25-75% of SOC around the world has been reduced because of intensive agricultural practices. Depleted SOC concentration of cropland soils in the upper 20 cm (i.e., SOC of 0.1%−0.5% in the plow layer) is one of the main causes of soil quality decline (Lal 2013). Arrouays and Pelissier (1994) found that after 35 years of using intensive farming practices, SOC storage in the upper 50 cm of soil declined by ~50%.

Many SOC studies done in the past have primarily focused on the upper ~30-50 cm of the soil. Soil scientists are now debating that to get more accurate SOC data, especially regarding tilled fields, deeper samples are needed to better understand SOC sequestration throughout the entire soil profile (Blanco-Canqui and Lal 2008). Blanco-Canqui and Lal (2008) argue that in deeper soil, SOC is stored inside soil aggregates which have lower turnover rates in conventional agricultural fields. They found that there is high variability in SOC depending on agricultural practice and sample depth. In the upper layers of the soil profile, SOC was relatively low for intensive tillage in certain samples (Blanco-Canqui and Lal 2008). Conversely, deeper in soil profiles with intensive tillage, SOC was at times higher compared to other agricultural practices (Blanco-Canqui and Lal 2008). Baker et al. (2007) found that when soils are tilled, crops may contain deeper roots, which can lead to a higher amount of SOC beneath the plowed layer. While more research needs to be done, this brings a new perspective on carbon sequestration in conventional agricultural fields. However, due to the wide-ranging environmental impacts, conventional agriculture as a whole has been criticized for decades, sparking debates and encouraging some farmers to find alternative methods.

2.5.2 Conservation Agriculture

Conservation agriculture is an approach to farming that has three main principles: minimize soil disturbance, diversify crops through crop rotations, and have continuous residue cover (e.g., cover crops or mulch) (Reicosky 2008). Conservation agricultural practices that will be investigated in this study are no-tillage, ridge tillage, and cover crops (single-species and multi-species) in croplands with corn-soybean rotations. These techniques are important for not only promoting soil health and reducing erosion, but they also have the potential to enhance carbon sequestration which could help reduce greenhouse gas emissions (Jat et al. 2020). Soil erosion has the most significant impact on SOC storage (Lal 2004), and no-till agriculture has the potential to greatly reduce erosion rates.

No-till agriculture is a technique that eliminates ground disturbance through plowing and instead leaves crop residue on the ground, then farmers use a special drill to insert seeds into the soil (Montgomery 2007). Organic matter remains on the surface, creating a barrier that increases infiltration and decreases runoff and erosion (Montgomery 2007). Besides reducing wind and water erosion and runoff, no-till has major environmental benefits including reducing water pollution, protecting water resources, increasing soil biodiversity, and reducing air pollution by using less energy compared to intensive tillage (Karayel and Šarauskis 2019). While it is not the main advantage, no-till has the potential to store high amounts of carbon in their soils, specifically the upper 30 cm (Blanco-Canqui and Lal 2008), due to increased input rates of SOC from plant root biomass and plant debris (Ontl et al. 2012) and decreased leaching, erosion, and mineralization of carbon (Lal et al. 2018).

Ridge tillage is a conservation agriculture practice in which farmers create a series of ridges on the top of previously planted rows and new crops grow from the residue of the older cultivation (Gregorich et al. 2001). While it is not as commonly used as no-till (Shi et al. 2012), ridge tillage has many benefits including enhancing soil fertility, reducing erosion, promoting multi-cropping, enhancing soil depth, and improving weed control (Lal 1990). Ridge tillage creates a unique soil environment due to its distinctive shape of alternating small ridges and troughs (Shi et al. 2012). Benjamin et al. (1990) emphasizes that having permanent ridges can promote plant growth and improve plant emergence due to the ridges and troughs providing superior water and temperature environments compared to flat fields. Similar to no-till agriculture, ridge tillage also has a high potential to store SOC. A study done by Shi et al. (2012), found that in ridge tillage fields, the inter-rows had the lowest SOC, the shoulder had a medium amount of SOC, and the crests had the highest amount of SOC. Compared to the ridge crests, the inter-rows had higher soil water content, but resistance to soil penetration was the opposite (Shi et al. 2012). This trend shows that ridge tillage can result in better soil physical conditions compared to no-till and in the ridge crest, higher SOC stock can be found compared to conventional tillage (Shi et al. 2012). Despite the advantages that ridge tillage has, this agricultural technique is underutilized because of the labor needed for upkeep, need for specialized equipment, possibility of increased phosphorus loss (Gaynor and Findlay 1995), and increased soil bulk density (Pikul et al. 2001).

Another form of conservation agriculture is planting cover crops. Cover crop's primary purpose is to benefit the successful growth of other future crops by reducing soil erosion, improving soil quality and fertility, crowding out weeds, controlling pests and diseases, and increasing biodiversity and wildlife (Fageria, Baligar, and Bailey 2005). Examples of common cover crops include cereal rye, buckwheat, and alfalfa as either a single species or part of a multi-species mix. In addition to many environmental benefits, cover crops also can enhance the ability of soils to sequester carbon (Lal 2004). Mazzoncini et al. (2011) did a study in Italy with cover crops in no-till fields and found that initially no-till fields increased SOC by 0.04 Mg C ha–1 y^{-1}, but after adding cover crops, SOC storage improved at a rate of 0.08 to 0.34 Mg C ha–1 y^{-1} in the upper 30 cm. Drinkwater et al. (1998) also found that cover crops can reduce carbon and nitrogen losses in soils. While the long-term effects of using cover crops to increase SOC in the terrestrial pool are not yet fully understood, like no-till and ridge tillage, cover crops can increase SOC in the short term and also have a plethora of environmental and soil benefits.

Conventional agriculture is still very prevalent across the world despite its negative impacts on soil, the environment, and climate change. Conservation farming techniques including no-tillage, ridge tillage, and cover crop all have major benefits including the reduction of soil disturbance and erosion, maintenance of permanent soil cover, plant diversification, and greenhouse gas depletion (Reicosky 2008). Sequestering carbon within soils is one of the best solutions for mitigating climate change and increasing SOC, at least in the short term, and can be accomplished using conservation agriculture methods. For these methods to be used more widely, farmers should be given compensation for switching to conservation agricultural practices, especially if their intentions for adopting these methods are to lower atmospheric carbon and sequester more SOC (Lal 2013).

2.5.3 Conservation Reserve Program

The Conservation Reserve Program (CRP) is one of the largest conservation programs in the United States. It was re-established as a federal conservation program with the 1985 farm bill and is designed to protect environmentally sensitive land from the impacts of agriculture. It is a voluntary program that pays farmers to convert cultivated cropland to native vegetation with the primary goals of reducing erosion, improving water quality, and establishing wildlife habitat (Phillips et al. 2015).

Farmers who are enrolled in CRP get a yearly rental payment, and in exchange, farmers must remove environmentally sensitive land from agricultural use and then plant species that will help enhance the land's overall environmental health (USDA 2022). Land is typically enrolled in CRP for 10-to-15-year periods. For land to be eligible for CRP enrollment, it must fit one or more of the following criteria: 1) "Highly erodible cropland that is planted or considered planted in 4 of the previous 6 crop years, and that can be planted in a normal manner; 2) marginal pasture that is suitable for use as a riparian buffer or for similar habitat or water quality purposes; 3) ecologically significant grasslands that contain forbs or shrubs for grazing; or 4) a farmable wetland and related buffers," (USDA 2022). CRP provides significant environmental benefits to the Great Plains region, including large portions of the PPR. From 2012 to 2021, total acres enrolled in CRP declined by more than 9 million acres, primarily due to expiring CRP contracts and reverting the land to crop production. Beginning in 2017, the USDA reduced CRP rental payments to landowners, which was likely a factor in several farmers deciding not to re-enroll in the program (USDA 2022).

While the primary goals of the CRP are to reduce erosion, protect water quality, and improve wildlife, by re-establishing native vegetation the carbon sequestration potential of lands enrolled in CRP may also increase. The effectiveness of the CRP in enhancing the ability of prairie potholes enrolled in CRP to sequester carbon in their soils is not well understood. Phillips et al. (2015) investigated prairie potholes enrolled in CRP and farmed potholes in North Dakota and determined that average values of SOC in the upper 10 cm of soil in CRP land (25.39 Mg ha^{-1} SOC) were significantly higher than in cropland (21.90 Mg ha^{-1} SOC). From a depth of 10-20 cm, SOC averaged 18.31 Mg ha^{-1} for cropland and 19.88 Mg ha^{-1} for land enrolled in CRP (Phillips et al. 2015). This study also indicates that sandy loam soils stored more SOC than clay loam soils. Reeder et al. (1998) conducted a similar study in Wyoming comparing carbon and nitrogen levels in long-term croplands, short-term cultivated fields, and converted grasslands after six years. In long-term croplands, SOC decreases by 23-26% over the six-year time period, mainly in the upper 2.5 cm. Cropland did have greater SOC content with increasing depth, likely due to deep plowing and mixing of horizons (Reeder et al. 1998). Short-term cultivated fields had similar results to the long-term cropland. In restored grasslands, SOC increased particularly in the upper 10 cm to the same amount or more than in native grasslands. This increase in SOC in restored grasslands is likely due to higher levels of plant biomass (Reeder et al. 1998).

2.6 Carbon Dynamics

2.6.1 Carbon Cycle

The carbon cycle is the continual process in which carbon moves between the five major global carbon pools: 1) oceanic pool (~38,000 Pg), 2) geologic pool (~4,130 Pg), 3) pedologic pool (~2,500 Pg), 4) atmospheric pool (~760 Pg), and 5) biotic pool (560 Pg) (Lal 2008). The amount of carbon in our planet and its atmosphere does not change because we are in a closed environment, rather carbon is constantly cycling between the various carbon pools (NOAA 2023). The carbon cycle can be divided into fast and slow carbon cycles. The fast carbon cycle can be completed within a few years to several decades, with carbon transferring between the atmosphere and the biosphere (Riebeek 2011). The slow carbon cycle takes much longer, sometimes millions of years, as carbon moves through the Earth's crust, oceans, soils, and atmosphere (Riebeek 2011). CO_2 and methane (CH_4) are the two main forms of carbon that exist in Earth's atmosphere. CO_2 contributes to the greenhouse effect more than methane because while methane in the atmosphere produces a larger greenhouse effect per volume, it is found in much smaller concentrations and is shorter-lived (Forster et al. 2007).

Photosynthesis is the primary process that removes CO_2 from the atmosphere and transfers it into the pedogenic (Figure 8) and oceanic pools (Lal 2008). The pedogenic pool is made up of two main components, SOC (~1,550 Pg) and soil inorganic carbon (SIC) (~950 Pg) (Lal 2008). SOC is made up of a mixture of living organisms, plants and animal remains in different phases of decomposition, and substances that have been chemically or microbiologically synthesized (Schnitzer 1991). SIC are chemical compounds that lack carbon-hydrogen bonds and are primarily comprised of minerals such as dolomite, calcite, and gypsum (Ghadban and Cheprasov 2023). Once carbon is transferred from the atmosphere to plant biomass, the biomass is converted into stable SOC through organo-mineral formations as the biomass breaks down (Lal 2018). As plant biomass decomposes in the soil, a portion of the biomass is mineralized to form SIC as carbonates and bicarbonates (Lal 2018).

Soil texture (i.e., percent sand, silt, and clay), also has a role in the amount of carbon stocks in soil (Ontl 2012). Soils that are made up of clay and silt are much more likely to store carbon than sand because they are more porous and can retain more organic matter (Iranmanesh and Sadeghi 2019). SOC levels also depend on high soil fertility, the potential of a certain soil to assist in plant growth, which is most common in clay and silty soils (Yost and Hartemink 2019). While sand overall may not store as much carbon as silt or clay, it still has the capacity to store carbon. Studies have suggested that SOC accumulation in sand seems to happen once clay and silt have reached their SOC capacity (Carter 2002). Research has also found that when sandy soils are fertilized, SOC tends to increase (Yost and Hartemink 2019). The effect that soil texture has on SOC is further complicated with the addition of land cover and what agricultural practice is being used (Six et al. 2002), so more research needs to be done to understand the full effects of soil texture on carbon storage.

Carbon returns to the atmosphere from the pedosphere when soils are degraded and organic matter decomposition outpaces accumulation (NOAA 2023). Humans play a fundamental role in the carbon cycle because of activities such as land use change and development (NOAA 2023). The conversion of lands to crop fields specifically has affected the carbon that is being released into the atmosphere. Soil decomposition increases when farming techniques, such as tilling, physically disrupt organic matter, which releases carbon back into the atmosphere (Janzen 2004). From 1850 to 2000, the net cumulative emissions were ~156 Pg C due to changes in land use (Houghton 2003). Humans are also disrupting the carbon cycle in a major way by burning fossil fuels. With the burning of fossil fuels, we are disturbing a carbon source that has been dormant for millions of years and bringing it back into the carbon cycle (Janzen 2004). If humans were to burn the entire coal supply on Earth, the CO_2 concentration in the atmosphere could reach ~2000 ppm (Kump 2002). That is why carbon sequestration in soils is so important, it is a crucial part of how we can balance out the excessive greenhouse gases that are entering the atmosphere and restore a balance to the carbon cycle.

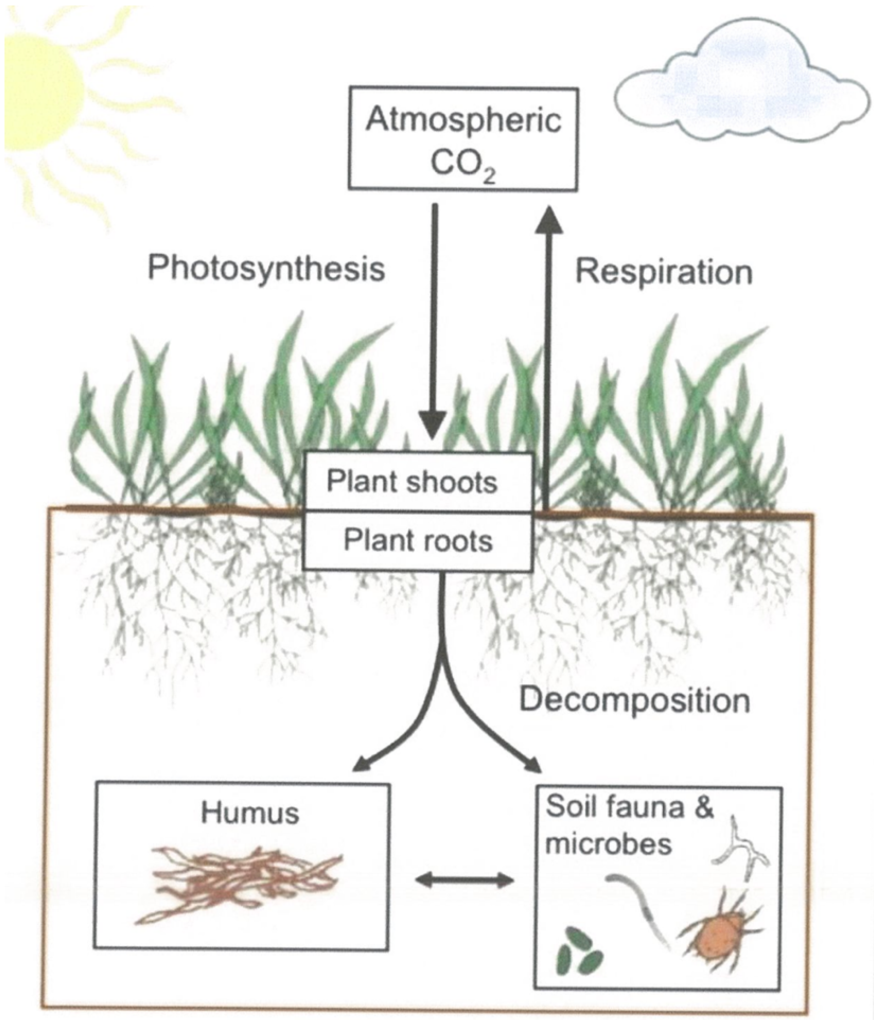

Figure 8: CO_2 moving throughout the soil and the atmosphere due to photosynthesis (Nature Education 2012).

2.6.2 Carbon Sequestration by Landscape Type

Given the current and projected impacts of climate change, reducing atmospheric greenhouse gas concentrations is of high priority. One of the most effective ways to reduce atmospheric CO_2 concentrations is by sequestering carbon in soils. However, various types of landscapes (e.g., croplands, grasslands, forests, and wetlands) have different soil carbon sequestration potentials due to differences in climate, soil development, soil texture, land use, land management, and the use of amendments (Lal 2018). Some of the landscapes that have the best potential to store carbon are croplands, grasslands, forests, and wetlands.

Croplands are some of the largest contributors to global greenhouse gas emissions, particularly CO_2. Croplands have some of the most depleted soil carbon stocks due to human disturbances to the land such as irrigation, fertilization, and especially tillage (Lorenz and Lal 2012). These activities lead to the decomposition of soil organic matter, changes in bulk density, and increased erosion, all of which negatively affects soil quality (Lindstrom, Lobb, and Schumacher 2001). This means that croplands have a high potential for SOC sequestration and soil function restoration because land improvement is possible (Lal 2018). Recommended management practices to create positive soil carbon budgets in croplands include no-tillage, cover crops, and erosion control to reduce carbon loss in soils while organic amendments such as compost, manure, and crop residues can increase carbon input to soils (Ontl 2012). With these changes in how croplands function, the improvement and maintenance of soil health can be achieved. Farmers can ultimately be at the forefront of reducing greenhouse gas emissions, sequestering carbon into their soils, and increasing resilience to extreme weather conditions associated with climate change.

Another landscape that has a high potential to store carbon is grasslands. Native grasslands are extremely important for global carbon storage, sequestering ~34% of terrestrial carbon (White et al. 2000). Due to their highly productive soils, ~50% of temperate grasslands and ~16% of tropical grasslands across the world have been converted into croplands or used for agricultural purposes (Castaño-Sánchez, Izaurralde, and Haynes 2021). Since native grasslands are a natural carbon sink, the conversion to agricultural land reduces the ability of the land to store sufficient amounts of carbon and contributes carbon into the atmosphere (Castaño-Sánchez, Izaurralde, and Haynes 2021). In more recent years, efforts have been put forward to convert some of these croplands back to grasslands. When former crop fields are restored to grasslands, the grasses can sequester carbon better than crops because of their high root productivity, which in turn can help reduce years of carbon deficiency caused by agricultural production (Ontl 2012). Due to the persisting nature of grasslands, their SOC stocks are high and there is a constant flux of carbon from aboveground vegetation into the soil through roots and plant decomposition (Zimmermann, Dauber, and Jones 2012). Carbon sequestration in grasslands can be increased by restoring degraded grasslands, applying fertilizer, improving grazing management, sowing certain species, bettering irrigation, and more (Ghosh and Mahanta 2014). SOC sequestration potential in grazing land and pasturelands globally is around 0.3–0.7 Pg C/year at an average rate of 0.3–0.7 Mg C ha^{-1} $year^{-1}$ (Lal 2008). Conversion from croplands to restorative grassland and the adoption of management practices have the potential to create a regenerative soil ecosystem which can lead to better carbon sequestration rates in their soils.

Due to rapid urbanization and deforestation in tropical and temperate areas, forest landscapes throughout the world have declined. Forests are an important carbon sink given their living biomass, root systems, and surface detritus (Fahey et al. 2010). Forests are organic matter rich, which provides soils with nutrients, enhances soil physical properties and water-holding capacity, and increases total carbon content in soil (Grigal and Vance 2000). Given the dramatic loss in forests and their role in the global carbon cycle, forest ecosystems need to be protected and resorted. Afforestation is the establishment of forest in an area currently lacking tree cover, which is an effective strategy to replenish SOC in depleted soils (Lal 2018). According to Dyson (1977), afforestation can mitigate CO_2 accumulation in the atmosphere at a rate of 4.5 Pg C/year annually. If management is successful, forests could be a net carbon sink, offsetting a portion of anthropogenic greenhouse gas emissions (Brown et al. 1996).

Wetlands are an important landscape type to mitigate climate change because of their potential to store large quantities of carbon. Due to their high primary productivity and anoxic conditions that slow decomposition rates, wetlands are possibly the best ecosystem for sequestering atmospheric CO_2 (Lal et al. 2018). Carbon dynamics in wetlands are complicated as the inputs and outputs of carbon depend on the geology and topographic position of the wetland, vegetation type and density, hydrology, soil moisture, temperature, pH, and wetland morphology (Adhikari, Bajracharaya, and Sitaula 2009). Peatlands specifically have been widely recognized as an important carbon storage pool since they store 400–500 Gt C while only covering 3% of land area globally (Roulet 2000). Wetland degradation and drainage has altered their hydrology and anaerobic conditions, leading to increased organic matter decomposition rates and loss of stored carbon to the atmosphere (Adhikari, Bajracharaya, and Sitaula 2009). Therefore, protecting wetlands is vital to retain and increase the existing carbon in their soils.

2.6.3 Carbon Dynamics by Land Covers and Topographic Position

This study investigates soil carbon dynamics in prairie potholes not only within different land covers (i.e., native grassland, CRP, conservation agriculture, and conventional agriculture) but also along toposequences (i.e., shoulder, backslope, toeslope, edge, half, and center positions). A toposequence is a sequence of soils along a slope that differ in topography but otherwise have similar features (Schaetzl and Anderson 2005). Topographic position is one of five soil-forming factors and influences a variety of geomorphic and pedogenic processes, resulting in significant differences in soil properties among landscape positions (Jenny 1941). As a result, carbon sequestration potential is likely in part controlled by topographic position.

Tangen and Bansal (2020) analyzed 549 wetlands in the PPR to study SOC in different positions of the landscape such as the upland, toeslope, wetland transition, and inner wetland as well as how different land uses and soil depths affect carbon accumulation. Results indicate that the inner landscape position had the highest SOC at 5.69%, 4.07%, and 4.29% for the natural, restored, and cropland land uses, respectively (Tangen and Bansal 2020). SOC stock decreased as the wetland transitioned to the upland for all land uses and at both depths (0-15 cm, 15-30 cm), with the inner wetland having the most SOC and the upland having the least (Tangen and Bansal 2020). Natural sites had the most carbon in every position and every depth besides the inner wetland at 15-30 cm, in which cropland had the highest SOC (Tangen and Bansal 2020). This study found that SOC decreased by ~1.5-2 times along toposequence from the inner wetland to the upland (Tangen and Bansal 2020). The inner position undergoes long periods of saturation which slows down decomposition rates, leading to higher SOC stocks due to large amounts of organic matter accumulation (Tangen and Bansal 2020).

De et al. (2020) investigated soil health, including SOC, along a series of chronotoposequences in the PPR to determine recovery time after converting cropland to CRP grassland at a variety of topographic positions. Results showed that native grasslands stored more SOC than cropland and most CRP soils. Mean SOC concentration of native grasslands was 39 ± 1.7 g SOC kg^{-1}, which is 38% greater than cropland soils (28.4 ± 1.3 g SOC kg^{-1}) and 19–62% greater than almost all CRP soils (24–33 g SOC kg^{-1}) (De et al. 2020). Soil that had been enrolled in CRP for 40 years still had lower SOC concentrations than native grasslands. It was determined that enrollment in CRP resulted in a mean annual increase of 0.18 g SOC kg^{-1} of soil (De et al. 2020). Topographic position also influenced SOC concentrations as mean concentrations of SOC were highest in the toeslope position and were ∼50% higher than in the shoulder position (25.1 ± 1.1 g SOC kg^{-1}) (De et al. 2020). The shoulder was the only position with a large increase in SOC over time (De et al. 2020). Investigating topographic position was extremely important in this study because the results showed that soil health is highly influenced by topographic position. It was found that the shoulder position had the greatest recovery overall when reestablished to grassland, likely because of extreme degradation due to earlier cropland cultivation (De et al. 2020).

Zhu et al. (2019) studied the effects of topography on SOC in semiarid alpine grasslands in China. This research focused on mountainous regions with more dramatic changes in topography than the PPR but provides insight into the impacts of changes in relief on SOC. Samples were taken from the summit, shoulder, backslope, footslope, and toeslope positions at three elevation-dependent grassland types (i.e., subalpine meadow, montane steppe, and montane desert steppe) and four different depths (i.e., 0–10, 10–20, 20–40, and 40–60 cm). SOC content varied by elevation zone, with subalpine meadow having the lowest elevation and highest SOC (~37.70 g m^{-2}), montane steppe with intermediate elevation and SOC (~18.21 g m^{-2}), and montane desert steppe with the highest elevation and lowest SOC (~11.06 g m^{-2}) (Zhu et al. 2019). SOC content also varied slightly along the toposequences. They found that the toeslope position had the highest SOC with 49.52 kg m^{-2}, 31.76 kg m^{-2}, and 14.98 kg m^{-2} for the subalpine meadow, montane steppe, and montane desert steppe, respectively (Zhu et al. 2019). The shoulder position had the lowest SOC stocks throughout by a factor of 1.44 for subalpine meadows, 2.31 for montane steppes, and 1.38 for montane desert steppes (Zhu et al. 2019). There were fewer variations among the other topographic positions in the subalpine meadow and montane steppe, but in the montane desert steppe, the summit position specifically had a very low SOC (Zhu et al. 2019). Researchers stated that high SOC in subalpine grasslands can be attributed to the warmer climate and poorer drainage compared to alpine areas. It was also emphasized that the toeslope position had the highest SOC stock generally because the lower landscape positions are less eroded compared to the upper positions (Zhu et al. 2019). These studies emphasize the importance of investigating topographic positions in relation to carbon sequestration.

Chapter 3 Study Area

This study includes 12 prairie pothole research sites distributed throughout three counties in southern Minnesota (i.e., Cottonwood, Martin, and Waseca counties) (Figures 9 and 10). Prairie potholes and their surrounding landscapes were investigated along a toposequence/catena in each county, with soil cores collected from the shoulder, backslope, toeslope, pothole edge, pothole half radius, and pothole center. Land use for research sites included conventional tillage agriculture with no cover crops (n = 1), ridge tillage agriculture with no cover crops (n = 1), Conservation Reserve Program grasses (n = 1), and native grasses (n = 1) in Cottonwood County, no-till agriculture with multi-species cover crops (n = 2), conventional tillage agriculture with no cover crops (n = 1), and Conservation Reserve Program grasses (n = 1) in Martin County, and no-till agriculture with single-species cover crops (n = 2) and Conservation Reserve Program grasses (n = 2) in Waseca County.

All three counties included in this study are located within the PPR, a region characterized by generally flat to gently rolling hills, with numerous lakes and fertile soils, which makes it highly suitable for intensive agricultural production. All three counties are within Natural Resources Conservation Service (NRCS) Land Resource Region M – Central Feed Grains and Livestock Region and Major Land Resource Area (MLRA) 103 – Central Iowa and Minnesota Till Prairies (Figure 11). Around 80% of land in the MLRA 103 is used for cropland since the soils and topography are ideal for agricultural production (NRSC 2006). Hydric soils are common due to lack of natural drainage in this relatively flat landscape dominated by clay-rich glacial tills. MLRA 103 is geologically young due to the retreat of the Wisconsin Glaciation around 14 to 10 ka (Prior 1991). The Des Moines Lobe of the Wisconsin Glaciation extended to Des Moines Iowa and covered most of southern Minnesota, including the Cottonwood, Martin, and Waseca counties. As the LIS melted and retreated it left behind blocks of detached ice that become buried over time and then melted fully, creating depressional prairie pothole wetlands (Wade 2013).

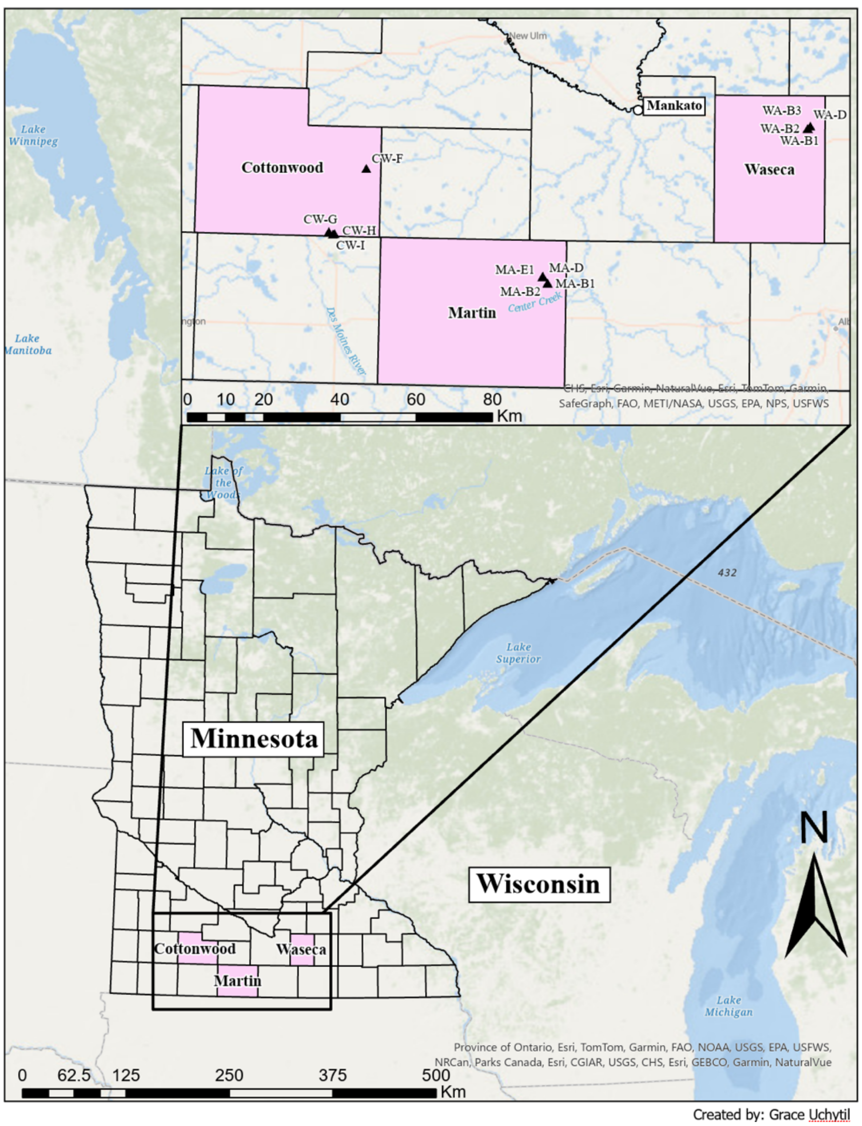

Figure 9: Prairie pothole research sites located in Cottonwood, Martin, and Waseca counties in southern Minnesota.

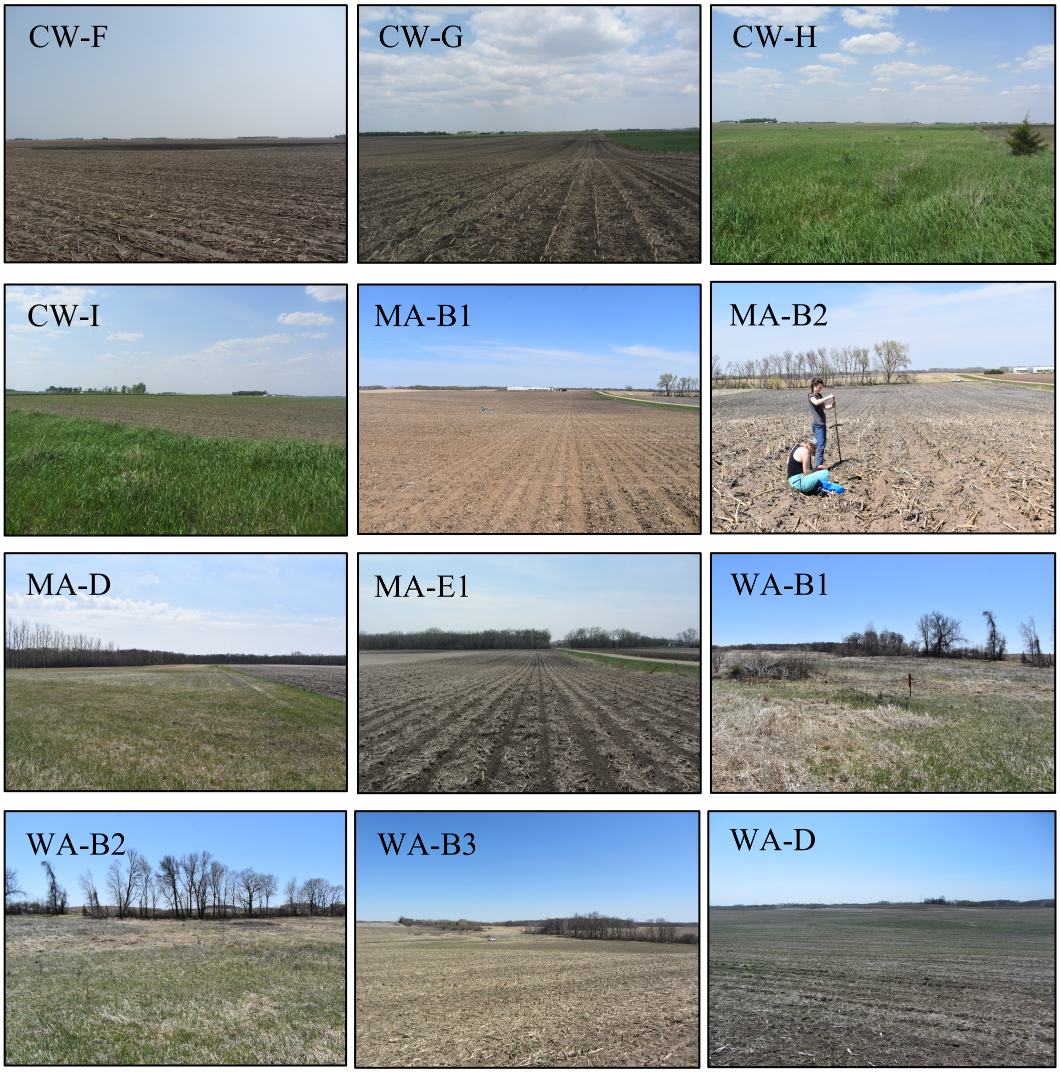

Figure 10: Photos of prairie pothole research sites.

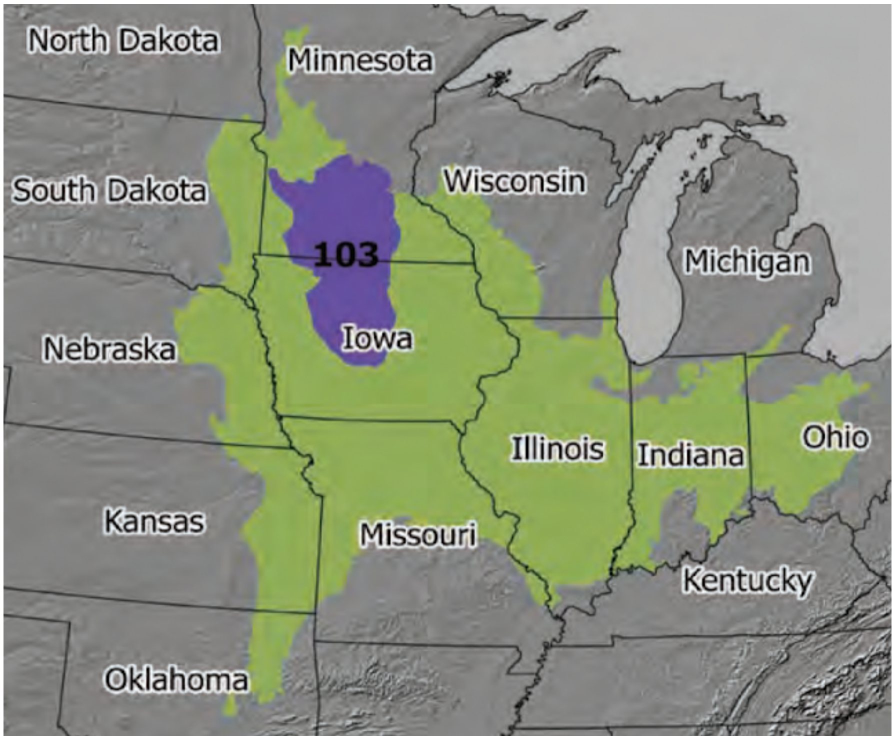

Figure 11: Research sites are located in Land Resource Region M: Central Feed Grains and Livestock Region (area shaded green) and Major Land Resource Region 103: Central Iowa and Minnesota Till Prairies (area shaded purple) (NRCS 2006).

3.1 Physiography and Topography

Southern Minnesota is characterized by relatively flat uplands with deeply incised drainage networks. Local relief on the uplands for most of the region is typically less than 6 m, while relief between uplands and floodplains can be greater than 500 m (NRCS, 2006). Research sites for this investigation were generally situated on the relatively low relief uplands. In Cottonwood County, sites F, G, H, and I had relief of 2.7 m, 4.9 m, 2.1 m, and 2.4 m from the shoulder position to the pothole center, respectively (Figures 12, 13, 14, and 15). In Martin County, sites B1, B2, D, and E1 had relief of 4.9 m, 4.6 m, 3.0 m, and 1.8 m from the shoulder position to the pothole center, respectively (Figures 16 and 17). In Waseca County, sites B1, B2, B3, and D had relief of 2.7 m, 1.5 m, 10.4 m, and 13.1 m from the shoulder position to the pothole center, respectively (Figures 18, 19 and 20).

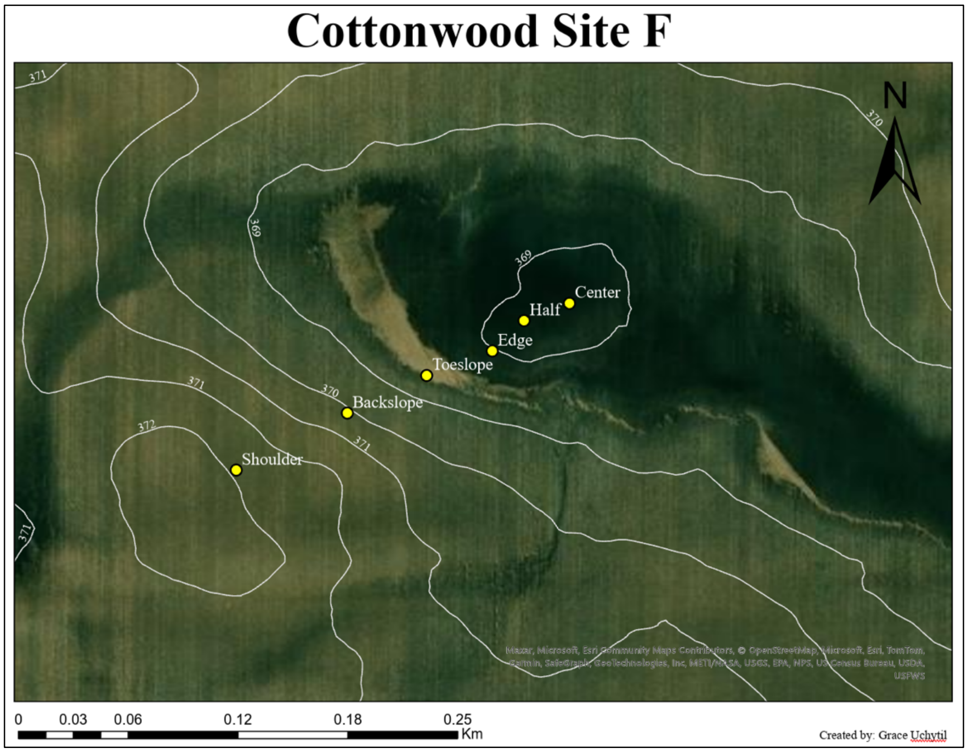

Figure 12: Aerial and topographic map of Site F in Cottonwood County (ArcGIS Pro).

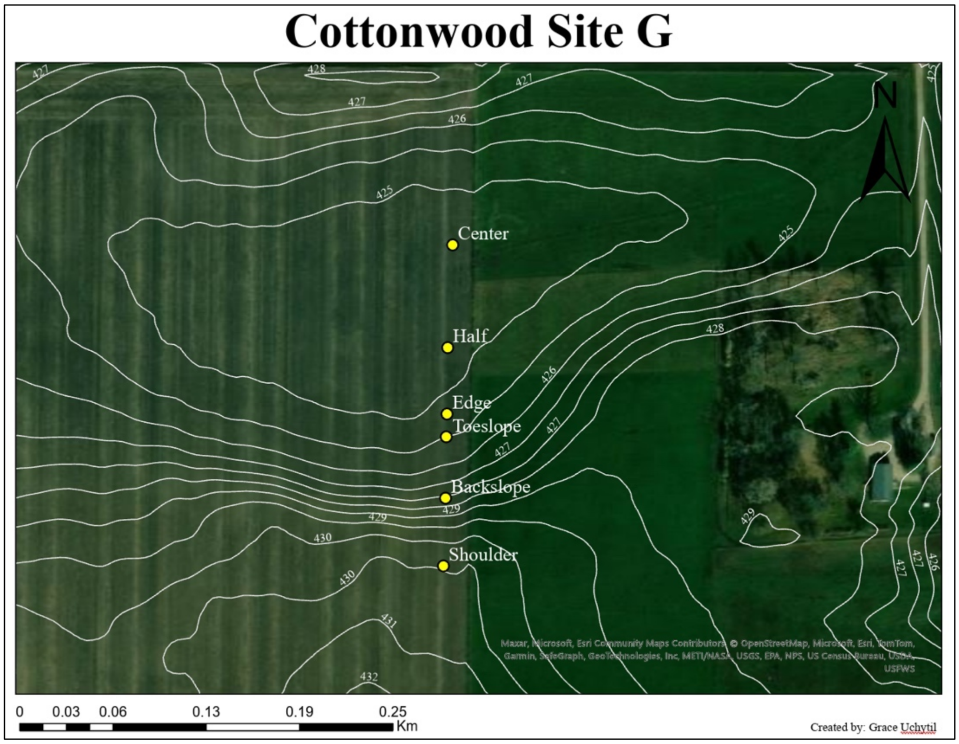

Figure 13: Aerial and topographic map of Site G in Cottonwood County (ArcGIS Pro).

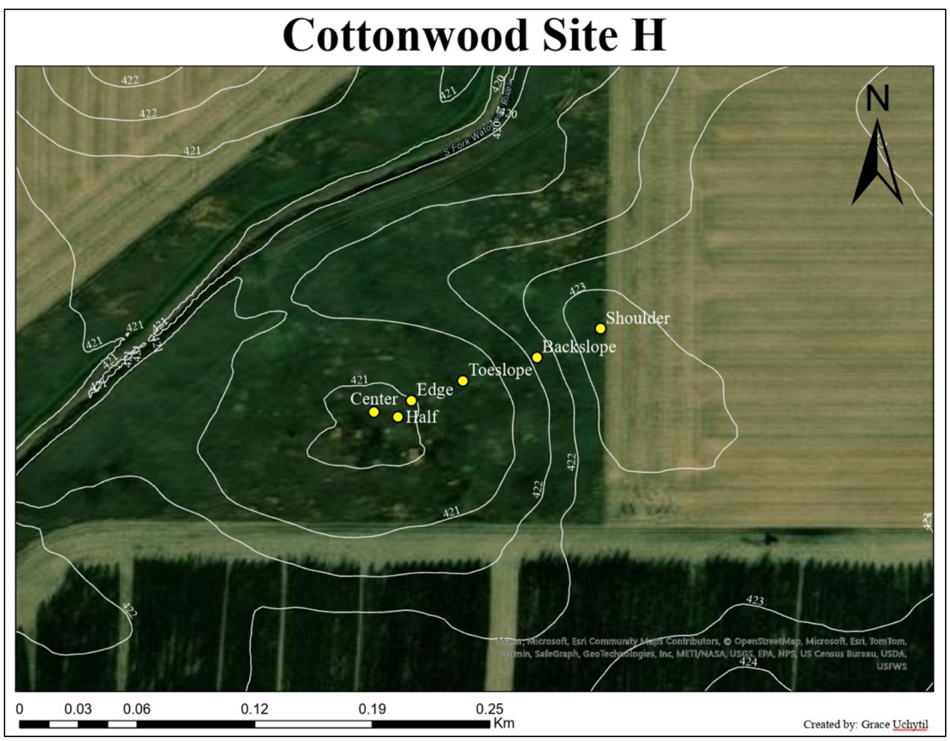

Figure 14: Aerial and topographic map of Site H in Cottonwood County (ArcGIS Pro).

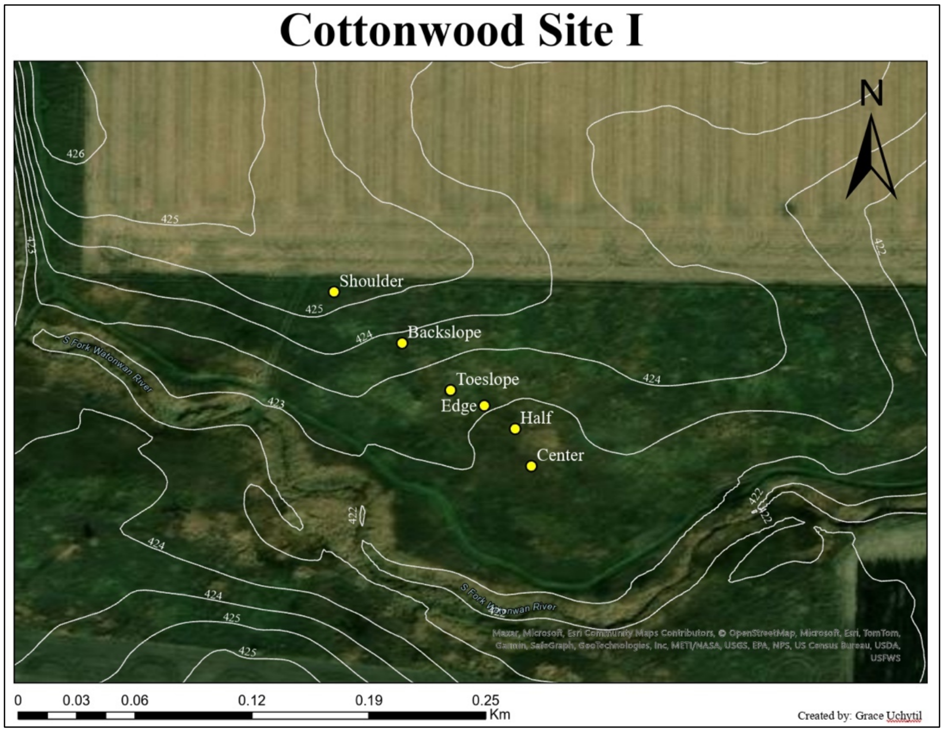

Figure 15: Aerial and topographic map of Site I in Cottonwood County (ArcGIS Pro).

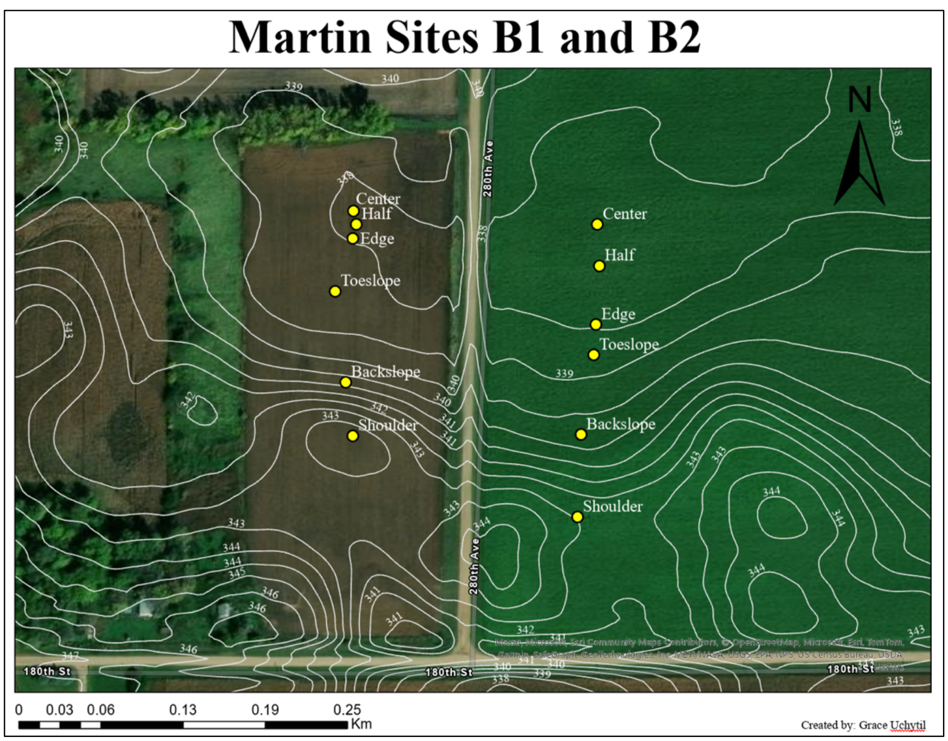

Figure 16: Aerial and topographic map of Sites B1 and B2 in Martin County (ArcGIS Pro).

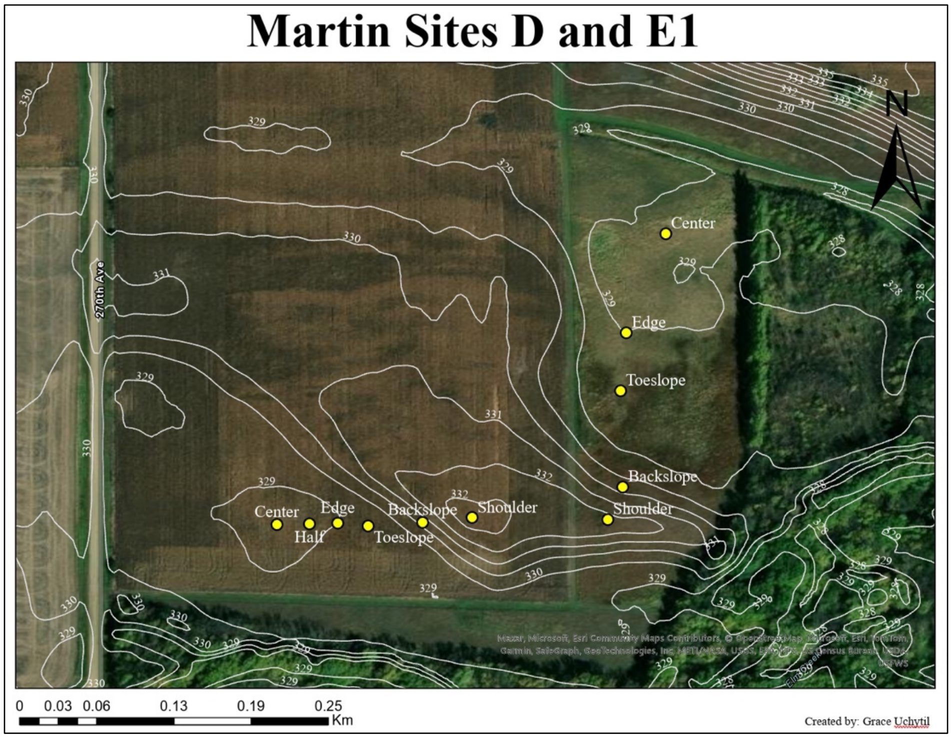

Figure 17: Aerial and topographic map of Sites D and E1 in Martin County (ArcGIS Pro).

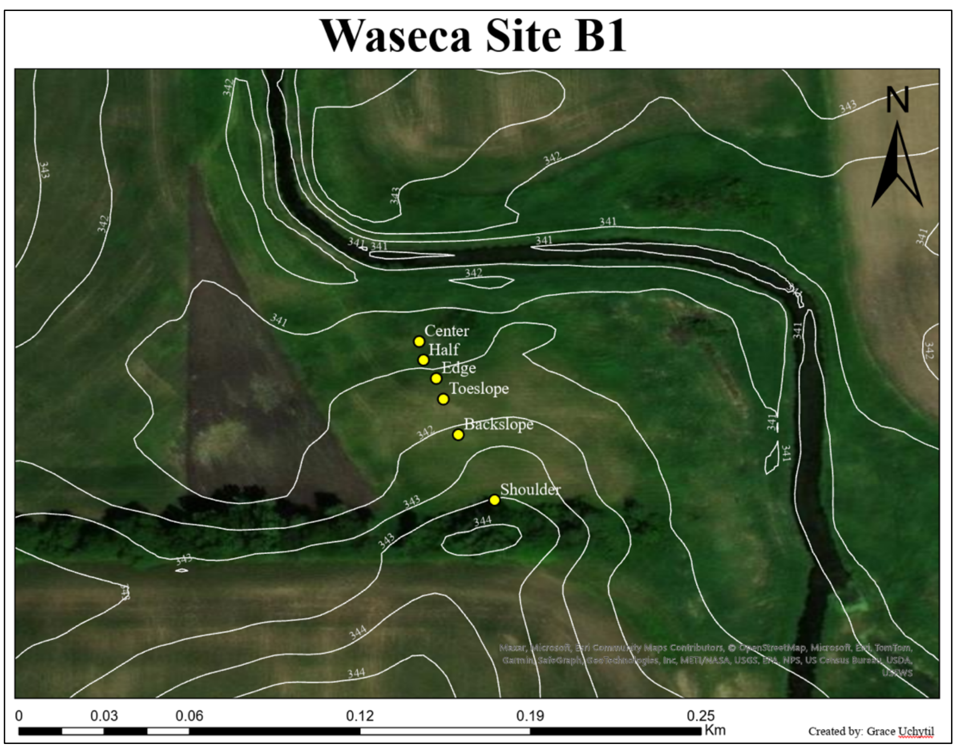

Figure 18: Aerial and topographic map of Site B1 in Waseca County (ArcGIS Pro).

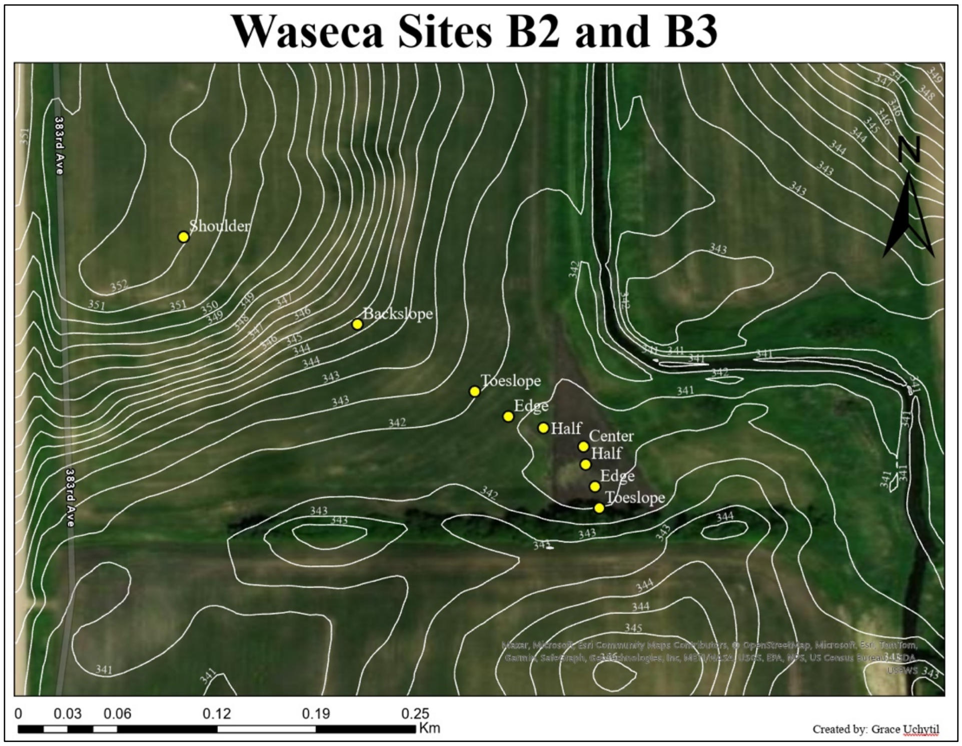

Figure 19: Aerial and topographic map of Sites B2 and B3 in Waseca County (ArcGIS Pro).

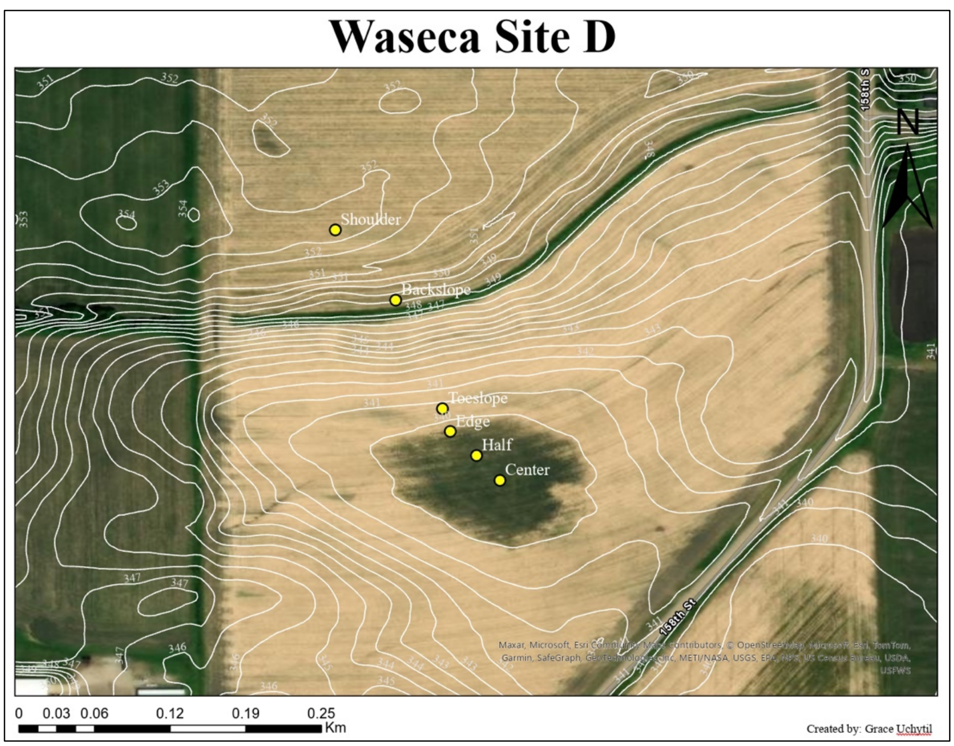

Figure 20: Aerial and topographic map of Site D in Waseca County (ArcGIS Pro).

3.2 Climate and Weather

Minnesota climate is classified as either Dfa (hot-summer humid continental) or Dfb (warm-summer humid continental) within the Köppen climate classification scheme (Figure 21). Cottonwood and Martin counties are located in the Dfa climate class and Waseca is located in the Dfb climate class. In the Köppen climate classification, "D" indicates that for at least one month of the year average temperature is below 0 degrees, “f” indicates there is no dry season, “a” indicates that for at least one month of the year average temperature is above 22°C, and “b” indicates that average monthly temperature for all months is below 22°C (Beck et al. 2005).

Climate is generally similar among Cottonwood, Martin, and Waseca counties. In Windom, MN (Cottonwood County), mean annual temperature is 8.1ºC (46.5ºF), ranging from a monthly mean of 23.1ºC (73.5ºF) in July to -8.3ºC (17ºF) in January (U.S. Climate Data 2023). Mean annual precipitation at Windom is 77.7 cm (30.6 in) with an additional 109.2 cm (43 in) of snowfall, and ranges from 11.5 cm (4.6 in) in June to 1.8 cm (0.7 in) in February with the bulk of the precipitation (~70%) falling from April to September (U.S. Climate Data 2023).

In Winnebago, MN (Martin County), mean annual temperature is 7.5 ºC (45.5 ºF), ranging from a monthly mean of 22.5 ºC (72.5ºF) in July to -9.7 ºC (14.5ºF) in January (U.S. Climate Data 2023). Mean annual precipitation in Winnebago is 83.1 cm (32.7 in) with an additional 114.3 cm (45 in) of snowfall, and ranges from 11.7 cm (4.6 in) in June to 2.0 cm (0.8 in) in February with the bulk of precipitation (~73%) falling from April to September (U.S. Climate Data 2023).

In Waseca, MN (Waseca County), mean annual temperature is 7.2 ºC (45ºF), ranging from a monthly mean of 22.2 ºC (72ºF) in July to -10.6ºC (13ºF) in January (U.S. Climate Data 2023). Mean annual precipitation in Waseca is 90.7 cm (35.7 in) with an additional 137.2 cm (54 in) of snowfall, and ranges from 12.1 cm (4.8 in) in August to 2.5 cm (1 in) in February with the bulk of precipitation (~69%) falling from April to September (U.S. Climate Data 2023).

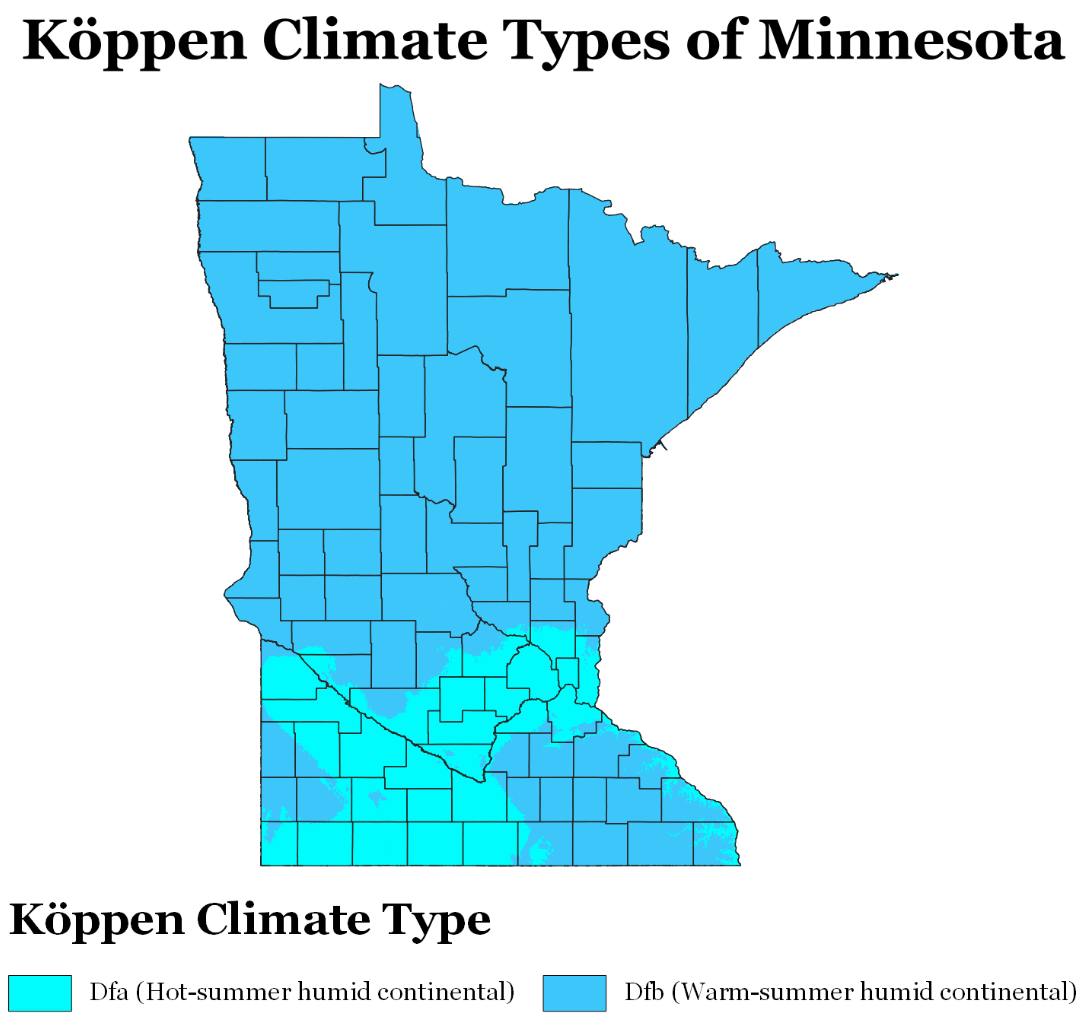

Figure 21: Minnesota Köppen Climate Map (PRISM Climate Group, Oregon State University 2023).

3.3 Surface and Groundwater Hydrology

Agricultural land in Minnesota is commonly drained using tile drainage to remove excess water from poorly drained soils and wet areas (Singh et al. 2006). Agricultural fields in southern Minnesota with a large number of prairie potholes are drained excessively to keep these fields dry due to the additional water that potholes store. This is important for farmers in Minnesota because tile drainage can extend their growing season, diversify crop options, and increase property access. Tile drainage also has environmental benefits. Hydrologically, tile-drained fields have more temporary storage space for water because tile drainage improves soil structure which increases porosity (Van Vlack and Norton 1944). More water is able to infiltrate into the soil profile, thus reducing surface runoff volumes. Reduced surface runoff can result in decreased soil, chemical, and nutrient losses from an agricultural field and can also decrease peak flows and total volumes lost from the watershed (Fraser et al. 2001). Tile drainage is ubiquitous in Cottonwood, Martin, and Waseca counties, and tile drains have been installed at all sites included in this study except Cottonwood I, a small portion of remnant prairie and Martin B2. Drainage ditches that receive outflow from tile drainage are immediately adjacent to sites H and I in Cottonwood County, sites D and E1 in Martin County, and sites B1, B2, and B3 in Waseca County.

Surface water is water located on top of land, forming waterbodies. Most surface water at these sites is produced by precipitation and run-off. While fields can capture surface water, rivers and lakes are the most abundant surface water sources in Minnesota. Minnesota’s total surface water area, including wetlands, is approximately 13,136,357 acres (Minnesota Department of Natural Resources 2013). Regionally, Fish Lake and multiple smaller lakes can be found near sites G, H, and I in Cottonwood County, Elm Creek passes by sites D and E1 in Martin County, and Rice Lake, Clear Lake, and Watkins Lake are located southwest of sites B1, B2, and B3 in Waseca County. Since these surface water areas are close to or within agricultural fields, they may be affected by phosphorous and nitrogen pollutants entering their waters. These chemicals can cause a variety of problems such as toxic algal blooms, loss of oxygen, loss of biodiversity, degradation of aquatic ecosystems, and diminishing the use of water for drinking (Carpenter 1998). Groundwater on the other hand is often pumped by surficial and bedrock aquifers which are common in southern Minnesota, they consist of thick, laterally extensive sequences of sandstone, siltstone, limestone and sedimentary dolostone (DNR 2023). The mean water table depth for Cottonwood, Martin, and Waseca counties is two feet (Minnesota Natural Resource Atlas 2024).

3.4 Land Use and Land Cover

Minnesota's natural land cover transitions from native grassland in the south and west to forested areas in the north and east (Figure 22). Native vegetation of southern Minnesota was predominantly tall grass prairie consisting of a variety of grasses and forbs such as Bluestems (*Andropogon gerardii*), Indian Grass (*Sorghastrum nutans*), Needlegrass (*Nassella viridula*), and Grama (*Boutelouinae Stapf*) grasses. However, little natural vegetation remains as most of the native prairie has been converted to cropland. Farmers in this region have introduced intensive cropping systems that have caused these grasslands to experience large anthropogenic transformations (Hoekstra 2005). Corn and soybeans are two of the main crops in Cottonwood, Martin, and Waseca counties. As of 2017, Cottonwood County at 168,080 hectares had 67,630 hectares in corn (~40% of the county) and 61,522 hectares in soybeans (~36.6% of the county) (USDA 2017). Martin County at 189,069 hectares had 97,641 hectares in corn (~51.6% of the county) and 72,474 hectares in soybeans (~38.3% of the county), and Waseca County at 112,146 hectares had 45,821 hectares in corn (~40.9% of the county), and 38,833 hectares in soybeans (~34.6% of the county) (USDA 2017).

In Cottonwood County, land use/land cover at research sites included conventionally cultivated corn with no cover crops (site F), ridge tillage corn with no cover crops (site G), native grasses that according to the landowner have never been cultivated (site H), and CRP grasses circa 2006-2008 (site I) (Table 1). Land use/land cover at research sites in Martin County included no-till corn planted into a multi-species mix of cover crops (site B1 and E1), conventional tillage corn with no cover crops (site B2), and CRP grasses circa 2015-2019 (site D) (Table 1). In Waseca County, land use/land cover at research sites included CRP grasses circa 2003 (site B1), CRP grasses circa 2021 (site B2), and no-till corn planted into a single-species cover crop of cereal rye (sites B3 and D) (Table 1).

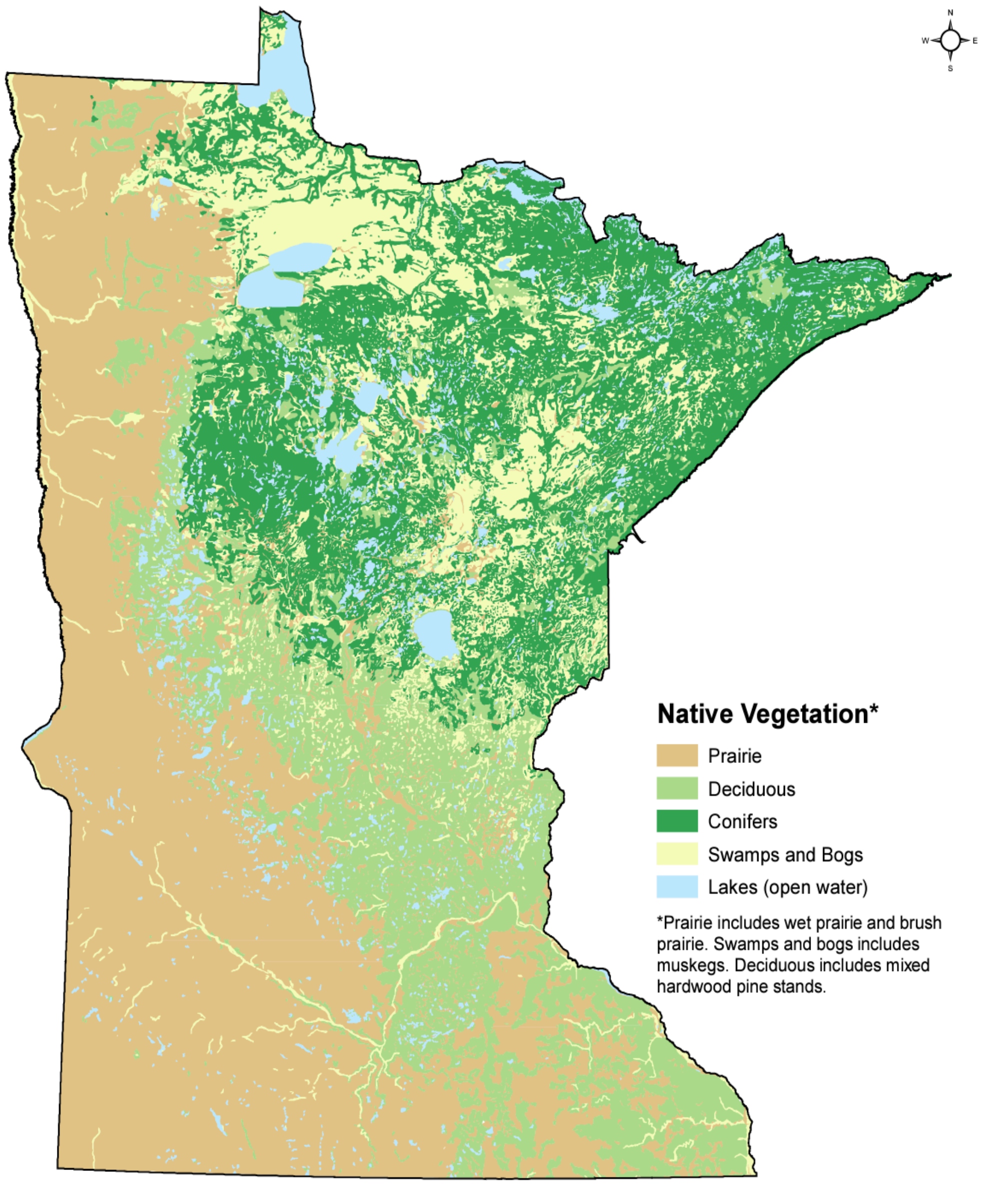

Figure 22: Minnesota native vegetation (Minnesota Department of Agriculture, Data summarizes Public Land Survey records from 1847 to 1907).

3.5 Geology

MLRA 103, including Cottonwood, Martin, and Waseca counties, has been heavily influenced by the Wisconsin glaciation. The retreat of the Des Moines lobe ~12 ka (Prior 1991) created moraines, glacial till plains, outwash, and glacial lakes in this region (NRCS 2006). Surficial geology of Cottonwood County primarily consists of the Ivanhoe Member and Dovray Member which are composed of end-moraine sediment, stagnation-moraine sediment, outwash, floodplain alluvium, and clayey sediment (Lusardi et al. 2019). Martin County surficial geology primarily consists of the Ivanhoe Member which is composed of end-moraine sediment, outwash, floodplain alluvium, and clayey sediment (Lusardi et al. 2019). Waseca county is primarily covered by the Heiberg Member which is composed of ice-contact sediment, stagnation-moraine sediment, floodplain alluvium, and clayey sediment (Lusardi et al. 2019).

Mesozoic and Paleoproterozoic bedrock is found in Cottonwood County, while Martin County has Paleozoic, Mesozoic, and Paleoproterozoic bedrock, and Waseca County has Paleozoic bedrock. Mesozoic and Paleozoic bedrock is common in Minnesota and consists of shale, limestone, dolomite, and sandstone (Jirsa et al. 2011). Paleoproterozoic bedrock consists of sedimentary rocks including slates, greywacke, iron formation, and volcanic rocks (Wisconsin Geologic and Natural History Survey 2005). Bedrock in Cottonwood County is ~74.37 meters deep, bedrock in Martin County is ~74.68 meters deep, and in Waseca County, the bedrock is ~57.00 meters deep (Minnesota Natural Resource Atlas 2024). Bedrock was not encountered near the surface at any of the study sites.

3.6 Soils

The dominant soil orders at research sites were Mollisols, Histosols, and Alfisols. Mollisols are thick soils that are dark in color due to their high amount of organic matter; they are often found in prairie regions and are a good agricultural soil (Schaetzl and Anderson 2005). Histosols are dark organic soils that are dominated by decomposing organic matter and are often saturated, while Alfisols are acidic soils that have enriched silicate clays in their B horizons (Schaetzl and Anderson 2005). Regional soils have a mesic soil temperature regime, an ustic or aridic soil moisture regime, mixed mineralogy, and a variety of textures (NRCS 2006).

At research sites, soil cores were collected from fourteen different soil types (Table 1). Soil cores collected from prairie pothole center, half radius, and edge positions primarily consisted of hydric soils, including Canisteo, Coland, Glencoe, Millington, Muskego, and Webster soils. Soil cores collected from the shoulder and backslope primarily consisted of non-hydric soils, including Angus, Clarion, Estherville, Grogan, Lester, Nicollet, Reedslake, and Terril soils. Toeslope soil cores consisted of hydric soils at ten research sites and non-hydric soils at two sites.

Canisteo soils (Typic Endoaquolls) are hydric soils characterized as very deep, poorly and very poorly drained soils, with fine-loamy texture, that formed in calcareous, loamy till or in a thin mantle of loamy or silty sediments (USDA 2015). These soils typically have slopes ranging from 0 to 2 percent and profiles with Ap, A, Bkg1, Bkg2, Cg1, and Cg2 horizons (USDA 2015). Coland soils (Cumulic Endoaquolls) are hydric soils characterized as very deep, poorly drained soils, with fine-loamy texture, that formed in alluvium (USDA 2015). These soils typically have slopes ranging from 0 to 5 percent and profiles with Ap, A1, A2, AB, Bg1, Bg2, and Cg horizons (USDA 2015). Glencoe soils (Cumulic Endoaquolls) are hydric soils characterized as very deep, very poorly drained soils, with fine-loamy texture, that formed in loamy sediments from till (USDA 2014). These soils typically have slopes ranging from 0 to 1 percent and profiles with Ap, A, Bg, Cg1, and Cg2 horizons (USDA 2014). Millington soils (Cumulic Endoaquolls) are hydric soils characterized as very deep, poorly drained soils, with fine-loamy texture, that formed calcareous alluvium on flood plains (USDA 2019). These soils typically have slopes ranging from 0 to 2 percent and profiles with A1, A2, AB, Bg1, Bg2, Cg1, and Cg2 horizons (USDA 2019). Muskego soils (Limnic Haplosaprists) are hydric soils characterized as very deep, very poorly drained soils that formed in herbaceous organic material over coprogenous limnic material (sedimentary peat) on glacial lake plains, flood plains, and till plains (USDA 2013). These soils typically have slopes ranging from 0 to 2 percent and profiles with Oap, Oa1, Oa2, Lco1, and Lco2 horizons (USDA 2013). Webster soils (Typic Endoaquolls) are hydric soils characterized as very deep, poorly drained, moderately permeable soils, with fine-loamy texture, that formed in glacial till or local alluvium derived from till on uplands (USDA 2014). These soils typically have slopes ranging from 0 to 3 percent and profiles with Ap, A, BAg, Bg1, Bg2, BCg, and Cg horizons (USDA 2014).

Angus soils (Mollic Hapludalfs) are non-hydric soils characterized as very deep, well drained soils, with fine-loamy texture, that formed in loamy calcareous till (USDA 2013). These soils typically have slopes ranging from 2 to 9 percent and profiles with Ap, Bt1, Bt2, BC, and C horizons (USDA 2013). Clarion soils (*Oxyaquic Hapludolls*) are non-hydric soils characterized as very deep, moderately well drained soils, with fine-loamy texture formed in glacial till (USDA 2005). These soils typically have slopes ranging from 1 to 9 percent and profiles with Ap, A1, A2, Bw1, Bw2, C1 and C2 horizons (USDA 2005). Estherville soils (*Typic Hapludolls*) are non-hydric soils characterized as very deep, somewhat excessively drained soils, with sandy texture, that formed in 25 to 50 centimeters of loamy sediments over sandy and gravelly outwash (USDA 2011). These soils typically have slopes ranging from 0 to 70 percent and profiles with Ap, A, Bw1, 2Bw2, 2C1, and 2C2 horizons (USDA 2011). Grogan soils (*Oxyaquic Hapludolls*) are non-hydric soils characterized as very deep, moderately well drained soils, with coarse-silty texture, that formed in calcareous lacustrine sediments on glacial lake plains, glacial deltas, and stream terraces (USDA 2006). These soils typically have slopes ranging from 0 to 6 percent and profiles with Ap, AB, Bw1, Bw2, Bw3, BC1 and BC2 horizons (USDA 2006). Lester soils (*Mollic Hapludalfs*) are non-hydric soils characterized as very deep, well drained soils, fine-loamy texture, that formed in calcareous, loamy till (USDA 2008). These soils typically have slopes ranging from 5 to 70 percent and profiles with Ap, Bt1, Bt2, Bk1, Bk2, and C horizons (USDA 2008). Nicollet soils (*Aquic Hapludolls*) are non-hydric soils characterized as very deep, somewhat poorly drained soils, with fine-loamy texture, that formed in calcareous loamy glacial till on till plains and moraines (USDA 2011). These soils typically have slopes ranging from 0 to 6 percent and profiles with Ap, A, Bw, Bg1, Bg2, BCg, and BCkg horizons (USDA 2011). Reedslake soils (*Oxyaquic Argiudolls*) are non-hydric soils characterized as very deep, well drained soils, fine-loamy texture, that formed in calcareous, loamy glacial till (USDA 1998). These soils typically have slopes ranging from 2 to 5 percent and profiles with Ap, Bt, Bk1, Bk2, and C horizons (USDA 1998). Terril soils (*Cumulic Hapludolls*) are non-hydric soils characterized as very deep, well and moderately well drained soils, fine-loamy texture, that formed in colluvium (USDA 2015). These soils typically have slopes ranging from 0 to 25 percent and profiles with Ap, A1, A2. A3, A4, Bw1, Bw2, and BC horizons (USDA 2015).

Table 1: Description of each studied prairie pothole's land cover and which soil type was present at each landscape position.

Site	Land Cover	Core Location Soils
Cottonwood F	Corn planted via intensive tillage and no cover crops	Shoulder and Backslope – Clarion (Oxyaquic Hapludolls; not hydric) Toeslope – Webster (Typic Endoaquolls; hydric soil) Edge, Half, and Center – Glencoe (Cumulic Endoaquolls; hydric)
Cottonwood G	Corn planted via ridge tillage and no cover crops	Shoulder and Backslope – Clarion (Oxyaquic Hapludolls; not hydric) Toeslope, Edge, Half, and Center – Canisteo (Typic Endoaquolls; hydric)
Cottonwood H	Native grassland	Shoulder – Nicollet (Aquic Hapludolls; not hydric) Backslope – Webster (Typic Endoaquolls; hydric) Toeslope, Edge, Half, and Center – Coland (Cumulic Endoaquolls; hydric)
Cottonwood I	CRP grasses since 2006-2008	Shoulder and Backslope – Nicollet (Aquic Hapludolls; not hydric) Toeslope, Edge, Half, and Center – Webster (Typic Endoaquolls; hydric)
Martin B1	Corn planted via no-till with multi-species cover crops	Shoulder – Grogan (Oxyaquic Hapludolls; not hydric) Backslope, Toeslope, and Edge – Canisteo (Typic Endoaquolls; hydric) Half and Center – Glencoe (Cumulic Endoaquolls; hydric)

Martin B2	Corn planted via intensive tillage with no cover crops	Shoulder and Backslope – Grogan (Oxyaquic Hapludolls; not hydric) Toeslope, Edge, Half, and Center – Canisteo (Typic Endoaquolls; hydric)
Martin D	CRP grasses since 2015-2019, previously corn planted via ridge tillage with no cover crops	Shoulder and Backslope – Estherville (Typic Hapludolls; not hydric) Toeslope, Edge, and Center – Millington (Cumulic Endoaquolls; hydric)
Martin E1	Corn planted via no-till with multi-species cover crops	Shoulder, Backslope, and Toeslope – Estherville (Typic Hapludolls; not hydric) Edge, Half, and Center – Coland (Cumulic Endoaquolls; hydric)
Waseca B1	CRP grasses since at least 2003	Shoulder, Backslope, and Toeslope – Angus (Mollic Hapludalfs; not hydric) Edge, Half, and Center – Glencoe (Cumulic Endoaquolls; hydric)
Waseca B2	CRP grasses since 2021, previously corn planted via no-till with cereal rye cover crops	Toeslope, Edge, Half, and Center – Glencoe (Cumulic Endoaquolls; hydric)
Waseca B3	Corn planted via no-till with cereal rye cover crops	Shoulder – Reedslake (Oxyaquic Argiudolls; not hydric) Backslope – Terril (Cumulic Hapludolls; not hydricl) Toeslope, Edge, and Half – Glencoe (Cumulic Endoaquolls; hydric)
Waseca D	Corn planted via no-till with cereal rye cover crops	Shoulder – Reedslake (Oxyaquic Argiudolls; not hydric) Backslope – Lester (Mollic Hapludalfs; not hydric) Toeslope, Edge, Half, and Center – Muskego (Limnic Haplosaprists; hydric)

Chapter 4 Methods

4.1 Site Selection Methods

For this study, soils were examined along a toposequence from the upper portion of a hillslope (i.e., shoulder position) into a closed depression (i.e., prairie pothole). A toposequence is a sequence of soils that differ from one another because of changes in topography, while other soil-forming factors (i.e., climate, organisms, parent material, and time) remain similar among sites (Schaetzl and Thompson 2015). Essentially, as topographic position changes along a slope, soil properties change due to differences in geomorphic and pedogenic processes at each position. For this study, the positions are described as follows: shoulder is the upper convex part of the slope, backslope is the linear section of the slope, toeslope is the concave base of the slope that represents a transition from the uplands to the pothole, edge is the break in slope from the pothole that stores water and the higher and drier landscape surrounding the pothole, half radius is halfway between the center and topographic edge of the pothole depression, and center is the middle of a closed depression (i.e., prairie pothole) (Figure 23).

Prairie pothole is not a wetland class in most wetland mapping systems, including the National Wetland Inventory, which typically includes prairie potholes as freshwater emergent wetlands along with several other wetland types (U.S. Fish & Wildlife Service 2021), so an objective standard was used to identify prairie potholes. To select prairie potholes for this study, multiple criteria were used. First, since cores were collected along a toposequence, hydric soils had to be mapped at the lowest position of the toposequence because hydric soils form under conditions of saturation (i.e., in a wetland). Since potholes are depressional wetlands, sites included in this study had to be delineated with at least one 2-foot contour line in the MnTOPO web application, which generates contour lines at a 2-foot interval based on LiDAR digital elevation data. Finally, in order to analyze and compare the carbon storage potential differences among landscape positions at each site (i.e., across the toposequences) and different land uses/land covers among the sites (i.e., native grassland, CRP, and conservation and conventional agriculture), land cover had to be consistent throughout each toposequence.

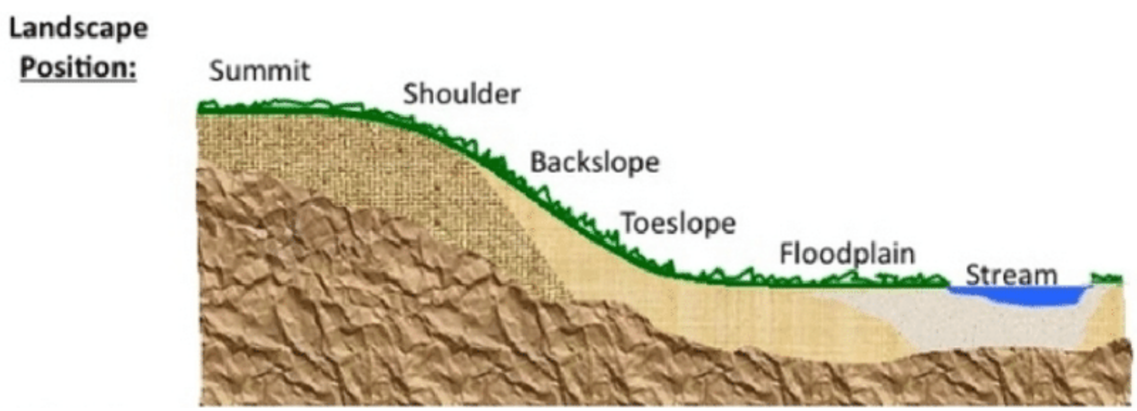

Figure 23: Landscape position diagram (Ontl 2012).

4.2 Field-Based Methods

Soil-sediment cores were collected using a JMC Backsaver© hand-coring device to a depth of 30 cm. Cores were collected using either a "dry tube" with a ¾" (~1.91 cm) diameter or "wet tube" with an 11/16" (~1.75 cm) diameter depending upon the moisture status of the soil. Cores were collected along a toposequence from prairie pothole shoulder, backslope, toeslope, edge, half, and center landscape positions at each site.

Once cores were collected, they were split into two samples by depth: 0-15 cm and 15-30 cm. In Martin and Waseca counties, duplicate hand cores were collected in close proximity from each landscape position, one for bulk density analysis and the other for total carbon and particle size analysis. In Cottonwood County, five cores were collected in close proximity from each landscape position: one for bulk density and the other four were homogenized to create a composite core for total carbon and particle size analysis. All cores were transported to the EARTH Systems Laboratory at Minnesota State University, Mankato for further analysis.

4.3 Laboratory-Based Methods

4.3.1 Bulk Density

The soil sediment core with the best recovery from each landscape position was used for bulk density analysis. Bulk density is the dry weight of soil divided by its volume. Each sample was first dried at 105°C for at least 48 hours. Bulk density was determined by dividing the dry weight of the soil sample (mdry) by the bulk volume of compacted soil:

$$\text{Bulk density (g/cm}^3\text{)} = \text{dry sample weight (g) / bulk sample volume (cm}^3\text{)}$$

Since collected cores had a cylindrical shape, bulk volume was determined using the following equation:

$$\text{Volume (cm}^3\text{)} = \Pi * \text{radius}^2 \text{ (cm}^2\text{)} * \text{height (cm)}$$

where radius was 0.9525 cm (dry tube) or 0.873125 cm (wet tube) and height was 15 cm. Thus, volume was either 42.75 cm^3 (dry tube) or 35.92 cm^3 (wet tube). Bulk density was used to convert percent total carbon in a sample to mass of carbon and then multiplying depth by mass of carbon to determine the carbon stock in the upper 30 cm of each pothole (Kukal and Bawa 2014).

4.3.2 Particle Size Analysis

Particle size distribution was analyzed using a Malvern Mastersizer 3000 laser diffractometer in the EARTH Systems Lab at Minnesota State University, Mankato. This method utilizes a laser beam to pass through a sample dispersed in water, and reports percent volume by size class for ~100 size classes ranging from 0.01 μm to 2.0 mm. To prepare samples for analysis, samples were dried at 60° C for at least 24 hours, ground with a mortar and pestle, passed through a 2 mm sieve, and soaked in a 5% sodium hexametaphosphate solution for at least 24 hours to break down aggregates. Once samples were ready for analysis, each was individually added to the machine by dispersal in water and sonicated for ~5 minutes to ensure all aggregates were dispersed. Following sonication, particle size was measured three times, and an average was calculated. The average value was used for all subsequent data analysis.

4.3.3 Carbon Content

Total organic carbon content was measured by the Soil, Water, and Forage Analytical Laboratory (SWFAL) at Oklahoma State University. Samples were prepared in the Earth Systems Lab before being submitted to SWFAL. To prepare samples, they were dried at <60° C for at least 24 hours, roots and other plant debris were removed, they were ground with a mortar and pestle and passed through a 1 mm sieve, and ~10-20 grams of sample was placed in a whirl-pak bag and submitted to the lab for analysis.

SWFAL determined total carbon content via dry combustion using an elemental analyzer to measure the CO_2 that was released during combustion (Hamilton 2016). Before combustion, the inorganic carbon content was measured by injecting a liquefied sample into a reaction chamber packed with phosphoric acid coated quartz beads. Under these acidic conditions, inorganic carbon was converted to CO_2, but organically bound carbon was not (Hamilton 2016). Total organic carbon was calculated by subtracting inorganic carbon content from total carbon content. Results were reported in percentage of carbon in the sample.

4.4 Statistical Analysis

Statistical analysis was done using the statistical software package R and all tests of significance set at a minimum of $p < 0.05$. Regression analysis was conducted to evaluate the relationships between total carbon, bulk density, and particle size (i.e., %clay, %silt, %sand). One-way analysis of variance (ANOVA) was conducted to assess differences in total carbon, bulk density, and particle size by topographic position and land use at 0-15 cm and 15-30 cm depths. When statistically significant differences were identified, the Tukey honest significant difference (HSD) test was utilized to determine which classes were significantly different. Two-way ANOVA was conducted to compare how topography, land use, and the interaction between them affected total carbon, bulk density, and particle size at 0-15 cm and 15-30 cm depths.

Chapter 5 Results

Results of this research include total carbon, bulk density, and particle size distribution for two depths (i.e., 0-15 cm and 15-30 cm) and six landscape positions (i.e., shoulder, backslope, toeslope, pothole edge, pothole half radius, and pothole center). However, there were no statistically significant differences in total carbon, bulk density, or particle size distribution between shoulder and backslope, toeslope and pothole edge, and half radius and pothole center positions (Table 2). Due to similarities in results and geomorphic and pedogenic processes, individual landscape positions were grouped into uplands (i.e., shoulder and backslope), lowlands (i.e., toeslope and pothole edge), and pothole (i.e., half radius and pothole center). Grouping positions simplifies comparisons and increases the number of samples per landscape position for statistical analyses. Results are presented by grouped landscape position (i.e., uplands, lowlands, and potholes) and by land cover class (i.e., native grassland, CRP, conservation agriculture, and conventional agriculture).

Results based on topographic position overall fit my predicted hypothesis that while progressing from the uplands to the potholes total carbon increases and bulk density decreases (Figures 24-26). Additionally, total carbon content is higher in the upper 0-15 cm and bulk density is higher in the lower 15-30 cm of sample cores. Results for land cover are more complex (Figures 28-30) and do not necessarily fit expected patterns due to complexities in landscapes, different land use histories, and a small number of sites in each land use category. By focusing on topographic position and the interactions with land uses and depth, results from this study will help determine which factors have the greatest influence on soil physical properties.

Table 2: Results of one-way ANOVA indicating no significant difference in total carbon, bulk density, clay, silt, and sand content among the shoulder and backslope, toeslope and pothole edge, and pothole half radius and center.

		P-Score				
Positions	**Depth (cm)**	**Total Carbon**	**Bulk Density**	**Clay**	**Silt**	**Sand**
Shoulder-Backslope (Upland)	0-15	0.9922	1.0000	1.0000	0.9993	0.9999
	15-30	0.9716	0.9992	0.8142	0.9896	0.8680
Toeslope-Edge (Lowland)	0-15	0.6422	0.5919	0.9999	0.9965	0.9984
	15-30	0.9612	0.8625	0.9987	0.9537	0.9999
Half-Center (Pothole)	0-15	1.0000	0.9811	0.9960	0.9991	0.9950
	15-30	1.0000	0.9506	1.0000	0.9975	0.9997

5.1 Influence of Topographic Position on Soil Physical Properties

5.1.1 Total Carbon Based on Topographic Position

Based on one-way ANOVA, total carbon content (%) (TC) is statistically significant by topographic position (Table 4). Additionally, TC by topographic position is significantly different between the two depth classes ($P < 0.001$) (Figure 24). The overall trend in TC based on landscape position is that carbon content progressively increases from the uplands to the pothole, and TC is higher in the upper 0-15 cm for all landscape positions.

TC is lowest in the upland landscape position (Figure 24, Table 3). Mean TC for the upland position from 0-15 cm is 1.97% and ranges from 0.92% to 3.33%. TC is lower from 15-30 cm, with a mean of 1.64% and a range of 0.58% to 2.77%. For the lowland position, TC is intermediate. Mean TC for the lowland position from 0-15 cm is 3.96% with a wider range compared to the upland position at 2.21% to 6.25%. TC from 15-30 cm has a mean of 3.20% and a range of 1.52% to 6.73%. TC is highest in the pothole position. Mean TC for the pothole from 0-15 cm is 4.58% with a range from 3.32% to 6.48%. TC from 15-30 cm has a mean of 3.60% and ranges from 1.66% to 6.61%.

Tukey HSD indicates that differences in TC for the two depth classes by landscape position are only significant between the uplands and the other two topographic positions ($P < 0.001$). TC is not significantly different between the lowland and pothole positions for either depth. Additionally, TC and bulk density exhibit an inverse relationship ($r^2 = 0.61$) (Figure 31A).

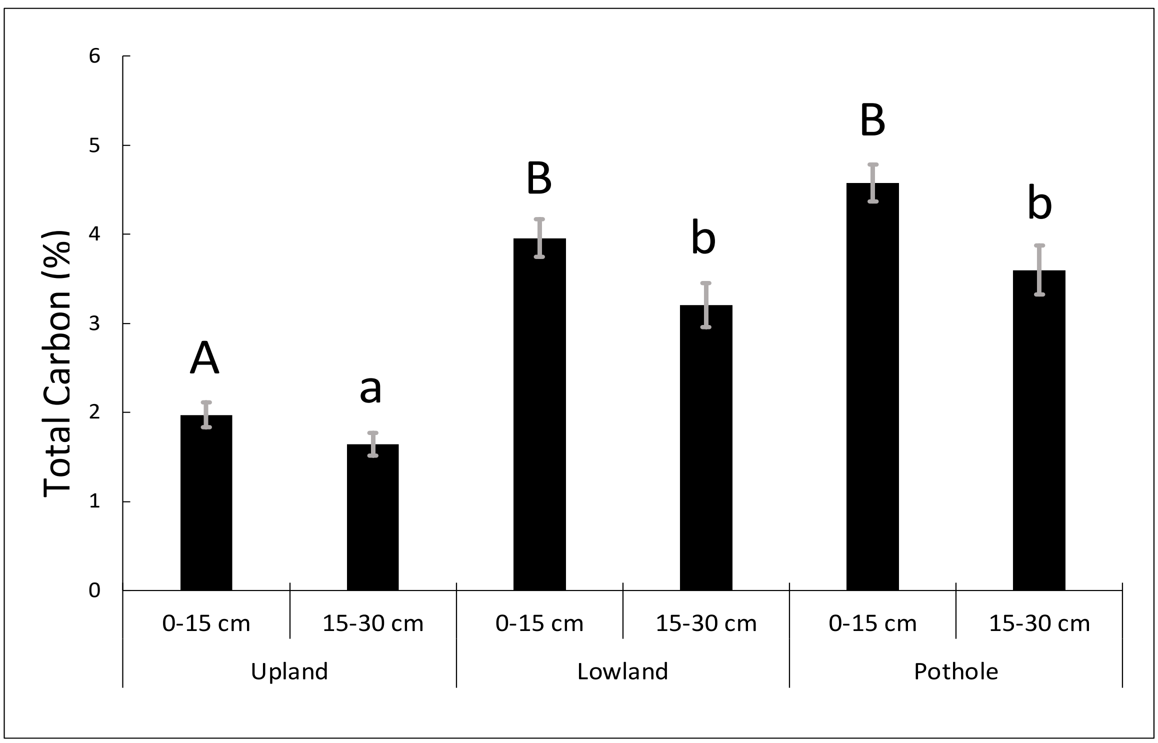

Figure 24: Mean percent total carbon based on topographic position and sample depth. Gray lines represent the standard error. Tukey HSD test shows that total carbon is significantly different by topographic

positions. Uppercase A and B represent the significant differences in 0-15 cm. Lowercase a and b represent the significant differences in 15-30 cm.

Table 3: Mean percent total carbon by topographic position and sample core depth.

	0-15 cm			**15-30 cm**		
	Upland	**Lowland**	**Pothole**	**Upland**	**Lowland**	**Pothole**
Mean	1.97%	3.96%	4.58%	1.64%	3.20%	3.60%
Min	0.92%	2.21%	3.32%	0.58%	1.52%	1.66%
Max	3.33%.	6.25%	6.48%	2.77%	6.73%	6.61%

Table 4: Results of one-way ANOVA comparing mean differences in total carbon, bulk density, clay, silt, and sand content grouped by topographic position (i.e., uplands, lowlands, and potholes) for the two depth classes (i.e., 0-15 cm and 15-30 cm). Significant values are bolded.

Positions	**Depth (cm)**	**F Score**	**P Score**
Total Carbon (%)	0-15	49.398	**<0.001**
	15-30	20.324	**<0.001**
Bulk Density (g/cm^3)	0-15	24.383	**<0.001**
	15-30	11.727	**<0.001**
Clay (%)	0-15	5.0569	**<0.01**
	15-30	3.8446	**<0.05**
Silt (%)	0-15	11.008	**<0.001**
	15-30	14.139	**<0.001**
Sand (%)	0-15	10.048	**<0.001**
	15-30	10.711	**<0.001**

5.1.2 Bulk Density Based on Topographic Position

One-way ANOVA indicates bulk density is statistically significant by topographic position (Table 4). Bulk density is also significantly different between the two depth classes ($P < 0.001$) (Figure 25). The overall trend in bulk density based on landscape position is that bulk density decreases from the uplands to the pothole, and bulk density is higher in the lower 15-30 cm for all landscape positions.

Bulk density is highest in the upland landscape position (Figure 25, Table 5). Mean bulk density for the upland position from 0-15 cm is 1.36 g/cm^3 and ranges from 1.10 g/cm^3 to 1.53 g/cm^3. Bulk density is higher from 15-30 cm, with a mean of 1.49 g/cm^3 and a range of 1.18 g/cm^3 to 1.84 g/cm^3. For the lowland position, bulk density is intermediate. Mean bulk density for the lowland position from 0-15 cm is 1.23 g/cm^3 and ranges from 0.99 g/cm^3 to 1.41 g/cm^3. Bulk density from 15-30 cm has a mean of 1.36 g/cm^3, ranging from 1.06 g/cm^3 to 1.49 g/cm^3. Bulk density is the lowest in the pothole landscape position. Mean bulk density for the pothole from 0-15 cm is 1.13 g/cm^3 and ranges from 0.85 g/cm^3 to 1.30 g/cm^3. Bulk density from 15-30 cm has a mean of 1.29 g/cm^3 and a range of 0.91 g/cm^3 to 1.56 g/cm^3.

Tukey HSD indicates that differences in bulk density from 0-15 cm are significantly different among all three topographic positions ($P < 0.001$). Bulk density from 15-30 cm is only significantly different between the upland and pothole position, while the lowland position is not significantly different than the other two positions.

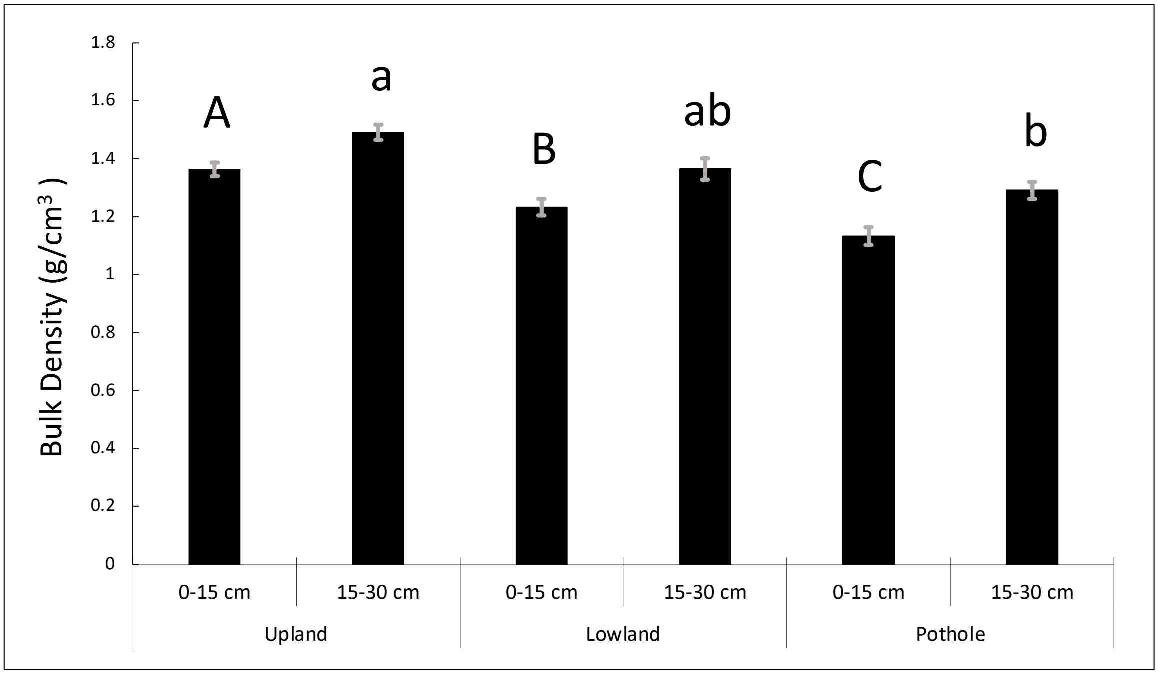

Figure 25: Mean bulk density (g/cm^3) by topographic position and sample depth. Gray lines represent the standard error. Tukey HSD test shows that bulk density is significantly different by topographic position. Uppercase A, B, and C represent the significant differences in 0-15 cm. Lowercase a, ab, and b represent the significant difference in 15-30 cm.

Table 5: Mean bulk density (g/cm^3) by topographic position and sample core depth.

	0-15 cm			**15-30 cm**		
	Upland	Lowland	Pothole	Upland	Lowland	Pothole
Mean	1.36 g/cm^3	1.23 g/cm^3	1.13 g/cm^3	1.49 g/cm^3	1.36 g/cm^3	1.29 g/cm^3
Min	1.10 g/cm^3	0.99 g/cm^3	0.85 g/cm^3	1.18 g/cm^3	1.06 g/cm^3	0.91 g/cm^3
Max	1.53 g/cm^3	1.41 g/cm^3	1.30 g/cm^3	1.84 g/cm^3	1.49 g/cm^3	1.56 g/cm^3

5.1.3 Particle Size Based on Topographic Position

Differences in percent clay, silt, and sand for the two depths are statistically significant by topographic position based on one-way ANOVA ($P < 0.05$, < 0.01, and < 0.001, respectively) (Table 4). Although differences are significant, particle size is generally similar throughout and dominated by silt and clay (Figure 26). Textural classes include loam (n =1), sandy loam (n = 2), silty clay loam (n = 3), clay (n = 6), clay loam (n = 9), and silty clay (n = 114) for all 135 samples (Figure 27).

Percent clay is lowest in the upland position (Figure 26). Mean percent clay for the upland position from 0-15 cm is 41.15% with a range from 19.55% to 51.38%. Mean percent clay from 15-30 cm is 41.06% ranging from 14.26% to 51.95%. Percent clay is intermediate in the lowland position. Mean percent clay for the lowland position from 0-15 cm is 43.77% with a range from 39.27% to 51.90%. Mean percent clay from 15-30 cm is 45.41%, ranging from 38.52% to 51.36%. Percent clay is highest in the pothole position. Mean percent clay for the pothole from 0-15 cm is 46.33% ranging from 40.59% to 54.95%. Mean percent clay from 15-30 cm is 45.51% with a range from 37.83% to 53.64%. Of the 135 samples, only 15 have less than 40% clay and only 2 have less than 20% clay.

Percent silt is similarly lowest in the upland position (Figure 26). Mean percent silt for the upland position from 0-15 cm is 41.36% ranging from 22.12% to 54.24%. Mean percent silt from 15-30 cm is 39.58% with a range from 17.35% to 48.70%. Percent silt is intermediate in the lowland position. Mean percent silt in the lowland position from 0-15 cm is 46.68% and has a range of 42.39% to 52.20%. Mean percent silt from 15-30 cm is 45.77%, ranging from 40.73% to 56.05%. Percent silt is the highest in the pothole position. Mean percent silt in the pothole position from 0-15 cm is 46.95% with a range from 39.18% to 53.29%. Mean percent silt from 15-30 cm is 47.26% ranging from 40.96% to 53.95%. Of the 135 samples, only 18 have less than 40% silt and only one has a silt content less than 20%.

Unlike clay or silt, percent sand is highest in the upland position (Figure 26). Mean percent sand for the upland position from 0-15 cm is 17.49% with a range from 0.21% to 58.33%. Mean percent sand from 15-30 cm is 19.36%, ranging from 5.59% to 68.39%. Percent sand is intermediate in the lowland position. Mean percent sand for the lowland position from 0-15 cm is 9.55% with a range of 3.87% to 16.64%. Mean percent sand from 15-30 cm is 8.82% ranging from 2.73% to 14.85%. Percent sand is the lowest in the pothole position. Mean percent sand in the pothole position from 0-15 cm is 6.73% with a range from 2.56% to 14.95%. Mean percent sand from 15-30 cm is 7.23% ranging from 1.00% to 19.56%. Of the 135 samples, only 2 have greater than 40% sand and only 13 have a sand content greater than 20%.

Particle size data for Martin County are significantly different than Cottonwood and Waseca counties (Figures 26 and 27). Clay and silt content in Martin County is ~5-6% lower and sand content is ~11% higher than the other two counties. This is primarily attributed to differences in the upland position in which clay, silt, and sand differ by ~13%, ~10%, and ~23%, respectively, between Martin County and the two other counties. Clay and silt content in Martin County are ~2-3% lower and sand content is 3-5% higher in the lowland and pothole positions compared to the other two counties

(Figure 26). Textural class of samples from Cottonwood and Waseca counties are primarily silty clay (86 samples; 96%) with only 4 samples classified as clay, and all 4 of those samples are within 1% clay content of being classified as silty clay (Figure 27). Textural class is more variable in Martin County with silty clay dominant (28 samples; 62%) and 17 samples distributed among 5 other textural classes (loam, clay, sandy loam, silty clay loam, and clay loam).

Tukey HSD reveals that there is a significant difference in clay content between the upland and pothole for both depth classes, but there are no significant differences in clay content between the lowland and the two other topographic positions. For silt and sand, there is a significant difference between the upland and the other two positions for both depths, but differences are not significant between the lowland and pothole positions.

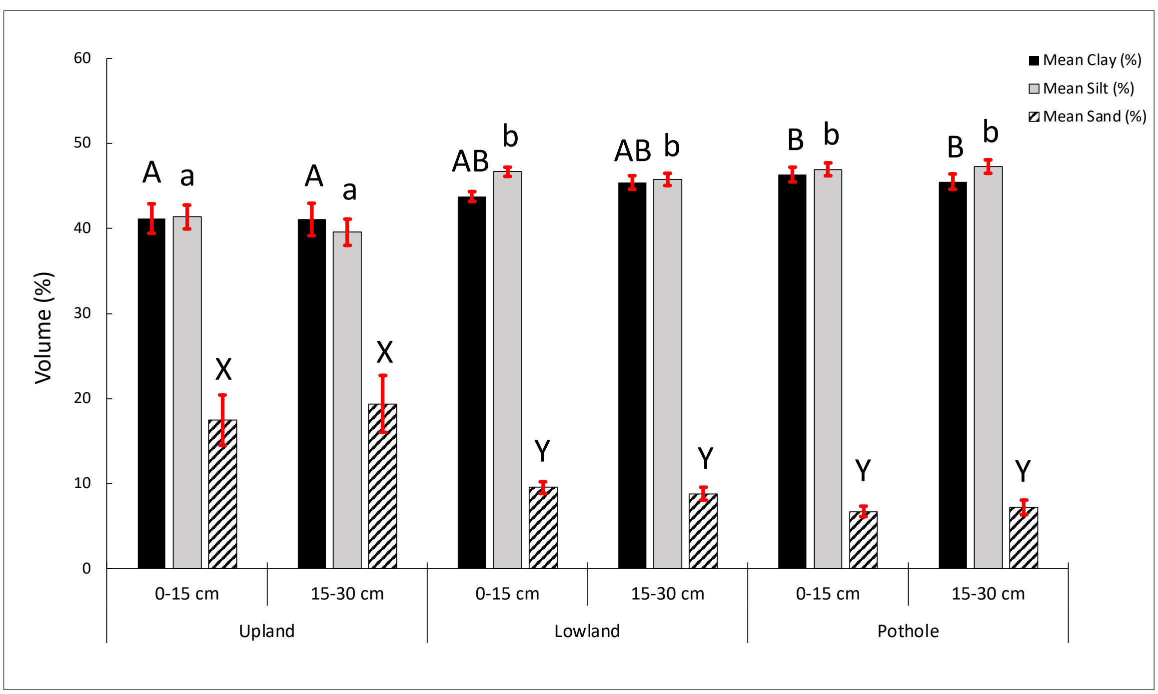

Figure 26: Percent clay, silt, and sand by topographic position and sample depth. Red lines represent standard error. Tukey HSD test shows that particle size is significantly different by topographic position. Uppercase A, AB, and B represent the significant differences in clay. Lowercase a, ab, and b represent the significant difference in silt. Uppercase X and Y represent the significant difference in sand.

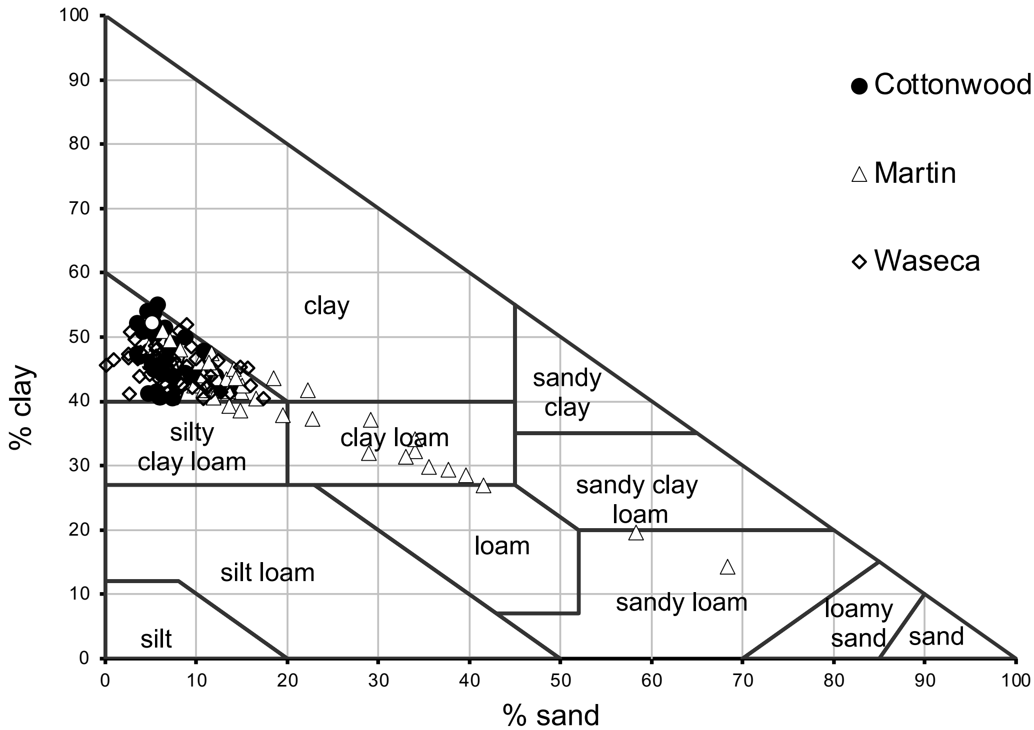

Figure 27: Particle size class for all samples collected.

5.2 Influence of Land Use on Soil Physical Properties

5.2.1 Total Carbon Based on Land Use

Based on the one-way ANOVA, differences in TC are not statistically significant by land use for either depth class (Table 6). The overall trend in TC based on land use is that the upper 0-15 cm has more TC than the lower 15-30 cm (Figure 28). Due to the large range in TC values and small sample size for each land use, there are no clear trends in TC by land use.

TC is highest in the native site (Figure 28, Table 6). Mean TC for the native site from 0-15 cm is 4.63% with a range from 3.08% to 5.90%. Mean TC from 15-30 cm is 3.11%, ranging from 2.23% to 3.81%. TC for the conventional sites is the next highest. Mean TC for the conventional sites from 0-15 cm is 3.71% with a range of 1.46% to 6.25%. Mean TC from 15-30 cm is 2.77% and ranges from 1.16% to 5.04%. TC for the conservation sites is the next highest. Mean TC for conservation sites from 0-15 cm is 3.53%, ranging from 0.92% to 6.48%. Mean TC from 15-30 cm is 3.10%, ranging from 0.58% to 6.73%. TC is lowest in the CRP sites. Mean TC for the CRP sites from 0-15 cm is 3.31% and ranges from 1.29% to 4.54%. Mean TC from 15-30 cm is 2.36% with a range from 0.89% to 3.80%.

Based on percent change of TC, conventional agriculture is 0.3% higher than conservation sites, 12.0% higher than CRP sites, and 19.4% lower than the native site. TC for conservation sites is 0.3% lower than conventional sites, 11.8% higher than CRP sites, and 19.8% lower than the native site. TC for CRP sites is 13.7% lower than conventional sites, 13.3% lower than conservation sites, and 35.8% lower than the native site. TC is highest for the native site and is 16.3% higher than conventional sites, 16.5% higher than conservation sites, and 26.4% higher than the CRP sites. Among all land use classes, TC of the upper 15 cm is 19.9% higher than 15-30 cm. However, ANOVA indicates that there are no significant differences in TC by land use for either depth class (i.e., 0-15 cm and 15-30 cm).

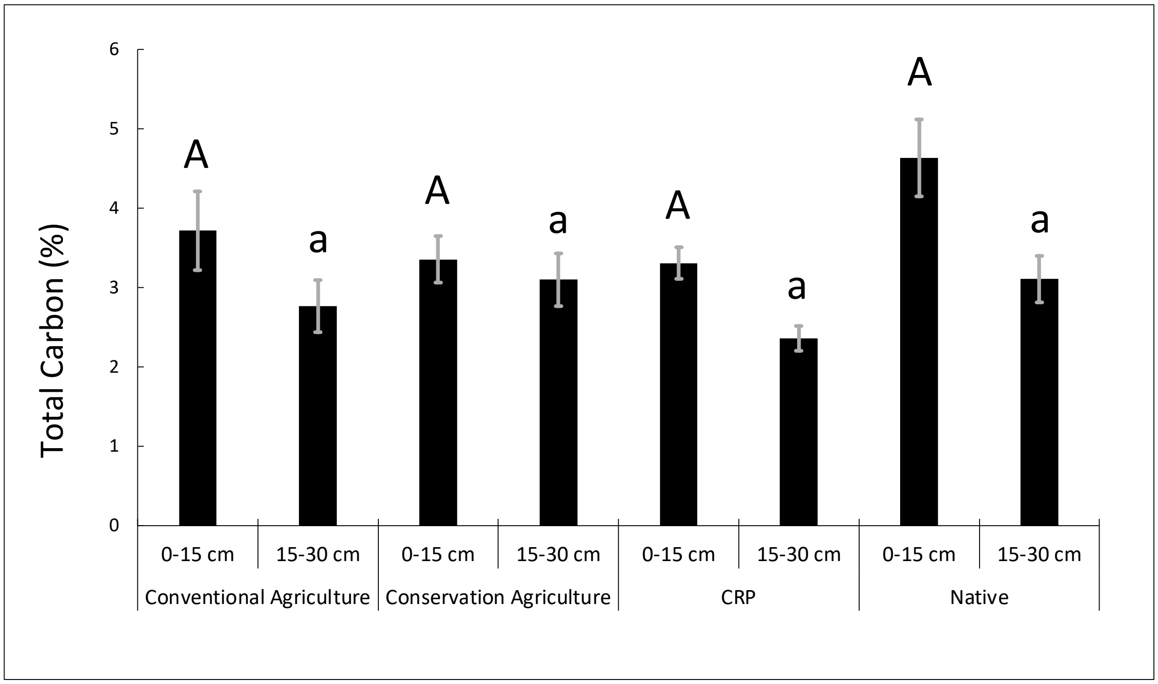

Figure 28: Mean percent total carbon based on land use and sample core depth. Gray lines represent the standard error. Tukey HSD test showing no statistical significance of land use in the soil core samples for total carbon. Uppercase A showing there is no significant difference is the upper 0-15 cm, lowercase a showing there is no significant difference in the lower 15-30 cm.

Table 6: Results of one-way ANOVA comparing differences in total carbon, bulk density, clay, silt, and sand content by land use (i.e., conventional agriculture, conservation agriculture, CRP, and native grasslands) for the two depth classes (i.e., 0-15 cm and 15-30 cm). Significant values are bolded.

Land Use	Depth (cm)	F Score	P Score
Total Carbon (%)	0-15	1.6279	0.1916
	15-30	1.2824	0.2882
Bulk Density (g/cm^3)	0-15	4.0187	**<0.05**
	15-30	1.3557	0.2647
Clay (%)	0-15	0.2473	0.863
	15-30	0.9519	0.4211
Silt (%)	0-15	2.5376	0.06439
	15-30	1.582	0.2025
Sand (%)	0-15	0.3757	0.7708
	15-30	0.6809	0.567

5.2.2 Bulk Density Based on Land Use

One-way ANOVA reveals differences in bulk density are statistically significant by land use for the upper 0-15 cm ($P < 0.05$) but not the lower 15-30 (Table 6). The overall trend for bulk density is that it is generally similar for all land uses, and bulk density is higher in the lower 15-30 cm compared to the upper 0-15 cm regardless of land use.

Bulk density is highest in conservation agricultural sites (Figure 29). Mean bulk density for conservation sites from 0-15 cm is 1.29 g/cm^3 with a range from 1.15 g/cm^3 to 1.42 g/cm^3. Mean bulk density from 15-30 cm is 1.39 g/cm^3 ranging from 1.24 g/cm^3 to 1.54 g/cm^3. Mean bulk density for conventional sites from 0-15 cm is 1.25 g/cm^3 with a range from 0.99 g/cm^3 to 1.53 g/cm^3. Mean bulk density from 15-30 cm is 1.40 g/cm^3 ranging from 0.91 g/cm^3 to 1.84 g/cm^3. Mean bulk density for CRP sites from 0-15 cm is 1.21 g/cm^3 with a range of 0.85 g/cm^3 to 1.49 g/cm^3. Mean bulk density from 15-30 cm is 1.40 g/cm^3 with a range from 1.14 g/cm^3 to 1.73 g/cm^3. Bulk density is the lowest in the native site. Mean bulk density for the native site from 0-15 cm is 1.10 g/cm^3 ranging from 1.04 g/cm^3 to 1.19 g/cm^3. Mean bulk density from 15-30 cm is 1.26 g/cm^3 with a range from 1.12 g/cm^3 to 1.38 g/cm^3.

Mean bulk density values do not have a wide range among the different land uses (Figure 29). Based on percent change of bulk density, conventional agriculture is 1.5% lower than conservation agriculture, 1.5% higher than CRP sites, and 11.4% higher than the native site. Bulk density for conservation agriculture is 1.5% higher than conventional agriculture, 3.0% higher than CRP sites, and 12.7% higher than the native site. For CRP sites, bulk density is 1.5% lower than conventional sites, 3.1% lower than conservation sites, and 10.0% higher than the native site. The native site has the lowest bulk density of the land use classes and is 12.8% lower than the conventional sites, 14.5% lower than the conservation sites, and 11.1% lower than the CRP sites.

Tukey HSD reveals that differences in bulk density by land use are only significant in the upper 0-15 cm between the native site and the conservation and conventional sites, which are not significantly different from each other or CRP (Figure 29). There are no significant differences in bulk density by land use for the lower depth class (i.e., 15-30 cm).

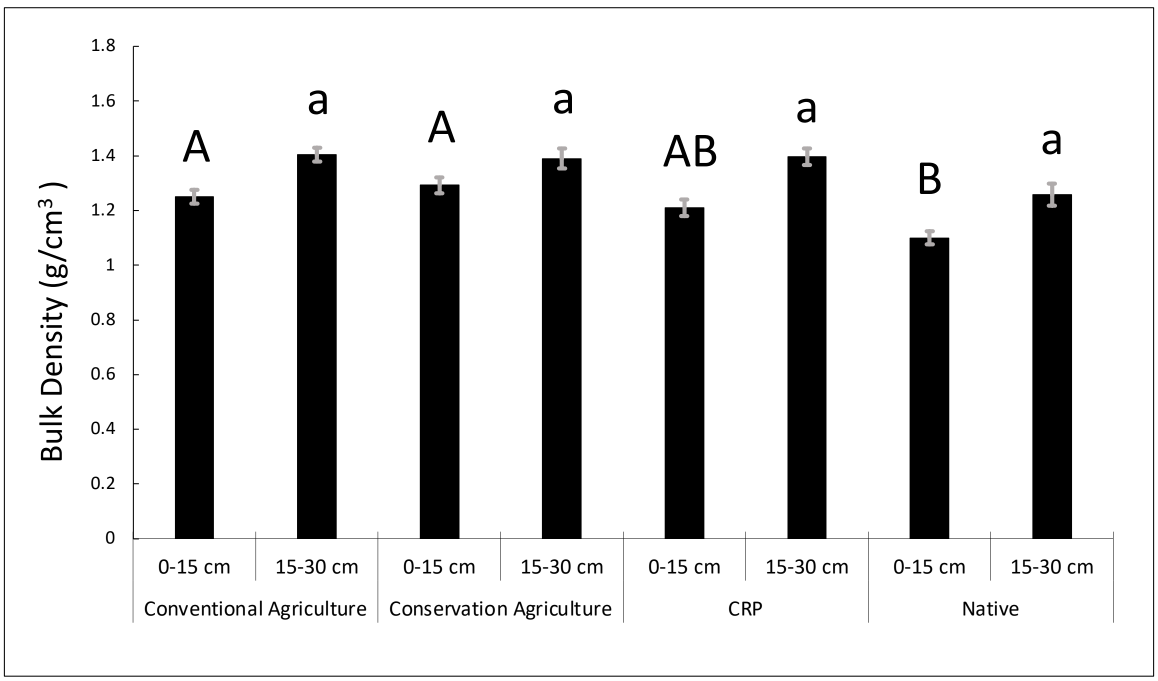

Figure 29: Mean bulk density based on land use and sample core depth. Gray lines represent the standard error. Tukey HSD test showing statistical significance of land use in the soil core samples for bulk density. Uppercase A, AB, and B represent the significant difference in 0-15 cm. Lowercase a showing there is no significant difference in the lower 15-30 cm.

5.2.3 Particle Size Based on Land Use

Particle size distribution is fairly consistent among the four land uses (Figure 30, Table 7). Clay and silt are in nearly equal proportions and comprise on average at least 86% of the soil volume for all land uses. Percent clay, silt, and sand are not significantly different by land use for either of the depth classes (Figure 30).

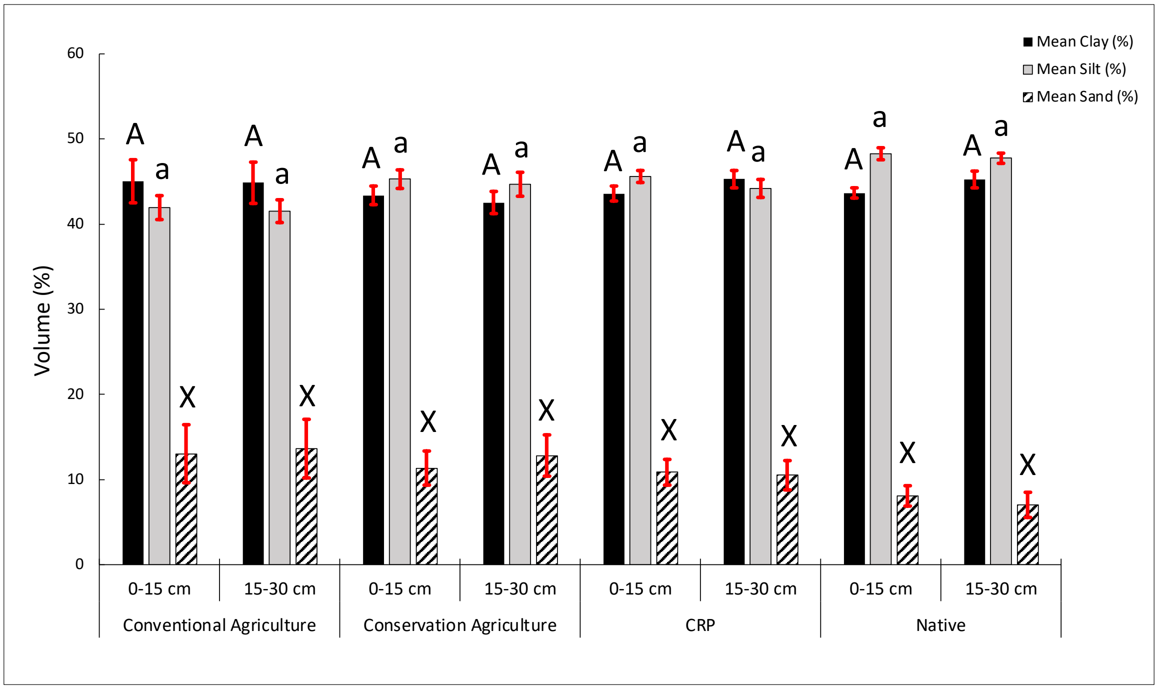

Figure 30: Percent clay, silt, and sand by land use and sample depth. Red lines represent standard error. Tukey HSD test shows that particle size distributions are not significantly different by land use. Uppercase A represents there is no significant difference in clay for either depth. Lowercase a represent there is no significant difference in silt in either depth. Uppercase X represents there is no significant difference in sand in either depth.

Table 7: Minimum, maximum, and mean particle sizes for each land use.

	Clay			Silt			Sand		
Land Use	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Conventional	26.85%	54.95%	44.50%	31.53%	47.77%	41.72%	4.77%	41.62%	13.33%
Conservation	14.26%	52.29%	42.94%	17.35%	56.05%	44.98%	0.21%	68.39%	12.08%
CRP	31.33%	52.11%	44.41%	31.78%	50.68%	44.89%	2.77%	34.04%	10.70%
Native	41.64%	47.78%	44.45%	45.49%	49.63	48.00%	3.62%	12.68%	7.55%

5.3 Interactions Among Topographic Position, Land Use, Depth and Soil Properties

To identify interactions among topographic position and land use for each soil property and depth, a two-way ANOVA was performed (Tables 8-11). The only statistically significant interaction is between topography and land use for total carbon at 15-30 cm with a P value of <0.05 (Table 8). Bulk density and particle size distribution did not exhibit significant interactions between topographic position and land use for either depth.

Regression analysis was also performed to assess relationships between soil properties (Figures 31 and 32). For linear regression in this project, if r^2 is 0-0.29 the relation is considered weak, 0.3-0.59 is moderate, and 0.6-1 is a strong correlation. A weak correlation was found between total carbon and clay, total carbon and sand, bulk density and clay, and bulk density and sand with r^2 values of 0.06, 0.27, 0.05, and 0.22

respectively. A moderate correlation was found between total carbon and silt with an r^2 value of 0.46 and between bulk density and silt with an r^2 value of 0.35. A strong correlation was found only between total carbon and bulk density with an r^2 value of 0.61.

Table 8: Results of two-way ANOVA comparing the interaction of topographic position (i.e., uplands, lowlands, and potholes) and land use (i.e., conventional agriculture, conservation agriculture, CRP, and native grasslands) for total carbon in the two depth classes (i.e., 0-15 cm and 15-30 cm). Significant values are bolded.

		Total Carbon 0-15 cm		Total Carbon 15-30 cm	
ANOVA Factor	DF	F Value	P Value	F value	P Value
Topography (T)	2	62.917	**<0.001**	25.157	**<0.001**
Land Use (LU)	3	5.289	**<0.01**	3.059	**<0.05**
T x LU	6	1.820	0.112	2.507	**<0.05**

* Significance level used was set at an alpha of 0.05, significant values are in bold. Df means the degree of freedom.

Table 9: Results of two-way ANOVA comparing the interaction of topographic position (i.e., uplands, lowlands, and potholes) and land use (i.e., conventional agriculture, conservation agriculture, CRP, and native grasslands) for bulk density in the two depth classes (i.e., 0-15 cm and 15-30 cm). Significant values are bolded.

		Bulk Density 0-15 cm		Bulk Density 15-30 cm	
ANOVA Factor	DF	F Value	P Value	F value	P Value
Topography (T)	2	31.265	**<0.001**	11.983	**<0.001**
Land Use (LU)	3	7.079	**<0.001**	1.858	0.148
T x LU	6	0.846	0.540	0.908	0.496

* Significance level used was set at an alpha of 0.05, significant values are in bold. Df means the degree of freedom.

Table 10: Results of two-way ANOVA comparing the interaction of topographic position (i.e., uplands, lowlands, and potholes) and land use (i.e., conventional agriculture, conservation agriculture, CRP, and native grasslands) for clay, silt, and sand content at 0-15 cm. Significant values are bolded.

		Clay 0-15 cm		Silt 0-15 cm		Sand 0-15 cm	
ANOVA Factor	DF	F Value	P Value	F Value	P Value	F value	P Value
Topography (T)	2	4.537	**<0.05**	11.390	**<0.001**	9.145	**<0.001**
Land Use (LU)	3	0.252	0.860	3.136	**<0.05**	0.433	0.730
T x LU	6	0.261	0.952	0.305	0.932	0.311	0.929

* Significance level used was set at an alpha of 0.05, significant values are in bold. Df means the degree of freedom.

Table 11: Results of two-way ANOVA comparing the interaction of topographic position (i.e., uplands, lowlands, and potholes) and land use (i.e., conventional agriculture, conservation agriculture, CRP, and native grasslands) for clay, silt, and sand content at 15-30 cm. Significant values are bolded.

		Clay 15-30 cm		Silt 15-30 cm		Sand 15-30 cm	
ANOVA Factor	DF	F Value	P Value	F Value	P Value	F value	P Value
Topography (T)	2	3.575	**<0.05**	15.050	**<0.001**	9.895	**<0.001**
Land Use (LU)	3	0.868	0.463	2.355	0.082	0.741	0.532
T x LU	6	0.317	0.925	1.010	0.428	0.317	0.925

* Significance level used was set at an alpha of 0.05, significant values are in bold. Df means the degree of freedom.

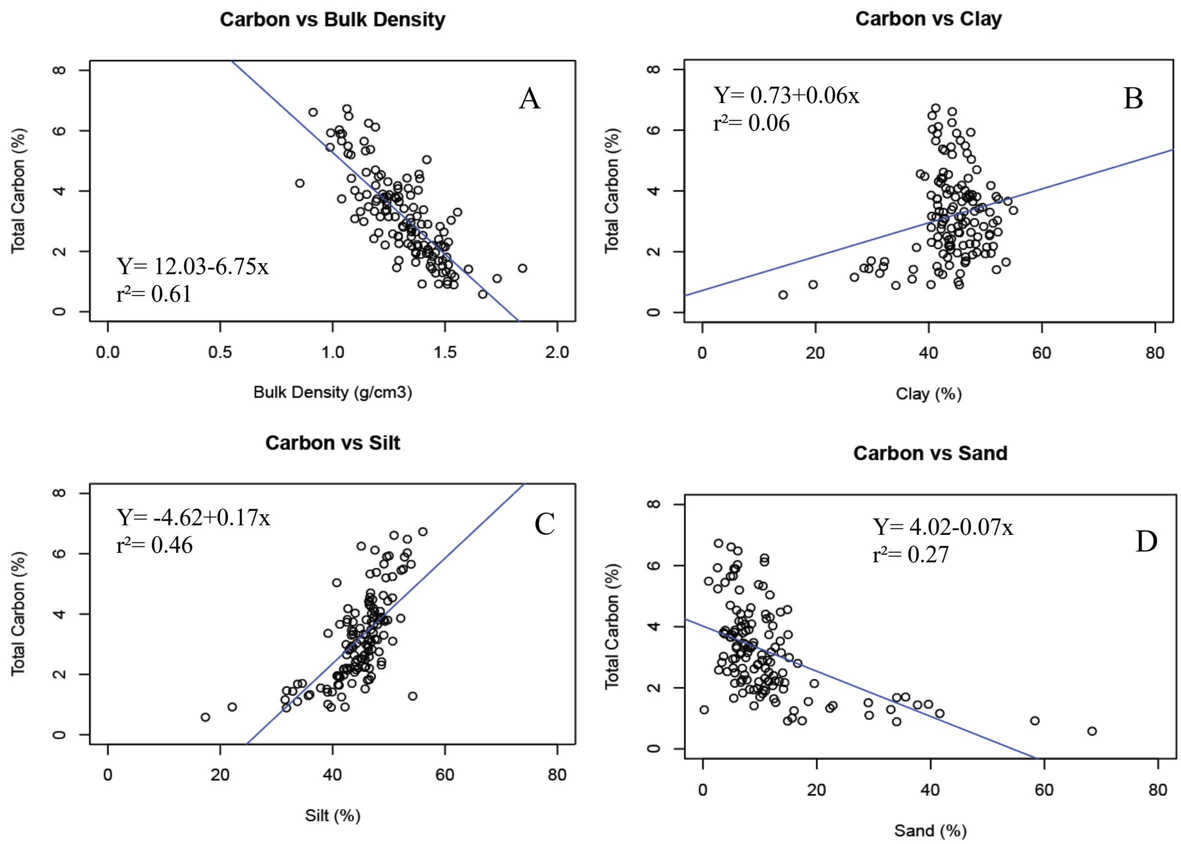

Figure 31: Regression analysis showing the relationship between total carbon and bulk density (A), total carbon and clay content (B), total carbon and silt (C), and total carbon and sand (D).

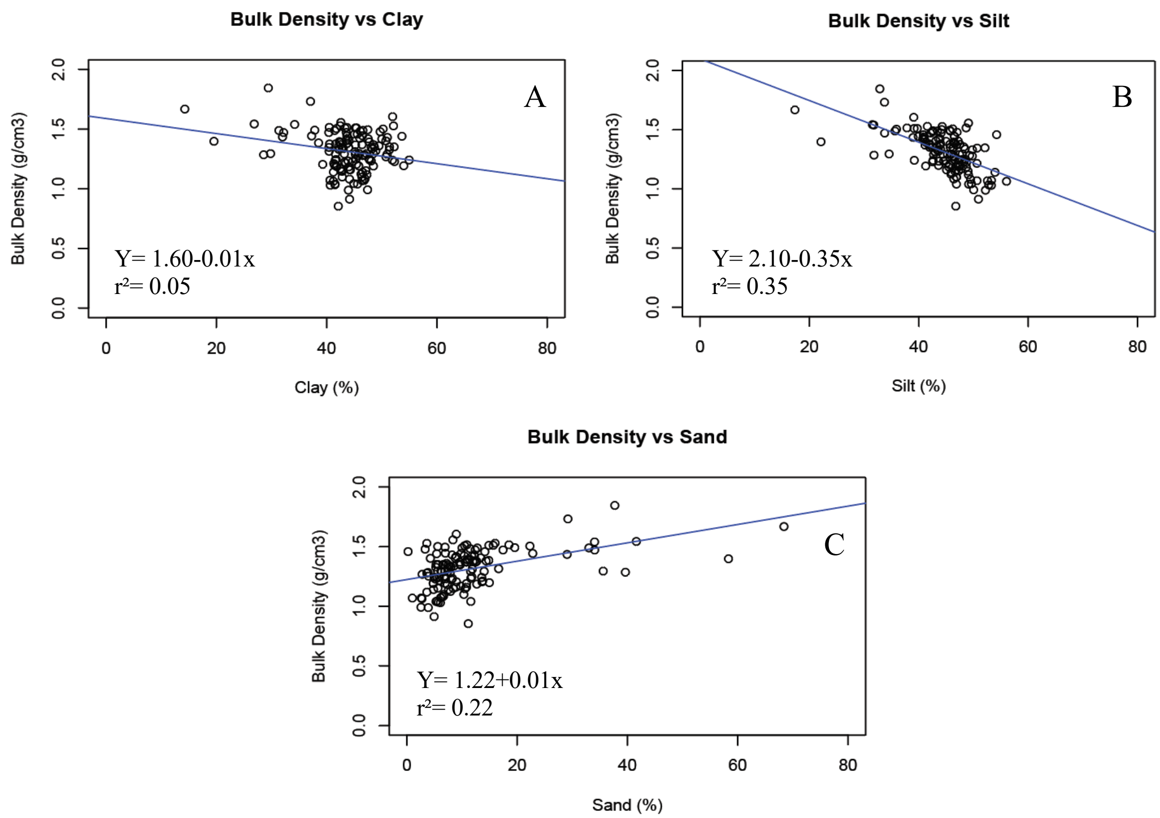

Figure 32: Regression analysis showing the relationship between bulk density and clay (A), bulk density and silt (B), and bulk density and sand (C).

Chapter 6 Discussion

Topographic position is the main factor influencing TC, bulk density, and particle size for samples included in this study. With topography being one of the main soil-forming factors (Jenny 1941), it has a pronounced influence on soil properties, even with the low relief found throughout the sites. This can be seen with TC increasing down the hillslope while bulk density decreases. Additionally, TC is higher in the upper 0-15 cm while bulk density is higher in the lower 15-30 cm. Clay and silt contents increase down the hillslope while sand content decreases. These are all expected results based on the standard model of soil development along a toposequence (Schaetzl and Anderson 2005).

Land use did not exhibit a pronounced effect on the soil properties included in this study, and relationships between land use and soil properties are more difficult to explain. This is primarily attributed to the small sample size for each land use examined for this study. Only one native site and two conventional sites were included, which is not a representative sample size and could dramatically affect the results. Five conservation agriculture sites and four CRP sites were also included. Additionally, land use history, specifically for conservation agriculture sites, is not as well known. There is likely considerable temporal variability when conservation practices were adopted among these sites. Also, more conservation agriculture sites were included in this study, so more of the inherent landscape heterogeneity is captured, which could help explain the lack of significant differences in soil properties by land use.

6.1 Influence of Topographic Position on Soil Carbon

6.1.1 Role of Geomorphic and Pedogenic Processes

Topographic position affects TC because of the geomorphic and pedogenic processes that influence how soil forms along a hillslope. The upland encompasses the convex section of the hillslope where there is maximum runoff and erosion, and minimal soil development (Schaetzl and Anderson 2005). The upland also has the steepest slope, which results in the greatest runoff and erosion, less infiltration, vegetation, and pedogenesis, and ultimately thinner, less developed soils that are highly variable (Schaetzl and Anderson 2005). Given that the upland is generally the most erosive position with the least amount of soil development, it is expected to have the lowest TC. The lowland is the gently sloping to level transition zone between the pothole depression and the steeper upland hillslope. This is a run-on area that receives water, sediment, plant debris, and other material from upslope, so the soils are complex and cumulic (Schaetzl and Anderson 2005). Because of this, the lowland is expected to have higher TC than the upland. The pothole is at the bottom of the hillslope at the lowest elevation, where groundwater interactions are more common and the soil tends to be the thickest, most complicated, and cumulic (Schaetzl and Anderson 2005). This soil is the most organic matter-rich and gleyed due to the accumulation of water and sediment which causes greater primary productivity and lower decomposition rates because of prolonged saturation (Schaetzl and Anderson 2005). Thus, the pothole is expected to have the highest amount of TC storage.

The results of this study follow the predicted pattern of soil development (and carbon storage) along a hillslope even with the low relief found at these sites (Figure 24). The upland has the least TC due to the steepness of this position along the hillslope which causes maximum erosion and runoff. The lowland has an intermediate amount of TC because this position accumulates water, sediment, and plant debris run-on from the upland, making soils more complex, cumulic, and organic-rich. The pothole has the most TC because this position is at the bottom of the hillslope, also accumulates run-on from the upland, and the pothole soils are saturated the longest, which slows decomposition rates and increases wetland plant productivity (Richardson, Arndt, and Freeland 1994). Statistical analyses revealed that although mean TC is slightly greater in the pothole, the lowland and pothole positions are not statistically different, while the uplands have significantly less TC than the lowlands and potholes (Figure 24). Lack of significant differences in TC between the lowland and pothole are likely because differences in slope and geomorphic and pedogenic processes between the two positions are minimal and both positions receive runoff from the uplands.

When considering depth, the upper 0-15 cm stored more TC than the lower 15-30 cm on average at each landscape position. This is because carbon contributions from plant roots are greatest near the surface and decrease with depth (Zimmermann, Dauber, and Jones 2012), and carbon from decomposing vegetation is primarily added to the soil surface. Higher plant inputs in the upper 15 cm of soil can create a positive feedback in which increases in carbon content leads to decreases in soil organic matter decomposition, further increasing carbon content (Lange et al. 2023).

Tangen and Bansal (2020) conducted a study investigating soil organic carbon stocks along a hillslope from the uplands to potholes and also determined that carbon storage increased from the upland position to the “inner” or pothole position. They found that sediment and organic matter from the uplands is eroded and deposited in the pothole. Because potholes are located at the base of hills, they are saturated for longer, typically are more productive, and decomposition rates are slower, ultimately resulting in higher TC (Tangen and Bansal 2020). Badiou et al. (2011) also studied carbon stocks along hillslopes ending in prairie potholes and found that carbon storage increases down the hillslope. Like my study, Badiou et al. (2011) found that carbon contents were similar among the non-upland positions due to run-on accumulation. In addition, other studies have reported similar trends, with carbon content increasing from the upland to the lowland/pothole positions (Olson et al. 2012; Tang et al. 2010; Zhu et al. 2019). This study and others illustrate that topography affects soil development and is a major control on geomorphic and pedogenic processes, which affects soil production and organic matter decomposition rates, therefore influencing carbon storage and other soil physical factors (Khormali et al. 2007; Zhu et al. 2019).

6.1.2 Role of Particle Size

Based on topography, silt and clay are the most dominate throughout each position. Except for the uplands in Martin County, silt and clay are each greater than 40% and combined exceed 85% in most samples, and silt and clay both increase slightly from upland to lowland to pothole positions. Sand content is highest in the uplands and decreases down the hillslope. Differences in particle size based on topographic position can also be attributed to differences in geomorphic and pedogenic processes along a hillslope. On the steeper and more eroded upland position, coarse materials like sand are often left behind because finer-grained soils are more easily erodible (Schaetzl and Anderson 2005). Thus, while sand content is generally low throughout study sites, it is highest in the upland position. Sandy soils have low surface area, nutrient retention, and water holding capacity and high water permeability (Wambeke 1991), which inhibits their ability to store carbon.

The lowland and the pothole positions have similar silt and clay contents due to similar geomorphic and pedogenic processes with both being run-on sites that accumulate finer-grained material eroded from the uplands. The pothole is similar to the lowland but is at a lower elevation and is a depression, so it experiences the maximum run-on and sediment accumulation and is saturated for longer, which has resulted in finer-grained and gleyed soils (Schaetzl and Anderson 2005). Clay and silt contents are significantly higher in the pothole compared to the upland position. These finer-grained potholes soils are able to store more carbon because they are saturated longer, and clay and silt have a high surface area to bind organic matter (Iranmanesh and Sadeghi 2019). While clay content and TC are not correlated ($r^2 = 0.07$), silt content and TC are moderately correlated ($r^2 = 0.46$), which also helps to explain why the lowland and pothole positions have higher TC than the uplands.

Tangen and Bansal (2020) evaluated carbon stock along a hillslope and similarly found that the uplands had the coarsest-grained soils and the least amount of carbon, while the wetlands had finer-grained soils and the most carbon (Tangen and Bansal 2020). Hamarashid et al. (2010) investigated the effects of soil texture on chemical composition in soils, including carbon mineralization, and found that carbon content in finer grained textures (i.e., silt and clay) were significantly higher ($P \leq 0.01$) compared to coarser grained textures (i.e., sand). These studies further support the strong relationship between particle size and carbon content along a hillslope identified in my study.

6.2 Influence of Land Use on Soil Carbon

6.2.1 Total Carbon Based on Land Use

The results of TC based on land use do not follow the expected outcome based on my hypotheses. I expected that native prairie potholes would store the most carbon followed by CRP sites and conservation agriculture sites, and conventional agriculture sites would store the least amount of carbon. However, TC is not significantly different among the land uses, likely due to a small sample size and a large range of TC values throughout the land uses.

The native site does have the most TC (Figure 28). This was expected because native prairie pothole soils have remained for the most part unchanged by anthropogenic activities and still have a high capacity to store carbon whereas conversion to other land uses normally results in TC loss (Mann 1986). Many studies have compared sequestration in native sites to other land uses and have found that native sites consistently have the highest carbon content (Tangen and Bansal 2020; Lal 2007; Wei et al. 2014; De et al. 2020). This is because when native landscapes are converted to agricultural systems, SOC is mineralized, and carbon is lost to the atmosphere as CO_2 (Wei et al. 2014). For this study, only one native site was sampled, so while it still has the most TC, having more native sites would be preferred for future studies. Having a larger number of samples would provide more reliable results because when sample sizes are larger, the standard error will be smaller, and the data are more representative of the total population (Lee et al. 2015).

Conventional agriculture sites have the next highest mean TC but average only 0.01% more TC than conservation agriculture and 0.39% more TC than CRP sites, and differences in TC by land use are not significant. Mean TC being similar for conventional, conservation, and CRP shows that current land use does not exert strong controls over TC and other factors, such as land use history, topography, and hydrology may play a more pivotal role in determining TC. Site MA-B2, which has high TC in the lowland and pothole positions, is not tile drained, so the lowlands and pothole are saturated for much longer than at drained sites. Conventional fields with prairie potholes that have been tiled, drained, and tilled, often experience enhanced organic matter decomposition and erosion (Lal 2004). For example, site MA-B1, a conservation agricultural site, is immediately adjacent to MA-B2 but it is tile drained and stores considerably less carbon, especially in the lowland and pothole positions. CW-F, a conventional agriculture site that is tiled drained, has a lower mean TC and the pothole position has the overall lowest mean TC of all sites.

Conservation and conventional agriculture sites have similar mean TC, which was not expected. I hypothesized that conservation sites would have higher amounts of TC because conservation agriculture uses practices that minimize soil disturbance, have more plant diversity, and have continuous residue cover (Reicosky 2008). Four out of the five conservation sites plant cover crops following fall harvest to increase soil quality and reduce soil erosion, in turn enhancing carbon sequestration (Lal 2004). However, only two of the five conservation sites have high TC, while two have very low TC. Sites CW-G and WA-D, which both have relatively large and deep pothole depressions, have higher pothole TC than even the native pothole, though upland TC is much higher for the native site. Conservation sites MA-B1, MA-E1, and WA-B3 all have low TC. While it is unclear why TC is so low at site WA-B3, MA-B1 and MA-E1 both have relatively high sand and relatively low silt content, particularly in the uplands. Also, according to the farmer, they have been experimenting with cover crops for only a few years and have had difficulty in getting them established. Although cover crops can help increase TC, they need to be a long-term management practice to significantly increase carbon sequestration (Lal 2004). Another reason why TC might be lower than expected for conservation agriculture sites is because the land use histories for these sites are not well-known. Landowners could not give precise dates on when conservation practices were adopted, and previous agricultural practices are not known. Thus, there is likely considerable temporal and spatial variability in the implementation and success of current conservation practices and in the intensities of previous practices.

CRP sites have lower TC than expected given that prairie potholes enrolled in CRP generally experience an increase in carbon sequestration over time, specifically in the top layer of soil due to organic matter accumulation (Phillips et al. 2015). CRP sites sampled for this study have been enrolled in CRP since 2003 (WA-B1), 2006-2008 (CW-I), 2015-2019 (MA-D), and 2021 (WA-B2). There are not clear trends in TC in the upland and lowland positions among these sites, but TC in the pothole progressively increases as length of time in CRP increases. Lack of trends over time for uplands and lowlands may be due to inherent landscape heterogeneity. For example, site WA-B2 has only been enrolled in CRP since 2021 but the lowland position has the highest TC of all CRP data. The lowlands are proximal to a fence line with a dense stand of trees, so the area receives organic inputs from CRP grasses as well as trees. Site MA-D has low TC on the uplands and lowlands, both of which have relatively high sand content. Thus, CRP appears to be effective at progressively increasing carbon storage over time in potholes, but other factors may limit the effectiveness in other landscape positions.

Tangen and Bansal (2020) investigated SOC in native, restored, and cropland sites and found that croplands had higher SOC than restored sites, and they attributed this to SOC taking a long time to recover following restoration. De et al. (2020) found that CRP sites take anywhere from 19 to more than 40 years, depending on topographic position, to have improved soil health, but even after 40 years carbon storage in CRP sites was not as high as in native sites. Ballantine and Schneider (2009) also studied restored wetland depressions and found that after 55 years of restoration, the wetlands only held about 50% of the carbon content that the native sites held. Range of recovery time depends on many factors including land use history, soil type, location, topography, hydrology, and more. These studies indicate it generally takes decades for soil carbon to recover, and since half of the CRP sites included in my study have been in CRP for less than 10 years and no sites have been in CRP for more than 20 years, there may not have been enough time to see a significant increase in TC.

6.3 Carbon Stock

Carbon stock is the amount of carbon held in any specific carbon pool, such as soil (European Environmental Agency 2022). Carbon stock was calculated for each landscape position to a depth of 30 cm by multiplying TC, bulk density, and depth (i.e., 15 cm) and then summing the results for 0-15 cm and 15-30 cm (Ellert et al. 2001). Given there are significant differences in total carbon and bulk density based on topographic position at my study sites, carbon stock was assessed for each landscape position. While there are no significant differences in the total carbon based on land use there are significant differences in bulk density, specifically in the upper 0-15 cm, so carbon stock was similarly evaluated for land use. By calculating carbon stock for each landscape position and land use, we can determine which position and land use on average stores the most carbon. This can have implications on agricultural practices and management strategies to help mitigate agricultural impacts to climate change.

6.3.1 Influence of Topographic Position on Carbon Stock

Carbon stock by topographic position follows similar trends to TC, the upland position has the lowest carbon stock (75.51 Mg/ha), the lowland position has intermediate carbon stock (137.48 Mg/ha), and the pothole position has the highest carbon stock (144.13 Mg/ha) even though the uplands have the highest bulk density and potholes have the lowest bulk density. TC and bulk density have a strong inverse linear correlation (r^2= 0.61), so as bulk density decreases TC increases. Since TC is significantly higher and bulk density is significantly lower in the pothole compared to the uplands for both depths, carbon stock is heavily impacted by topographic position.

Tangen and Bansal (2020) conducted a study of carbon stocks along transects from the uplands to prairie potholes throughout the PPR and found that soil carbon stock progressively increased from the uplands to the pothole for natural, restored, and cropland sites. De et al. (2020) examined bulk density and soil organic carbon content along transects from the hillslope shoulder to toeslope for sites enrolled in CRP in Minnesota and Iowa and found that bulk density progressively decreased and soil organic carbon progressively increased, resulting in carbon stock increases down the hillslope. De et al. (2014) examined the role of slope and other factors on SOC in India and similarly found that SOC stock was lowest on the shoulder and greatest in the footslope. Thus, the trend of decreasing bulk density and increasing soil carbon and carbon stock from uplands to lowlands have been documented throughout the PPR, southern Minnesota, and diverse regions around the world.

Particle size also plays a role in bulk density and carbon stock. Sandy soils typically have a higher bulk density due to lack of internal porosity and lower carbon content because of low surface area for carbon to bind to (Hao et al. 2008). Soils with a higher bulk density typically have larger macro-pores and store less water (Biswas et al. 2012). Bulk density often decreases when soils have higher clay content because fine-grained soils have higher pore space (Lal and Kimble 2000), causing them to store more water. The uplands have the highest sand content and the pothole has the highest clay content, which in part explains why potholes have the highest carbon stock and uplands have the lowest carbon stock.

Given differences in carbon stock among topographic positions, topography is important to consider when developing management practices for carbon sequestration. Despite the low levels of relief, potholes still store almost twice as much carbon per hectare as the uplands, which emphasizes that prairie potholes are a major carbon pool that should be considered when promoting and implementing conservation practices. When pothole soils are drained and converted to cultivated cropland, they have the potential to release more carbon to the atmosphere than other landscape positions. By focusing management practices on these carbon "hotspots", potholes and lower topographic positions would be able to store more carbon (Hemes et al. 2019) and provide a more significant contribution to mitigating climate change.

6.3.2 Influence of Land Use on Carbon Stock

Carbon stock for land use exhibits similar trends to TC, with the native site having the highest carbon stock (133.95 Mg/ha), followed by conventional sites (125.38 Mg/ha), then conservation sites (121.93 Mg/ha), and CRP sites have the lowest carbon stock (107.50 Mg/ha). Differences in carbon stock among land uses are not as great as differences by topographic position for my study because of the large range of TC values for each land use. But the implication that there are differences among land uses highlights the importance of land management and conservation for carbon sequestration and storage.

Li et al. (2023) investigated SOC stocks based on land use change under different soil types in Illinois over 167 years using a space-for-time substitution method. In their study, native prairies have on average the highest carbon stock (147.4 Mg/ha), followed by forests (76.1 Mg/ha), then wetlands (72.2 Mg/ha). Croplands on average had a much lower carbon stock (59.5 Mg/ha) especially compared to the prairie land cover (Li et al. 2023). This study further illustrates the importance of carbon hotspots and how small areas of land (e.g., remnant prairie and wetlands) can be either major sinks or sources for atmospheric CO_2 depending upon land management decisions. Dolan et al. (2006) conducted a study on how conventional tillage, no-till, and residue affect carbon stock in Minnesota soils. They found that mean carbon stock for conventional tillage was ~107 Mg/ha to ~112.5 Mg/ha for chisel plow and moldboard plow respectively, while mean carbon stock for no-till was ~107 Mg/ha and 79 Mg/ha in fallow fields (Dolan et al. 2006). Carbon stock was similar among the conventional and conservation practices, with conventional practices having higher carbon stock than conservation practices when crop residue is returned to the soil. Results are similar to my study, showing how complex carbon stock is based on land use due to confounding factors such as topography, soil physical properties, and climate.

In my study, the native site having the highest carbon stock shows how important keeping grasslands in their natural state is. Agricultural practices of any kind can reduce the amount of carbon in a landscape, with agricultural soils often losing 25-75% of their original carbon storage (Lal 2013). Conventional sites having higher carbon stock than conservation and CRP sites was unexpected, but this is likely because undrained site MA-B2 had a higher carbon stock than even the native site in the lowland and pothole positions, but considerably lower carbon stock in the uplands. This undrained site shows how important other land use practices such as tile drainage are for carbon stock, especially in lowland and pothole positions because the other conventional site, CW-F, is tile drained and has a much lower carbon stock than the native site, particularly in the pothole position.

Conservation sites all have high carbon stock in the pothole position, some sites even store more carbon than the native site. CRP potholes also have a moderately high carbon stock. However, there are no clear improvements in carbon stock in the upland and lowland positions for the conservation and CRP sites. For example, in Martin County the carbon stock in the upland position is very low for conservation, conventional, and CRP sites, all of which have high sand content. Conservation strategies appear effective at increasing carbon storage over time, at least within the pothole, but other landscape factors like particle size and tile drainage can reduce the effectiveness of these strategies.

Veloso et al. (2018) conducted a 30-year study on the effects that no-till and cover crops have on SOC in Brazil. They found that over the 30 years, in the top 0-20 cm, conventional agriculture decreased SOC stocks by 3.8 Mg ha^{-1} while all soils with legume cover crops experienced increases in SOC stocks. They attributed the increase in SOC to land management changes that increased plant C inputs. Olson and Lang (2014) studied impacts of planting via no-till, chisel plow, and moldboard plow with and without cover crops on SOC sequestration in Illinois over a 12-year period and found that all systems had an increase in SOC when cover crops were added, with no-till having the highest SOC overall (Olson and Lang 2014). Li et al. (2017) studied carbon sequestration rates of CRP lands in western Texas that had been under CRP for a range of 6-26 years. They found an increase in SOC for CRP lands at a rate of 69.82 kg C ha^{-1} y^{-1} for 0-10 cm and 132.87 kg C ha^{-1} y^{-1} for 0-30 cm. Li et al. (2017) predicted it would take around 75 years for CRP lands to reach a carbon stock equivalent to native rangelands.

While conservation practices and CRP do have the ability to increase carbon sequestration rates, they are long-term solutions that can take several decades for significant increases in carbon storage to occur. By informing farmers about the potential that land management decisions have, and encouraging them to implement conservation strategies, carbon stock can increase and help with climate change mitigation.

Chapter 7 Conclusion

Climate change is a prevalent issue around the world. Greenhouse gas emissions, specifically CO_2, in the atmosphere have been increasing since the Industrial Revolution due to anthropogenic activities. Environmental hazards that are affecting humans and wildlife as well as the natural world will continue if atmospheric greenhouse gas concentrations are not reduced. The pedologic carbon pool stores a large amount of carbon (~2,500 Pg), but has the potential to store more, especially in wetland soils. Prairie potholes, found in the Great Plains region of the United States and Canada, could be a major source for carbon sequestration, but many potholes have been modified for agricultural production. Conversion of wetlands, such as prairie potholes, to conventional agricultural systems often inhibits their ability to sequester carbon and can cause these landscapes to become a source of CO_2 for the atmosphere through organic matter decomposition due to drainage and tillage. Alternative approaches to agriculture, such as no-till farming and establishing cover crops, are emerging techniques to reduce soil degradation, improve soil health, and reduce greenhouse gas emissions. Federal conservation programs such as the CRP are also popular ways for farmers to restore native vegetation, reduce erosion, and become a positive part of the climate change conversation.

The purpose of this project was to evaluate the effects that topographic position has on carbon content of soils in agricultural landscapes with prairie potholes in southern Minnesota. To do this I quantified carbon content of prairie potholes based on their topographic position and land use and I characterized prairie pothole soil physical properties (i.e., bulk density and particle size). Prairie potholes form at the base of hillslopes, so topographic position can have major impacts on geomorphic and pedogenic processes that ultimately impact carbon storage across the landscape. I hypothesized that based on topographic position, potholes would have the highest soil carbon contents, lowlands would have an intermediate amount of carbon, and uplands would have the lowest soil carbon contents. I also hypothesized that based on land use, native prairie potholes would have the highest carbon content, followed by CRP sites, then conservation agriculture, and conventional agriculture soils would have the lowest carbon content. Lastly, I hypothesized that bulk density would have an inverse relationship with carbon content and that clay-rich soils would store the most carbon and sand-rich soils would store the least.

Soil samples were collected along a toposequence and split into two samples by depth: 0-15 cm and 15-30 cm to determine total carbon content, bulk density, and particle size. One and two-way ANOVA statistical analyses were done to evaluate statistical significance of total carbon, bulk density, and particle size by topographic position, land use, and the interaction between them at 0-15 cm and 15-30 cm depths. If ANOVA identified significant differences among topographic positions or land uses, the Tukey HSD test was utilized to determine which classes were significantly different. A regression analysis was also conducted to evaluate the relationships between total carbon, bulk density, and particle size.

Results showed that topographic position fit my predicted hypothesis that while progressing from the uplands to the potholes, TC increases and bulk density decreases;

TC was also higher in the upper 0-15 cm and bulk density was higher in the lower 15-30 cm of sample cores. Additionally, clay and silt content increased down the hillslope while sand content decreased. This is because fine grained soils (i.e., silt and clay) are eroded from the steep slopes of the uplands and are deposited at the lowland and pothole positions. Lowland and pothole soils accumulate water and sediment from the uplands which causes greater primary productivity and lower decomposition rates because of the high saturation, thus increasing carbon content. Overall, topography has a strong influence on how soils form along a hillslope, which then affects soil properties and carbon content. Results for land cover did not follow my hypothesis and were more complicated. Conventional sites had more TC than expected, this was due to only two sites being sampled and one having very high carbon content, increasing the overall average. Conservation sites had slightly less TC than conventional, due to a wide range of TC values, poor cover crop growth, not enough pothole samples taken and uncertainty in land use history. CRP sites had the least amount of TC, likely due to two of the four sites being enrolled in CRP for only a few years, which is not long enough to see significant change.

This work is significant because by focusing on topographic position and the interaction with land uses and depth, this study helps add to the pool of knowledge about which factors have the greatest influence on soil physical properties, specifically carbon sequestration. Because the prairie pothole itself stores the most carbon, we know that depressional features and lowland positions at the bottom of hillslopes should be prioritized for conservation practices and agricultural practices that reduce their ability to store carbon such as draining or tillage should be limited. The low levels of relief for each site proves how important changes in elevation are to soil formation, and even with small changes, carbon storage can be majorly affected. The native site had the highest carbon content emphasizing how important it is to protect natural landscapes. Due to the complexities and confounding factors that lead to uncertainties in land use impacts on soil carbon, more research is needed to better understand how different land use practices affect carbon sequestration. Additionally, previous studies have found that by adopting conservation management practices, soils can replenish carbon storage that they may have lost to conventional agricultural practices. While these practices may take decades to see significant carbon increases, farmers need to be informed of these findings so that they can do their part and be on the forefront of climate change mitigation.

Future studies should prioritize having more land use samples and more standardized randomness when selecting sites to allow for more robust and accurate analyses. Also, taking deeper samples (e.g., 1 m) would help with understanding deep carbon storage and how topography and land use are affecting the subsurface. This project is the first step of a larger study that will take place over the next several years investigating prairie potholes and carbon sequestration, but the initial findings are positive regarding the potential for carbon storage to increase in soils in the PPR. As mentioned, more research needs to be done, specifically in regard to land use effects on carbon storage, because by understanding this complex issue we can potentially greatly increase carbon sequestration, continue the fight against climate change, and help protect the natural environment and human life.

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