Dynamics of Soil Aggregate Formation in Different Ecosystems

By

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ABSTRACT

Soil aggregate formation is essential to establish good soil structure which provides better soil functionality and ecosystem services. Different sizes, shapes, and stability of soil aggregates are under the influence of soil formation factors. Similarly, aggregation affect the sensitivity of soil to erosion and plant-soil-water dynamics. In this study, we investigated the dynamics of soil aggregate formation in various land uses.

Chapter 2 of this work mainly focused on increasing our understanding of the mechanisms responsible for C stabilization which are associated with soil structure. Two long-term (>20 years) land uses were identified (agriculture and woods) on two soil series that represented non-eroded and eroded soil conditions. A third land use of non-eroded grassland was selected as a comparison of a land use with high C accumulation potential. Intact soil cores were collected from 0-30 cm, 30-60 cm, and 60-90 cm depths in spring 2017. In general, the managed land use had a greater presence of smaller aggregates and soil organic carbon content at 0 – 30 cm depth, whereas woodland soils had higher carbon and nitrogen ratio, δ_{13}C, and δ_{15}N at this same depth. In addition, erosion negatively influenced soil aggregation, aggregate stability, and SOC. Silt content appeared to have an important role in soil aggregation, possibly because it was the predominant soil particle size class. Soils with greater albite content and clay minerals had better aggregation and higher carbon and nitrogen ratio in 1-2 mm aggregates, while quartz was positively correlated with the proportion of smaller aggregates. The physical stabilization of

SOC and soil minerals had a strong relationship with aggregate size distribution and the predominant soil particle size, silt, played a vital role.

The following section of this work focused on the relationship between hydraulic properties, soil carbon, and soil structure. In this part of the research work, the same samples collected in the above-mentioned work were used, plus another set of intact cores in stainless steel liners was collected for soil hydraulic properties determination. The difference between these two sections of the research was that one focused on parameters that are more static, and this section focused on dynamic soil properties, mainly hydraulic ones. In general, soil disturbance in the agroecosystems negatively affected soil structure, soil hydraulic properties and total soil carbon content, but these soils had a greater amount of labile carbon as cold-water extractable carbon and dissolved organic carbon. The wooded land-use helped build soil carbon content the most, whereas grassland had better hydraulic properties as indicated by greater K_{sat}, soil water retention and proportion of fine-mesopores. However, soil pH, bulk density, and water extractable labile carbon fractions were negatively correlated with total carbon content. Mesopore volume was negatively correlated with labile carbon fractions.

Finally, the last section of this work evaluated soil aggregate re-formation dynamics after disturbance in short-and long-term time scales. This study was conducted on research plots with conventional tillage and no-tillage with or without solid dairy manure applications on a 2-6% slope with a silt-loam soil in Arlington, Wisconsin. Soils under no-tillage had a greater proportion of larger aggregates (>1 mm), carbon content, bulk density, soil water retention, and micropores compared to conventional tillage at 0-20 cm depth during 2018 and 2019. In contrast, conventional tillage had a greater proportion of smaller (<1 mm) aggregates. In addition, within season soil disturbance by spring tillage resulted in a lower proportion of larger aggregates and smaller pores, whereas the long-term effects of tillage mainly affected aggregates smaller than 2 mm. It appears that larger soil aggregates can recover annually but aggregates smaller than 2 mm do not recover when annual disturbances are present.

In conclusion, soil organic carbon has coupled interactions with soil physical properties and soil minerals, where these associations helped soil aggregate formation and stabilization. Soil disturbance from management negatively affected soil aggregation, likely from a decrease in total organic carbon content. Conversely, labile carbon fractions studied were more abundant in disturbed land uses. Also, the percent range of silt content was the dominant particle size in these soils and appeared to be an influencing factor for aggregate size distribution and organic carbon accumulation. Larger aggregates can re-form under annual disturbance, but smaller aggregates may not be able to re-form within a year after disturbance. Long term management appeared to mainly affect aggregates smaller than 2 mm in different land uses.

DEDICATION

I would like to foremost dedicate this dissertation to my grandfather, Mehmet Ozlu, whose love and respect for the Soil was instilled in me.

BIOGRAPHICAL SKETCH

Ekrem Ozlu was born in Cihanbeyli and grew up in Konya, Turkey, with his grandparents-Elife and Mehmet, parents-Guler and Halil Ibrahim, brother, and three sisters. He attended Ismail Hakki Tonguc Primary School and Selcuklu Gazi High School. He earned a Bachelor of Agricultural Engineering with an emphasis in Soil Science and Plant Nutrition under the supervision of Dr. Kenan Barik at Ataturk University in Erzurum, Turkey (2007-2011). He spent six months at Ankara University Language School in Ankara, Turkey, and a year at ELS-Language School in Chicago, River Forest, IL, USA. He studied Plant Sciences under the supervision of Dr. Sandeep Kumar at South Dakota State University (2015-2016). Upon completing his Ph.D., he will take up a postdoctoral position at the Great Lakes Bioenergy Research Center at Kellogg Biological Station, Michigan State University.

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Table of Contents

LIST OF FIGURES

LIST OF TABLES

Chapter 4

LIST OF ABBREVIATIONS

Chapter 2

BS	Bulk soil
C	Carbon
C:N	Carbon and nitrogen ratio
DR	Disaggregation reduction
N	Nitrogen
SOC	Soil organic carbon
TC	Total carbon
PAS	Percentage of one aggregate size
C_e	eroded cornfield
W_e	eroded woodland
C_f	non-eroded cornfield
W_f	non-eroded woodland
G_f	non-eroded grassland
$_{13}C/_{12}C$	$_{13}C$ to $_{12}C$ ratio
$_{15}N/_{14}N$	$_{15}N$ to $_{14}N$ ratio

Chapter 3

EC	Electrical conductivity
C	Carbon
SOC	Soil organic carbon
SOM	Soil organic matter
CWEC	Coldwater extractable carbon
DOC	Dissolved organic carbon
C:N	Carbon and nitrogen ratio
TN	Total nitrogen
ρb	Bulk density
K_{sat}	Hydraulic conductivity
SWR	Soil water retention
BS	Bulk soilC_e eroded cornfield
W_e	eroded woodland
C_f	non-eroded cornfield
W_f	non-eroded woodland
G_f	non-eroded grassland

Chapter 4

C	Carbon
NT	No-till
CT	Conventional Tillage
SOC	Soil Organic Carbon
TN	Total Nitrogen
pb	Bulk Density
SWR	Soil Water Retention
EC	Electrical Conductivity
K_{sat}	Hydraulic Conductivity
SOM	Soil Organic Matter
C: N	Carbon and Nitrogen Ratio
CTNM	Conventional Tillage with No Manure
CTSM	Conventional Tillage with Manure
NTNM	No-tillage with No Manure
NTSM	No-tillage with Solid Manure Application

CHAPTER 1

GENERAL INTRODUCTION

Soil structure is the organization of soil particles (i.e., sand, silt, and clay), which are bound together by organic and inorganic compounds and shaped into aggregates of different dimensions and geometries (Tisdall, 1996). The development of soil structure is important for soil functions and ecosystem services (Sparks and Banwart, 2017). Soil structure influences water holding capacity of the soil, water movement, air exchange, availability of soil nutrients, microbial activities, soil erodibility, and soil heat conduction. Intra-aggregate and inter-aggregate pores have different dynamics for air and water exchange. Soil structure might implicitly influence decomposition through encapsulation against microbes (Balesdent et al., 2000) within soil aggregates. The mineralization of SOM is strongly dependent on the air and water equilibrium within the soil (Balesdent et al., 2000).

Soil aggregation has been studied mainly to address questions regarding its formation (Semmel et al., 1990), stabilization (Amezketa, 1999; Imeson and Vis, 1984), and the dispersion by different forces (Zhu et al., 2009). As explained in the conceptual model (Figure 1) on the role of SOC in the aggregate formation (Golchin et al., 1994) and modified by Balesdent et al. (2000), and Puget et al. (2000), the formation of aggregates begins with plant residues, which are a source of energy for soil microbes.

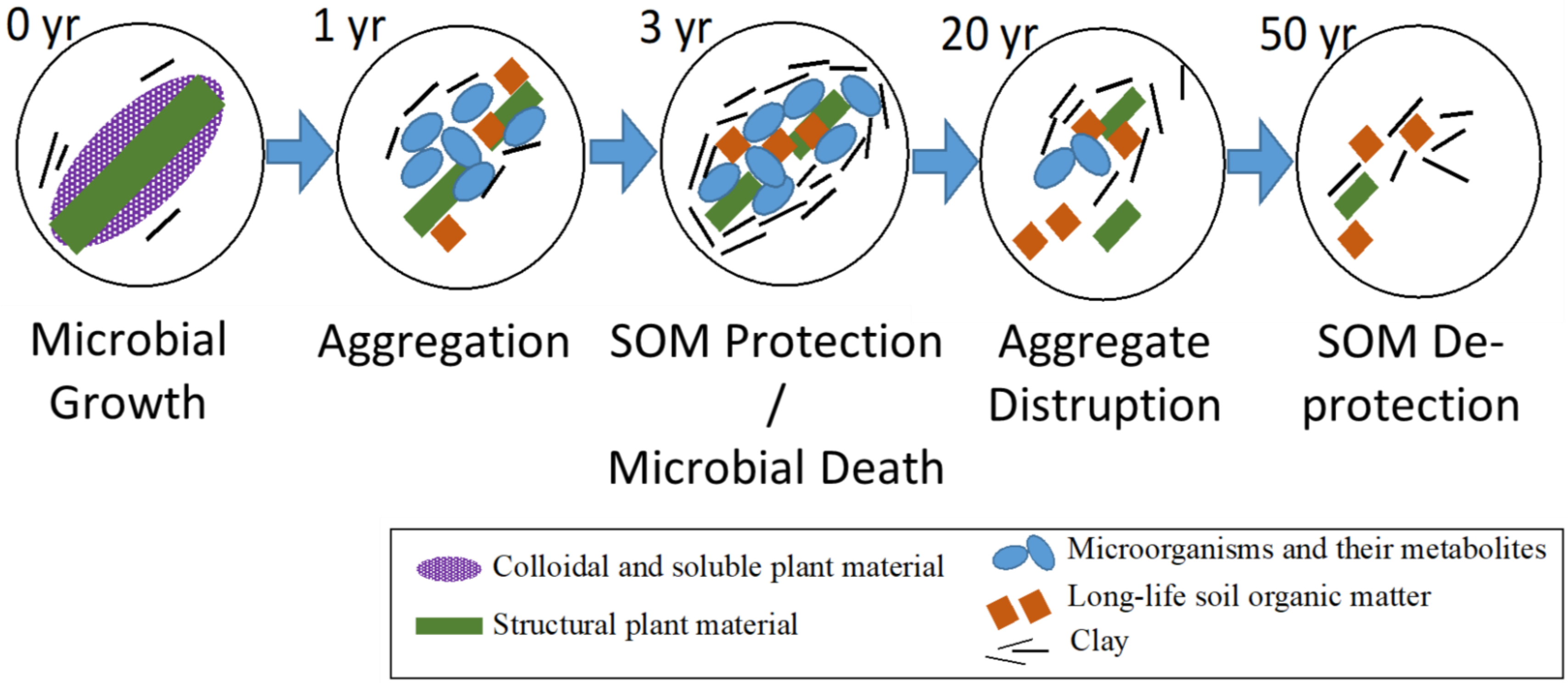

Figure 1. A modified schematic view of SOM protection during aggregate formation and soil aggregation disruption affecting SOM protection. Golchin et al. (1994), Balesdent et al. (2000), and Puget et al. (2000).

During the decomposition of plant tissue, microorganisms form organic molecules that facilitate the physical attachment of soil particles. The SOM produced in this process acts as a binding agent that promotes aggregation, but at the same time also gets protected within the formed aggregates. However, soil disturbances can cause physical aggregate disruption. Soil organic matter formation and degradation are affected by microbial enzyme activities (Burns et al., 2013). Additionally, the chemical nature of these organic C compounds is important. The rate at which different enzymes degrade different organic C structures varies. For example, aromatic molecules are decomposed gradually in comparison to cellulose and proteins (Haider, 1991; Martin et al., 1980). Although SOM is strongly adsorbed on mineral surfaces and protected within micro-pores and mesopores, the protection of SOM from enzymatic activities due to such adsorption is still not well understood.

Denef et al. (2004) reported that microaggregate-associated C drove increases in SOC content under conservation tillage compared to those under no-tillage. Six et al. (2000) documented similar associations of C with mineral fractions under tillage. Therefore, soil management affects the C stored in the soil, and it is a factor for soil aggregate formation besides the quantity of stored C. Intensive agricultural practices, such as tillage and over-fertilization, can cause disruption of aggregates, interrupt microbial activities, and lead to soil colloid and particle dispersion. However, mechanisms in this aggregate formation model can be different for aggregates of various sizes because different processes and binding agents are involved (Tisdall, 1996). Soil aggregate formation is a process influenced by different factors, environmental conditions, and mechanisms in the soil as it is the nature of its development. Some of these factors are soil moisture, particle size distribution, mineralogy, quantity and quality of SOM

(Denef and Six, 2005; Ramesh et al., 2019; Singh et al., 2018), and microbial activity (Gupta and Germida, 1988). Factors can vary under different managements and ecosystems.

Soil organic C is associated with aggregate formation in two ways: (i) SOC is protected or stabilized by the formation of aggregates (encapsulation of SOC in pores), and (ii) by C binding to soil particles, thus creating and stabilizing soil aggregates. Total porosity and soil pore size distribution, as well as the stability of these pores, are therefore important for protecting SOC from decomposition and stabilization through encapsulation within aggregates (Six et al., 2002). Land-use and management affect soil pore structure given the many factors and conditions in and around the soil environment, especially aggregate size distribution, and aggregate stability, and at the same time, these factors are influenced by different processes (Miedema, 1997). Organo-mineral associations are one way that soil particles interact with SOC and create soil aggregates. Several factors affect the interaction between organic molecules and mineral surfaces, including (i) the type, abundance, and charge characteristics of surface functional groups, (ii) the size, shape, and surface topography of primary minerals; and (iii) aggregate stability and size distribution (Ram A. Jat, 2012).

Soil aggregates are more stable with higher clay contents in soil (Angst et al., 2017; Kemper and Koch, 1966; Zhao et al., 2017). This underlines the importance of mineral surfaces, which vary depending on the amount and the type of charge on surfaces of the mineral-organic associations (Ram A. Jat, 2012). Soil erosion and different land-uses affect soil aggregation due to their impact on SOC. As topsoil is lost during the erosional processes, a different soil environment is created on which plant residues can accumulate over time (Issaka and Ashraf, 2017), whereas in non-eroded soil, the process of C accumulating from litterfall has possibly reached a relatively steady-state (Levi et al., 2020). In this situation of steady state, the quality and quantity of SOC is more important for aggregate formation and improving aggregate stability and hydraulic properties.

Soil moisture can be a limiting factor for plant primary production (Green et al., 2019) by causing water stress (Humphrey et al., 2018; Zhao and Running, 2010), and vegetation mortality (Schwalm et al., 2017), with droughts expected to be more frequent due to increasing extreme weather events (Seneviratne et al., 2010). Loss and accumulation of soil C fractions depend on various soil hydraulic properties that are present in different land-use ecosystems and with different management practices. Soil management practices, soil degradation, and soil recovery can noticeably alter labile soil C fractions (Franko, 1997; Ozlu et al., 2019). However, soil aggregation impacts hydraulic properties by creating larger pore sizes than those found between individual sand, silt, and clay particles (Nimmo, 2004).

Besides the factors mentioned above, soil management practices in different ecosystems impact aggregate formation. For instance, intensive agricultural practices, such as tillage and over-fertilization, can cause disruption of aggregates, interrupt microbial activities, and lead to soil colloid and particle dispersion (Haynes and Naidu, 1998). It is essential to evaluate how these disturbed aggregates re-form. Mechanisms in this aggregate formation model can be different for aggregates with different sizes because various processes and binding agents are involved (Tisdall, 1996). Soil aggregate size distribution and stability are important as they affect: (i) the sensitivity of land to erosion, and (ii) plant-soil water dynamics (Kemper and Chepil, 1965; Tisdall, 1996). Soil aggregate size distribution can aid in determining how aggregates of different sizes form; therefore, it is an important indicator of soil physical stability of SOC given the relationship described previously on SOC stability and aggregate sizes.

In this study, the dynamics mentioned above were investigated within different experiments using already existing land use and soil management schemes. Thus, the focus of this study was to investigate the dynamics of soil aggregate formation in various management and ecosystems. For this work, the association between soil aggregate formation and soil mineralogy, soil hydraulic properties, and quality and quantity of SOC, respectively, under different managements and land uses were considered. These factors also impact soil aggregate re-formation and the turnover of aggregates under short- and long-term time scales were also explored. We think the formation of different aggregates sizes varies according to the response of SOC, and hydraulic properties to soil management where re-formation of aggregates might be faster for soils containing more C, clay minerals, and improved water characteristics. Specifically, the objectives of this study were to:

(i) improve our knowledge on the role of carbon and soil mineralogy for a greater proportion of stable aggregates in diverse ecosystems (Chapter 2)

(ii) understand the association between soil carbon, soil hydraulic properties, pore size structures, and soil aggregation (Chapter 3)

(iii) evaluate the re-formation process of soil aggregates under short- (months) and long-term (years) effects of disturbance factors, such as tillage, crop growth within a season, and harvest (Chapter 4).

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CHAPTER 2

THE ROLE OF CARBON STABILIZATION AND MINERALS ON SOIL AGGREGATION

ABSTRACT

Soil physical structure under different land-uses is influenced by many factors and conditions in and around the soil environment, especially aggregate size distribution, aggregate stability, soil organic carbon (SOC), and soil particle size distribution. These soil properties, in turn, are also affected by a variety of mechanisms and factors. The present study focuses on increasing our understanding of the mechanisms responsible for C stabilization, which are associated with soil structure. Five fields on two soil series were identified to study these mechanisms at the Arlington Agricultural Research Station, where each field represented one long-term (>20 years) land-use. The selected sites were flat, or non-sloping, woodland (W_f), flat grassland (G_f), flat row crop (C_f), eroded woodland (W_e), and eroded row crop (C_e). Triplicate soil cores were collected from each land-use in spring 2017. Each soil core was analyzed by three depths: 0-30 cm, 30-60 cm, and 60-90 cm. In general, the more intensively managed system (i.e., C_f) had lower disaggregation reduction (DR) in 1 – 2 mm aggregates, and lower relative mass of aggregates smaller than 0.5 mm at 0 – 30 cm depth compared with the other flat non-eroded fields. However, the W_f land-use had a significantly higher carbon and nitrogen ratio (C: N), δ_{13}C, and δ_{15}N at 0 – 30 cm depth. Particularly, soil δ_{13}C was considerably higher deeper in the soil profile ($P \leq 0.01$). It was also found that the eroded land-uses (i.e., W_e and C_e) had lower DR, C: N, δ_{13}C, and δ_{15}N of 1-2 mm aggregates 1-2 mm aggregates at 0 – 30 cm depth. Interestingly, the mass of 1-2 mm aggregates and DR were correlated to silt content across the five land-uses at all depths, but not with clay content. Further, the relative percentage of quartz was positively correlated with the mass of smaller aggregates. In contrast, albite and clay

minerals were positively correlated with the mass of 1-2 mm aggregates, DR, and C: N of 1 – 2 mm aggregates at all depths. Given the nature of how aggregates of different sizes form, soil aggregate size distribution would be as likely an important factor when considering the physical stability of SOC. In addition, the physical stabilization of SOC and aggregate size distribution appears to be affected by the dominant soil particle, which was silt with a range of 60-76% in this study.

INTRODUCTION

Carbon (C) storage, stabilization, and sequestration in soils are part of the global C cycle. Estimates of global soil organic carbon (SOC) stocks for the top 0.2 meters and the 3 meters depth in the soil are 615 Gt-C and 2,344 Gt-C, respectively (Fontaine et al., 2007), both of which are greater than the total carbon (TC) in aboveground biomass and the atmosphere combined (Lehmann and Kleber, 2015). However, atmospheric carbon, which affects climate change, has drastically increased since the industrial revolution. Soil C stabilization plays a critical role in mitigating C emissions from the terrestrial system to the atmosphere by lengthening the turnover time, increasing the capacity of soil to sequester C, and hence enriching soil C content. However, the impacts of climate change on SOC pools (Bellamy et al., 2005; Luo et al., 2001) under different land-use and soil management practices remain uncertain.

One way that land-use and erosion status influence C stabilization is through changes in the physical structure of the soil, including formation, stabilization, and dispersion of stable aggregates. Aggregates can stabilize SOC by physically protecting it from decomposition through encapsulation in smaller pores (Six et al., 2002). Soil particles come together to form different sizes and shapes of pores where C is stored and protected. Soil pore structure under different managements and/or land-uses depends on many factors and conditions in and around the soil environment, especially the aggregate size distribution, aggregate stability, and particle size distribution , while the aggregate size distribution and aggregate stability are influenced by different mechanisms (Miedema, 1997). For instance, lands planted with cover crops may help micro-aggregate formation, which has higher stability compared to macro-aggregates (Edwards and Bremner, 1967). Cover crops impact soil aggregate formation directly by the crop root structure, and increasing SOC and N contents (Sainju et al., 2003). This difference is related to changes in the binding mechanisms, including organic materials or microbial products, which are less critical for macro-aggregate stability (Degens et al., 1996). This shows that soil structure and SOC have coupled interactions that are influenced by complex mechanisms and factors. However, these mechanisms and factors are not well understood.

Organo-mineral associations are one way that soil particles interact with SOC. Mineral organic associations are affected by organic material inputs, such as plant residue type and soil mineralogy composition. Sparks (2012) identified the predominant soil minerals that result in mineral-organic associations as metal oxides, hydroxides, oxyhydroxides, phyllosilicates, and short-range ordered aluminosilicates. The main factors affecting the interaction between organic molecules and minerals surfaces include (i) the type, abundance, and charge characteristics of surface functional groups, (ii) the size, shape, and surface topography of the primary minerals; and (iii) aggregate stability and size distribution (Sparks, 2012). However, this enrichment in fresh SOC was only observed in smaller aggregates, while larger aggregates still contained older C from C3 crops (Urbanek et al., 2011). Similarly, soil aggregates were more stable when there was a higher amount of clay and Fe charges in soil (Angst et al., 2017; Kemper and Koch, 1966; Zhao et al., 2017). These findings point to how the role of mineral surfaces varies depending on the amount and the type of surface charges on the formation of mineral-organic associations (Sparks, 2012).

Soil erosion decreases terrestrial C at the eroded sites owing to aggregate breakdown and hence lower soil nutrients compared to non-eroded fields (Jacinthe et al., 2002; Lal, 2004). This, in turn, decreases macropores and water-stable aggregates over time (Ozlu and Kumar, 2018). Mineral associations with C are also affected in eroded soils. As the topsoil is lost during the erosion process, a different environment is created onto which plant residues can accumulate over time (Issaka and Ashraf, 2017), whereas in non-eroded soil, the process of C accumulation from litterfall might possibly reached a relatively steady-state (Levi et al., 2020). Organic material added to soil undergoing erosion might result in changes in the soil structural development and hence change the pore architecture. Further, deeper soil layers with different properties are exposed closer to the soil surface as upper soil layers are lost from eroded soils, fundamentally changing the properties of that soil profile. Soils with increasing severity of historical erosion have decreased soil C storage capacities due to a reduction in profile depth and a higher clay content near the soil surface, likely resulting in changes to mineral-organic associations (Arriaga and Lowery, 2005).

Most research studies on C stabilization evaluate only one or two mechanisms at a time, while how different mechanisms work together to protect SOC against mineralization and what their significances are, is still largely unclear (Lehmann and Kleber, 2015). With that, we think more stable C may lead to higher macro and micro aggregate formation where soil minerals play a critical role in the stability of these aggregates. In order to test this, contrasting landscape positions and land-uses were used to provide a range of C:N, aggregate stability, aggregate size distribution, a relative proportion of soil minerals, and other conditions for soils that should otherwise be relatively similar. Therefore, the present study focuses on increasing our understanding of (i) the coupled interaction between C stabilization and different aggregate sizes, and (ii) the role of relative proportion of soil minerals on this interaction.

MATERIALS AND METHODS

Study Site Description

Five fields on two soil series were identified at the Arlington Agricultural Research Station. The two-soil series reflect erosion conditions on the landscape, mainly indicated by whether the field was sloping or non-sloping. Four long-term (>20 years) land-uses were identified under both sloping (an agricultural and a woodland) and non-sloping (an agricultural and a woodland) as a comparison. A third land-use of non-sloping grassland (>30 years) was selected to compare a condition with high C accumulation potential to the other land-uses. Sampling sites are referred to in the following manner: flat grassland (G_f), flat wooded (W_f), flat row crop (C_f), eroded wooded (W_e), and eroded row crop (C_e). The two soil series were Plano (Fine-silty, mixed, superactive, mesic Typic Argiudolls) and Griswold (Fine-loamy, mixed, superactive, mesic Typic Argiudolls). The two eroded sites were on 4-6% slopes, whereas the other three non-eroded land-uses had less than 1% slope. Specifically, the C_f land-use represented a conventional-continuous corn (*Zea mays* L.) within the Wisconsin Integrated Cropping Systems Trial (WICST), which is a long-term study with an emphasis on resilient agriculture (Cates and Ruark, 2017). A combination of tillage and herbicides were used for managing weeds at this site whose fertility included chemical N-P-K. In contrast, the G_f and W_f land-uses had not received any fertilizer or tillage for about 30 years.

Soil Sampling and Processing

Triplicate intact soil core samples were collected from each field (45 cores in total) in spring 2017. The three sampling locations within each field were the same distance from each other on a triangle. Cores were collected using a truck-mounted hydraulic probe inside plastic sleeves with 7.5 cm diameter and 100 cm height. Sampling below 50 cm depth was prevented due to a distinctive dense soil layer in the eroded land-uses. After the samples were extracted from the soil and capped, they were then transferred to the laboratory. Each soil core was cut longitudinally with a sharp spatula into halves and then separated into three depths: 0-30 cm, 30-

60 cm, and 60-90 cm. After air-drying, one half for each depth was used for aggregate fractionation, while the other half was passed through a 2-mm sieve for analysis as bulk soil (BS).

Soil Analysis

Aggregate Size Distribution

The aggregate size distribution analysis was performed with a dry-sieve procedure (Nimmo and Perkins, 2002). Half-core soil samples were dropped from 1-meter height to disperse the aggregates physically. Given that air-dried samples with similar masses were dropped from the same height to the ground, it was assumed that the force used to break apart aggregates was similar between samples. The resulting shattered aggregates were then transferred to a 4-mm sieve (Chepil, 1962; Lyles et al., 1970) and placed on top of a nested stack of sieves of 2-mm, 1-mm, 0.5-mm, 0.25-mm, and 0.053-mm, respectively. A pan was placed at the bottom of the sieve nest to collected soil passing through all the sieve sizes. The entire nest was placed on a mechanical shaker device for 30 seconds. Hence, six size fractions were obtained (<0.053 mm, 0.053-0.25 mm, 0.25-0.5 mm, 0.5–1 mm, 1–2 mm, and 2-4 mm). The mass of each individual sieved aggregate per size fractions was used to determine the percentage of each aggregate fraction relative to that of the total soil-sample mass, by the following equation:

$$\text{PAS (\%)} = \left(\frac{xi}{\sum_{i=1}^{n}(xi)}\right) * 100$$

where PAS is the percentage of one aggregate size, and xi is the mass of that aggregate size class.

Disaggregation Reduction (DR) and Particle Size Distribution

The DR analysis of the 1-2 mm aggregate fraction was performed according to a procedure developed by Rawlins et al. (2013) using a laser light granulometry approach. Following, the particle size distribution of the same soil aggregate fraction was measured by following the procedure developed by Arriaga et al. (2006). Therefore, the laser granulometry techniques conducted two measurements of the continuous size distribution (<2000 µm) of a sample. More specifically, the first measurement was conducted on the aggregate samples in circulating water without dispersion. Immediately after the first measurement was finished, the sample was dispersed with sodium hexametaphosphate and sonication followed by a second laser measurement. The DR was calculated as the difference in mean weight diameters of these two measurements (Rawlins et al. (2013). The greater the DR value, the more stable the aggregates were in the sample.

$$DR = (MWD_a – MWD_b)$$

Where DR is disaggregation reduction, MWD_a is mean weight diameter of first run (aggregate size distribution, and MWD_b is mean weight diameter of second run after addition of sodium hexametaphosphate and sonication).

Carbon and Nitrogen Ratio (C: N) and Stable Isotope (δ_{13}C and δ_{15}N) Analysis

Bulk soil samples were analyzed for total C and N by dry combustion after soil was pulverized using a handheld coffee grinder. A subsample (8–10 mg) of the pulverized soil was packed into 5 – 9 mm tin capsules. Total C and N contents were measured with a Flash EA

1112CN Automatic Elemental Analyzer (Thermo Fisher Scientific, Waltham, MA). Total C was assumed to be equal to SOC because soil inorganic C was insignificant (Paul et al., 2001).

Pulverized bulk soil samples were sent to the Cornell University Isotope Laboratory (COIL) for δ_{13}C and δ_{15}N isotope analysis. The analysis was performed by a Delta V Isotope Ratio Mass Spectrometer (Thermo Fisher Scientific, Waltham, MA). The soil C isotope ratio (δ_{13}C) and N isotope ratio (δ_{15}N) were also calculated using δ_{13}C and δ_{15}N values with the following equations:

$$\delta^{13}C = [\frac{(\,^{13}\mathrm{C}/\,^{12}\mathrm{C})\ \mathrm{sample}}{(\,^{13}\mathrm{C}/\,^{12}\mathrm{C})\ \mathrm{standard}} - 1] * 1000$$

$$\delta^{15}N = [\frac{(\,^{15}\mathrm{N}/\,^{14}\mathrm{N})\ \mathrm{sample}}{(\,^{15}\mathrm{N}/\,^{14}\mathrm{N})\ \mathrm{standard}} - 1] * 1000$$

X-ray Diffraction

Pulverized sub-samples of the bulk soils were analyzed for mineral composition at the S.W. Bailey X-ray Diffraction Laboratory of the Geoscience Department at the University of Wisconsin – Madison with a Rigaku D/Max Rapid II diffractometer with a curved two-dimensional imaging plate (Rigaku Corporation, Tokyo, Japan).

Statistical Analysis

Soils of this study were analyzed in the form of bulk soil and 1 – 2 mm aggregate from three different soil depths (0 – 30 cm, 30 – 60 cm, and 60 – 90 cm). Therefore, statistical analysis were performed to determine the impacts of different (i) erosion, (ii) land-uses, (iii) depths, (iv) interaction of land-use x depth, and (v) forms of soils (BS and 1-2 mm aggregates) by using readxl , multcompView, and multcompLetters packages in R software.

An analysis of variance was performed, included in tables and figures where a Tukey's honest significance test (HSD) test at a significant level of $\alpha = 0.05$ was also used. In this test, treatments were fit as fixed factors and pseudo-replications as a random factor. Like treatments, to analyze depth and erosion these were fit as fixed factors and pseudo-replications as a random factor. A separate statistic analysis was performed to evaluate differences between BS versus 1-2 mm aggregates and eroded versus non-eroded land-uses by using the Tukey's HSD test at α = 0.05. Table 3 includes the comparisons of C: N, δ_{13}C, and δ_{15}N, in the form of BS and 1-2 mm aggregates with letter classification to identify differences between factor means. Moreover, a comparison of all soil properties was included in this study between eroded and non-eroded land-uses, but the grassland (G_f) land use was not included during this analysis since an eroded grassland land-use was not present. Therefore, the erosion comparison was conducted between C_f (flat, long-term corn), W_f (flat, long-term wood), C_e (eroded, long-term corn), W_e (eroded, long-term wood) land-uses.

A Pearson's correlation analysis (in R) and Principle Component Analysis (in JMP) of all the soil properties reported in this study were performed to evaluate their relationships and the overall impacts of different land-use for 0–30 cm depth.

RESULTS

Effects of land-use on C: N, δ_{13}C and δ_{15}N isotopes

Erosion (C_e and W_e) lowered the C: N of BS compared to non-eroded land-uses (C_f, W_f, and G_f) at 0 – 30 cm depth ($P \leq 0.01$; Figure 1). In addition, at the 60 – 90 cm depth, C: N of BS under C_f was significantly greater than that under W_f and G_f by 85% and 90%, respectively ($P \leq 0.01$).

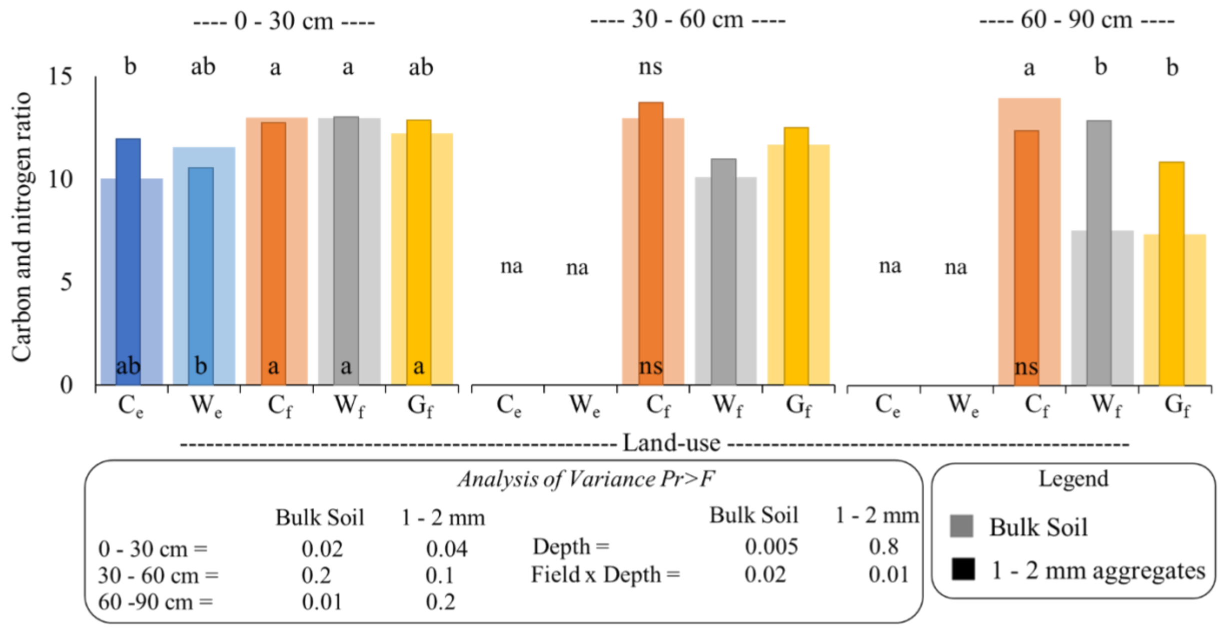

Figure 1. Soil carbon: nitrogen ratio of bulk soils and 1-2 mm aggregates for 0-30 cm, 30-60 cm, and 60-90 cm depths as influenced by different land-uses in Arlington, Wisconsin. C_e, eroded cornfield; W_e, eroded woodland; C_f, flat surface cornfield; W_f, flat surface woodland; G_f, flat surface grassland. Different superscript letters are significantly different at $\alpha = 0.05$. Lowercase letters above the bars indicate significance due to land-use impacts in bulk soils whereas lowercase letters inside the bars refer to effects of land-use in 1 – 2 mm aggregates. ns, no significant difference; na, not available data.

For non-eroded fields, the impacts of soil depth and field x depth were statistically significant; however, there was no clear trend of C: N throughout the soil profile. Overall, it can be stated that land-use, depth, and land-use x depth significantly impact C: N, where soil erosion decreased the C: N. The C: N of 1-2 mm aggregates showed a similar trend with those of BS at 30-60 cm depth; however, differences were not significant. The C: N of 1-2 mm aggregates was higher than that of BS under C_e and G_f at 0 – 30 cm depth and under W_f at 60 – 90 cm depth (Table 1). These differences in C_e ($P \leq 0.01$) and G_f ($P \leq 0.01$) at 0 – 30 cm depth and W_f ($P \leq 0.01$) at 60 – 90 cm depth were significant (Table 1), whereas differences in C:N between BS and 1-2 mm aggregates under W_e, C_f, and W_f at 0 – 30 cm depth were not significant.

In addition, the δ_{13}C of 1-2 mm aggregates significantly differed from those in BS in C_e and W_f at 0 – 30 cm depth (Table 1), whereas differences in δ_{13}C between BS and 1-2 mm aggregates in W_e, C_f, and G_f were not significant. At 0-30 cm depth, the δ_{13}C of BS under C_e, W_e, and G_f were higher than those of 1-2 mm aggregates whereas the δ_{13}C of BS under C_f and W_f was lower than those of 1-2 mm aggregates.

Table 1. Probability values for C: N, δ_{13}C, and δ_{15}N comparisons between bulk soil and 1 – 2 mm aggregates at 0-30 cm, 30-60 cm, and 60-90 cm depths as influenced by different land-uses in Arlington, Wisconsin.

Field	C: N	δ_{13}C	δ_{15}N
	------- 0 - 30 cm -------		
C_e†	0.01††	0.01	0.2
W_e	0.1	0.2	0.2
C_f	0.2	0.2	0.2
W_f	0.2	0.01	0.2
G_f	0.01	0.2	0.2
	------- 30 - 60 cm -------		
C_e	na	na	na
W_e	na	na	na
C_f	0.1	0.2	0.2
W_f	0.1	0.2	0.2
G_f	0.1	0.2	0.2
	------- 60 - 90 cm -------		
C_e	na	na	na
W_e	na	na	na
C_f	0.1	0.2	0.2
W_f	0.01	0.01	0.2
G_f	0.1	0.01	0.2

†C_e, eroded cornfield; W_e, eroded woodland; C_f, flat surface cornfield; W_f, flat surface woodland; G_f, flat surface grassland; ns, not significant; na, no available data.

Moreover, δ_{13}C of 1-2 mm aggregates significantly differed from those in BS in W_f and G_f at 60 – 90 cm depth. As shown in Table 2, δ_{13}C of BS in W_f at 0 – 30 cm and that in W_f and

G_f at 60 – 90 cm depth were higher than those of 1-2 mm aggregates, whereas $\delta^{13}C$ of 1-2 mm aggregates were higher than that of BS in C_e at 0 – 30 cm depth. Nevertheless, differences in $\delta^{15}N$ between BS and 1-2 mm aggregates were not significant at any depth or land-use. The $\delta^{13}C$ and $\delta^{15}N$ were lower in the eroded land-uses compared to those of the non-eroded land-uses at the 0-30 cm depth (Table 2).

Table 2. Soil $\delta^{13}C$ and $\delta^{15}N$ of bulk soils and 1-2 mm aggregates for 0-30 cm, 30-60 cm, and 60-90 cm depths as influenced by different land-uses in Arlington, Wisconsin.

Land-use	----- $\delta^{13}C$ -----		----- $\delta^{15}N$ -----	
	Bulk Soil	*1 - 2 mm*	*Bulk Soil*	*1 - 2 mm*
		----------- 0 - 30 cm -----------		
C_e†	-20.3^{bc}††	-21.6^{c}	5.1^{c}	4.7^{b}
W_e	-21.5^{c}	-23.0^{c}	6.0^{bc}	5.5^{b}
C_f	-19.3^{b}	-18.5^{b}	6.8^{ab}	7.6^{a}
W_f	-15.7^{a}	-15.2^{a}	7.4^{a}	7.9^{a}
G_f	-19.6^{b}	-21.6^{c}	6.4^{ab}	5.7^{b}
		----------- 30 - 60 cm -----------		
C_e	na	na	na	na
W_e	na	na	na	na
C_f	-17.0^{b}	-16.7^{ns}	7.3^{b}	7.9^{b}
W_f	-13.5^{a}	-13.5	8.5^{a}	9.3^{a}
G_f	-16.6^{b}	-16.9	8.6^{a}	8.5^{ab}
		----------- 60 - 90 cm -----------		
C_e	na	na	na	na
W_e	na	na	na	na
C_f	-15.4^{a}	-15.5^{ns}	8.18^{a}	8.4^{a}
W_f	-15.0^{a}	-15.9	7.6^{a}	7.5^{ab}
G_f	-18.0^{b}	-19.5	6.4^{b}	6.8^{b}
		Analysis of Variance Pr>F		
0 -30 cm	≤0.01	0.01	≤0.01	≤0.01
30 -60 cm	≤0.01	0.10	0.02	0.02
60 -90 cm	≤0.01	0.06	≤0.01	≤0.01
Depth	≤0.01	≤0.01	≤0.01	≤0.01
Land-use x Depth	≤0.01	0.02	0.02	≤0.01

†C_e, eroded cornfield; W_e, eroded woodland; C_f, flat surface cornfield; W_f, flat surface woodland; G_f, flat surface grassland. ††Means within the same column, followed by different superscript letters are significantly different at $\alpha = 0.05$.

In addition, W_f had significantly ($P \leq 0.01$) higher $\delta_{13}C$ and $\delta_{15}N$ in both BS and 1-2 mm aggregates at 0 – 30 cm and 30 – 60 cm depths compared to other land-uses. However, at the 60-90 cm depth, soil $\delta_{13}C$ and $\delta_{15}N$ in both BS and 1-2 mm aggregates were greater in C_f and W_f compared to G_f, but differences were not always significant. Overall, $\delta_{13}C$ and $\delta_{15}N$ in BS and 1-2 mm aggregates in the W_f land-use were significantly greater, while soil erosion was not a factor.

Relationship between Aggregate Size Distribution, Aggregate Stability, and Particle Size Distribution

The particle size distribution of 1-2 mm aggregates was determined to investigate the impact of particle size distribution on aggregation (Figure 2). The clay content in 1-2 mm aggregates of eroded fields was slightly greater. However, soil clay content, in general, were relatively low. The highest clay content in 1-2 mm aggregates was observed in W_e, followed by G_f, W_f, C_e, and C_f accordingly in descending order. Silt content of 1-2 mm aggregates ranged from 60.0% in C_f to 76.5% in W_f. Silt content in W_f was significantly greater by 7.1%, 7.9%, 15.6%, and 27.5% in G_f, C_e, W_e, and C_f, respectively. The sand content of 1-2 mm aggregates was higher in C_f than those in W_e, C_e, G_f, and W_f by 73%, 79%, 98%, and 186%, respectively. Overall, silt content was higher than clay and sand content in all the fields with W_f having the highest silt content, and W_e had the highest clay content.

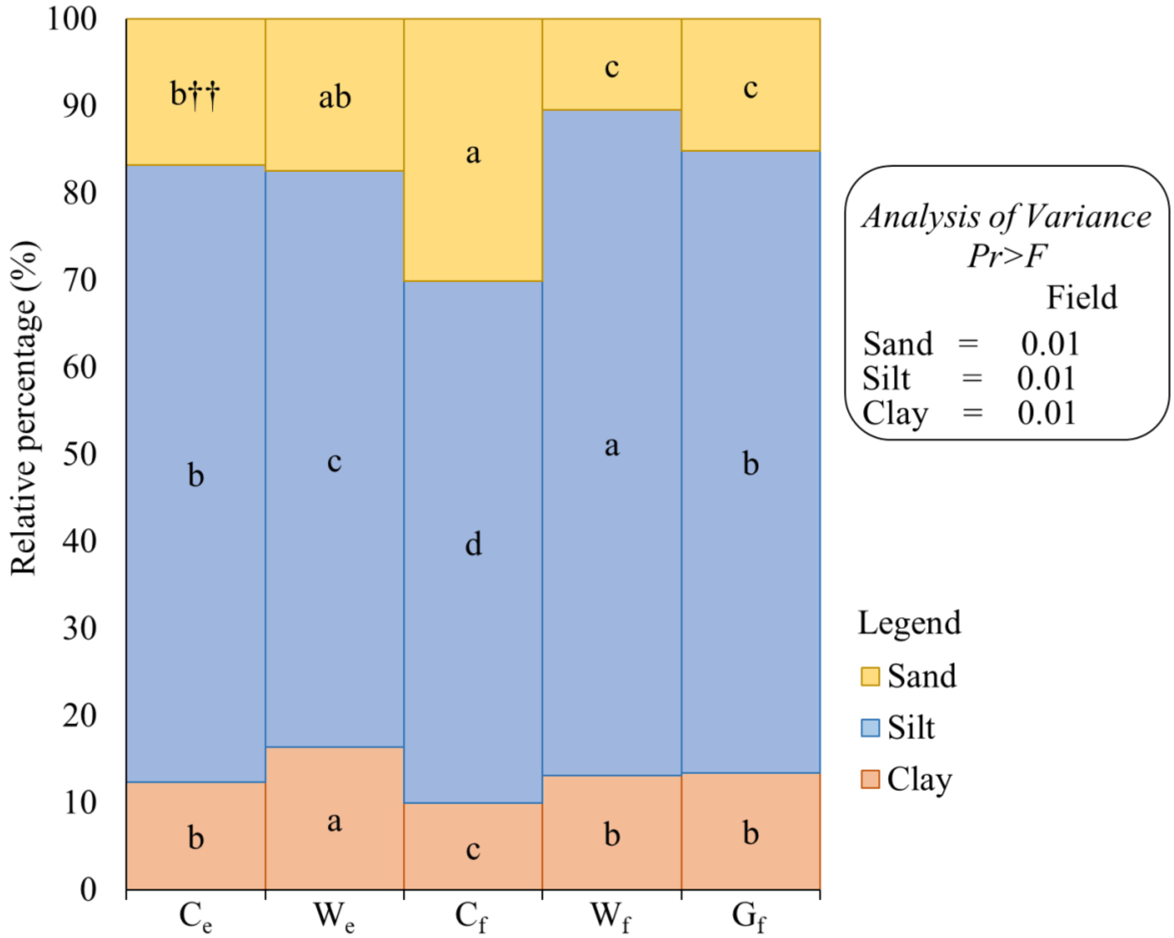

Figure 2. The particle size distribution of 1 – 2 mm aggregates for 0-30 cm depth as influenced by different land-uses in Arlington, Wisconsin. C_e, eroded cornfield; W_e, eroded woodland; C_f, flat surface cornfield; W_f, flat surface woodland; G_f, flat surface grassland. ††Different superscript letters are significantly different at α = 0.05.

X-ray diffraction results of BS at 0 – 30 cm depth showed that soils of land-uses in this study had a greater relative mass of quartz, ranging from 74% in W_f to 90% in C_f (Figure 3). The percentile of soil clay minerals at 0 – 30 cm depth was significantly greater (P <0.01) in W_f than that in W_e, G_f, C_e, and C_f by 19%, 27%, 41%, and 188%. Further, soil albite ranged from 3.4% in C_f to 8.2% in W_e at 0 – 30 cm depth.

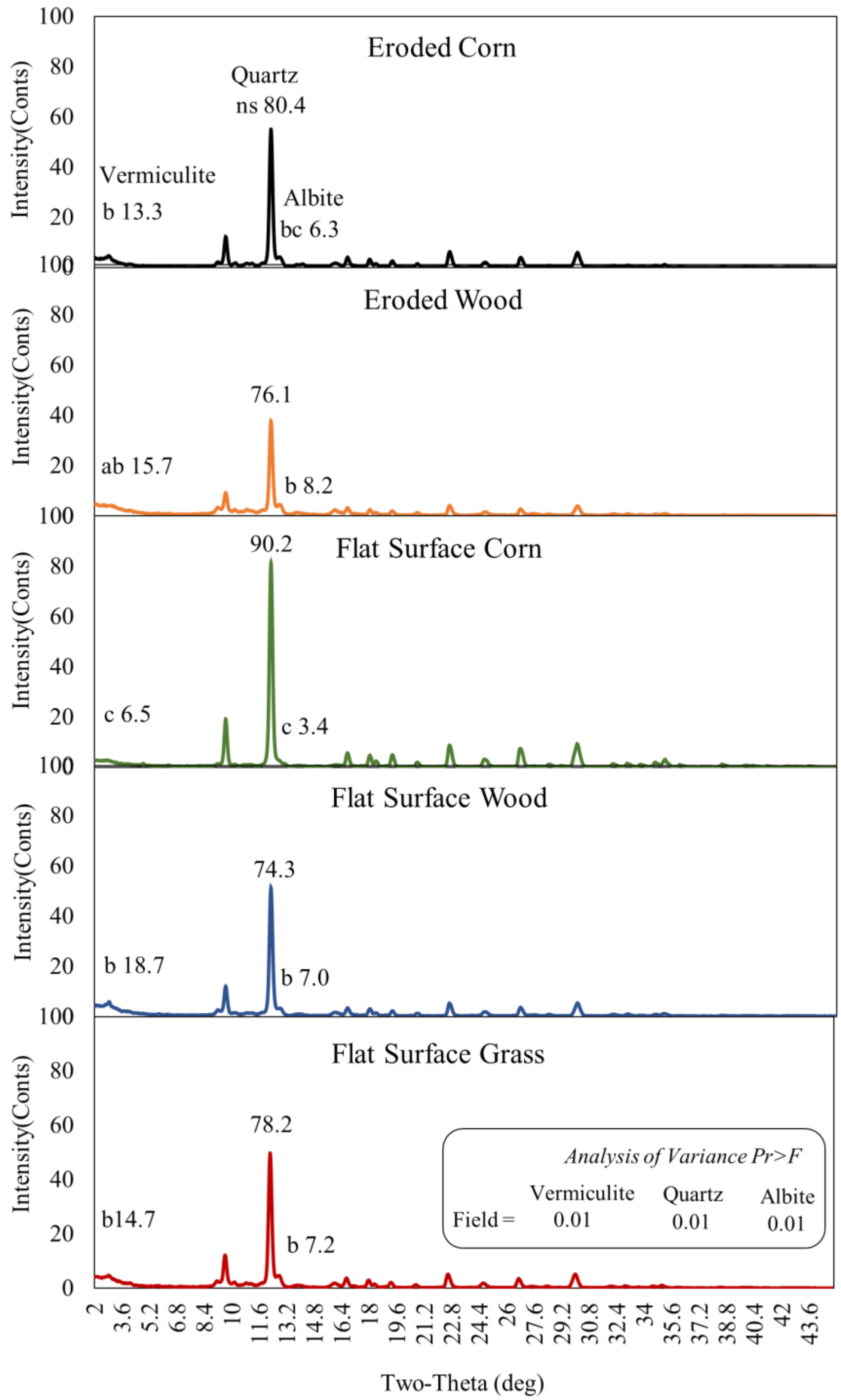

Figure 3. X-ray diffraction (%) of bulk soils for 0-30 cm soil depth as influenced by different land-uses in Arlington, Wisconsin. Means within the same column, followed by different superscript letters, are significantly different at α= 0.05. Lower cases indicate significance due to land-use.

Table 3. Aggregate size distribution for 0-30 cm, 30-60 cm, and 60-90 cm depths as influenced by different land-use in Arlington, Wisconsin.

Field	Aggregate size (mm)					
	2 - 4	1 - 2	0.50 - 1	0.25 - 0.50	0.053-0.25	<0.053
	---------------------------- *0 - 30 cm (%)* ----------------------------					
C_e†	47.1^{a††}	24.0^{b}	13.3^{b}	6.6^{c}	6.8^{ab}	2.2^{ns}
W_e	48.5^{a}	22.7^{c}	13.2^{b}	7.7^{b}	6.2^{b}	1.7
C_f	39.1^{b}	21.3^{c}	14.2^{ab}	11.8^{a}	11.2^{a}	2.5
W_f	36.1^{c}	27.0^{a}	17.5^{a}	8.7^{a}	7.8^{a}	2.8
G_f	43.6^{b}	25.7^{ab}	14.9^{ab}	7.5^{b}	6.0^{c}	2.3
	---------------------------- *30 - 60 cm (%)* ----------------------------					
C_e	na	na	na	na	na	na
W_e	na	na	na	na	na	na
C_f	30.6^{b}	21.5^{b}	18.1^{a}	13.2^{a}	13.0^{a}	3.6^{ns}
W_f	42.5^{a}	26.2^{a}	14.4^{b}	7.1^{b}	7.3^{b}	2.6
G_f	43.3^{a}	24.3^{ab}	14.7^{b}	7.4^{b}	7.2^{b}	3.1
	---------------------------- *60 - 90 cm (%)* ----------------------------					
C_e	na	na	na	na	na	na
W_e	na	na	na	na	na	na
C_f	32.8^{b}	25.6^{a}	18.5^{a}	11.0^{a}	9.9^{ns}	2.3^{ns}
W_f	45.0^{a}	23.5^{ab}	14.1^{b}	8.3^{b}	6.9	2.2
G_f	43.8^{a}	22.6^{b}	14.3^{b}	7.6^{b}	8.0	3.8
	Analysis of Variance Pr>F					
0 - 30 cm	0.01	0.01	0.01	0.01	0.01	0.09
30 - 60 cm	0.02	0.03	0.01	0.01	0.01	0.50
60 - 90 cm	0.02	0.03	0.01	0.01	0.10	0.10
Depth	0.60	0.30	0.90	0.70	0.30	0.40
Field x Depth	0.01	0.01	0.01	0.01	0.08	0.10

†C_e, eroded cornfield; W_e, eroded woodland; C_f, flat surface cornfield; W_f, flat surface woodland; G_f, flat surface grassland.††Means within the same column, followed by different superscript letters are significantly different at $\alpha = 0.05$.

The relative mass of 2 – 4 mm aggregates at 0-30 cm depth was greatest in the eroded land-uses, of which W_e were greater (Table 3). In addition, the relative mass of 1 – 2 mm, 0.5 – 1 mm, and <0.053 mm were all greater in W_f, and those of 0.25 – 0.5 mm and 0.0053 – 0. 25 mm aggregates were both higher in C_f. However, the relative mass of 2 – 4 mm and 1 – 2 mm aggregate fractions in W_f were significantly higher than those in C_f and not different from that in G_f at 30 – 60 cm depth. The aggregates smaller than 1 mm in the C_f were significantly higher than those in W_f and G_f. A similar trend was observed at a depth of 60 – 90 cm, except that the relative mass of 2 – 4 mm aggregates was greater ($P < 0.02$) in W_f than in C_f by 37%. Overall, flat fields had a greater proportion of aggregates of 0.25 - 2 mm relative size range, whereas eroded lands had a higher relative mass of 2 – 4 mm aggregates at 0 – 30 cm depth.

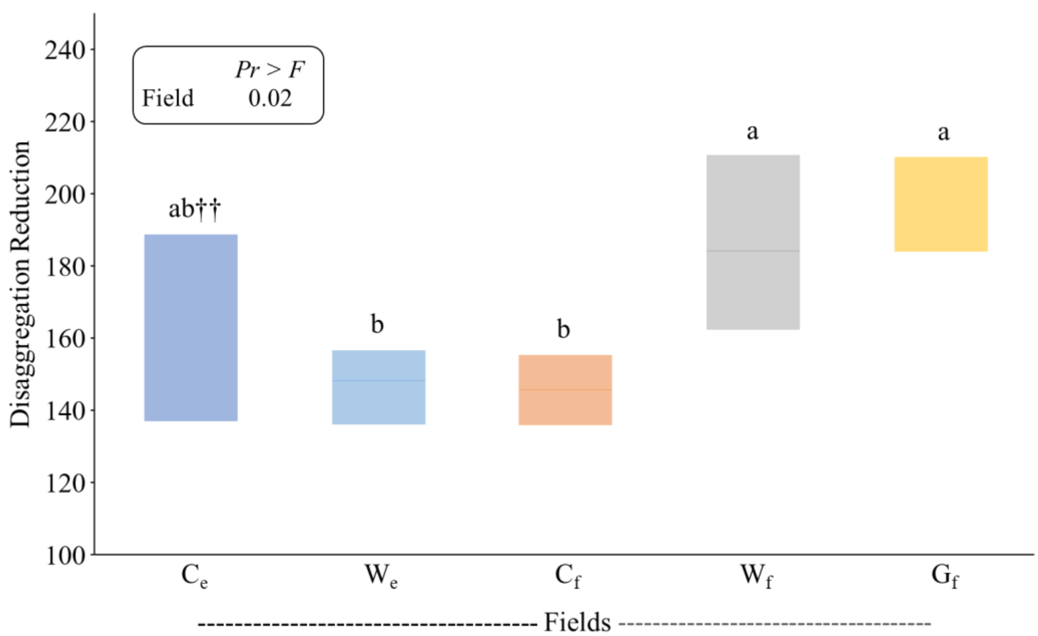

Figure 4. Disaggregation reduction in 1-2 mm aggregates for 0-30 cm depth as influenced by different land-uses in Arlington, Wisconsin. C_e, eroded cornfield; W_e, eroded woodland; C_f, flat surface cornfield; W_f, flat surface woodland; G_f, flat surface grassland. ††Different letters indicate statistically significant differences at $\alpha = 0.05$.

Soil DR is an indicator of aggregate stability for 1-2 mm aggregates, with greater DR values been indicative of greater aggregate stability. The DR at 0 – 30 cm depth was greater for G_f and W_f ($P \leq 0.02$) than those for W_e and C_f. However, the DR value for C_e was similar to W_f and G_f, and those of W_e and C_f (Figure 4).

The role of particle size distribution and mineralogy in aggregate size distribution, C:N, $\delta_{13}C$ and $\delta_{15}N$ under impacts of erosion

In order to further investigate the impact of erosion on aggregation and related factors, the studied soil properties of BS and 1-2 mm aggregates were compared relative to erosion effect (Table 4). In particular, 2 – 4 mm aggregates were significantly greater ($P \leq 0.01$) in eroded soil, while there was no difference in 1 – 2 mm size. Soil C:N of BS, and $\delta_{13}C$, and $\delta_{15}N$ of 1-2 mm aggregates were lower in eroded soils compared to non-eroded land-uses. Soil clay content was significantly greater in eroded soil with no differences in silt and sand contents. These results indicate that aggregates smaller than 1 mm were associated with C:N, $\delta_{13}C$, and $\delta_{15}N$, but these aggregates were not associated with soil mineral composition.

Table 4. Soil properties of bulk soils and 1-2 mm aggregates for 0-30 cm depth as influenced by erosion in Arlington, Wisconsin.

Soil Properties of long-term land-uses	Soil Fraction	Eroded	Flat	Pr > F
2 - 4 mm	- Aggregate Sizes -	a	b	0.01
1 - 2 mm	- Aggregate Sizes -	ns		0.60
0.50 - 1	- Aggregate Sizes -	b	a	0.01
0.25 - 0.50	- Aggregate Sizes -	b	a	0.01
0.053-0.25	- Aggregate Sizes -	b	a	0.01
<0.053	- Aggregate Sizes -	b	a	0.02
C:N	----- Bulk Soil -----	b	a	0.01
$\delta_{13}C$	----- Bulk Soil -----	b	a	0.01
$\delta_{15}N$	----- Bulk Soil -----	b	a	0.01
Vermiculite	----- Bulk Soil -----	ns		0.50
Quartz	----- Bulk Soil -----	ns		0.30
Albite	----- Bulk Soil -----	ns		0.10
Clay	1 - 2 mm aggregates	a	b	0.04
Silt	1 - 2 mm aggregates	ns		0.90
Sand	1 - 2 mm aggregates	ns		0.50
DR	1 - 2 mm aggregates	ns		0.30
C:N	1 - 2 mm aggregates	ns		0.20
$\delta_{13}C$	1 - 2 mm aggregates	b	a	0.01
$\delta_{15}N$	1 - 2 mm aggregates	b	a	0.01

†C_e, eroded cornfield; W_e, eroded woodland; C_f, flat surface cornfield; W_f, flat surface woodland; G_f, flat surface grassland.

Pearson's Correlation Analysis

Pearson's correlation analysis (Figure 5) showed that the relative mass of aggregates between 2 mm and 4 mm was negatively correlated with C: N, $\delta_{13}C$, and $\delta_{15}N$ in BS. However, the relative mass of 1 – 2 mm aggregates were positively correlated with silt content, DR, C:N of 1-2 mm aggregates, $\delta_{13}C$ of both BS, and relative percentile of clay minerals (vermiculite) and Albite, whereas the relative mass of 1 – 2 mm aggregates were negatively correlated with sand content and quartz. In addition, the relative mass of 1 – 2 mm aggregates were not correlated with clay content. Moreover, the relative mass of aggregates between 0.053 to 1 mm was positively correlated with C: N, δ_{13}C, and δ_{15}N in BS.

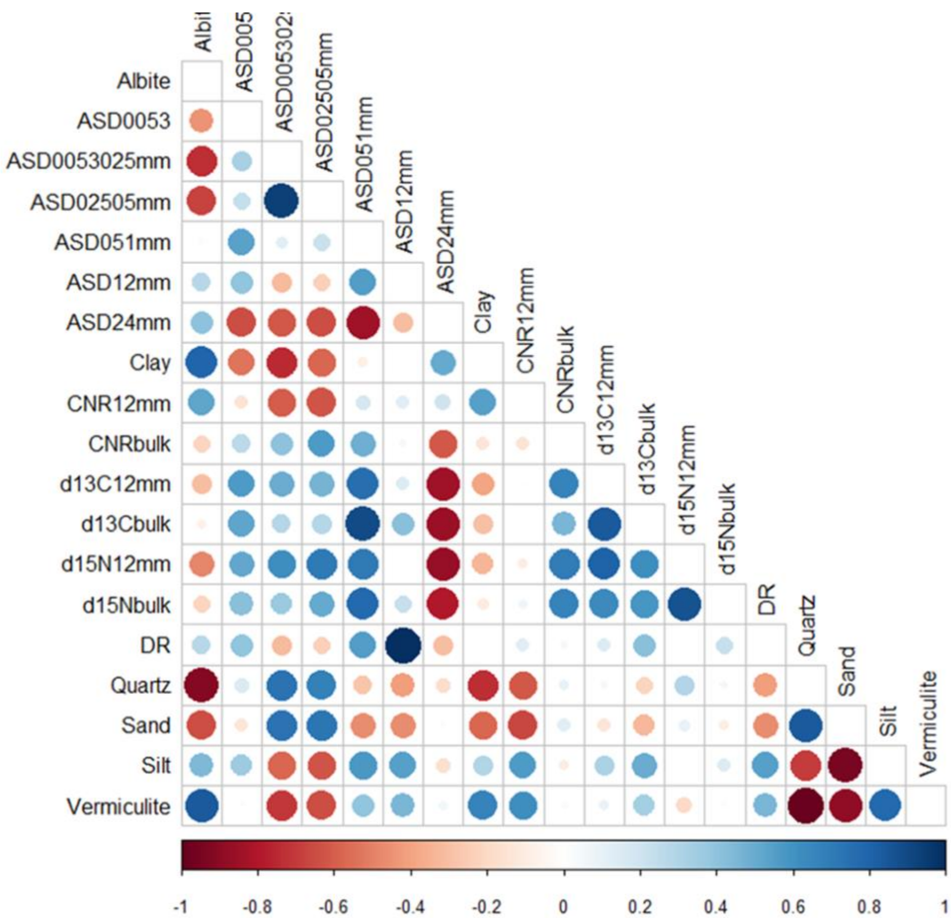

Figure 5. Pearson's correlation analysis of soil properties as impacted by long-term land-use and erosion for 0 – 30 cm depth in 2017. The color and size of the pie chart denote the magnitude and direction of the relationship. ASD24mm, the percentile of aggregates between 2-4 mm diameter; ASD12mm, the percentile of aggregates between 1-2 mm diameter; ASD051mm, the percentile of aggregates between 0.5-1 mm diameter; ASD02505mm, the percentile of aggregates between 0.25-0.5 mm diameter; ASD0053025mm, the percentile of aggregates between 0.0053-0.25 mm diameter; ASD0053mm, the percentile of aggregates smaller than 0.0053 mm diameter; C:Nbulk, carbon, and nitrogen ratio in bulk soils; C:N12mm, carbon, and nitrogen ratio in 1-2 mm aggregates; d13Cbulk, δ_{13}C isotope ratio in bulk soils; d13C12mm, δ_{13}C isotope ratio in 1-2 mm aggregates; d15Nbulk, $_{15}N_{14}N$ isotope ratio in bulk soils; d15N12mm, $_{15}N_{14}N$ isotope ratio in 1-2 mm aggregates; Clay, clay content; Silt, silt content; Sand, sand content; DR, disaggregation reduction; Quartz, the percentile of quartz; Vermiculite, the percentile of vermiculite (clay minerals); Albite, the percentile of Albite.

Principal Component Analysis

The principal component analysis (Figure 6) revealed that the relative mass of 1-2 mm aggregates was respectively related to DR, C:N in 1-2 mm aggregates, and silt content, and seemed to be the predominant property affected the most in W_f.

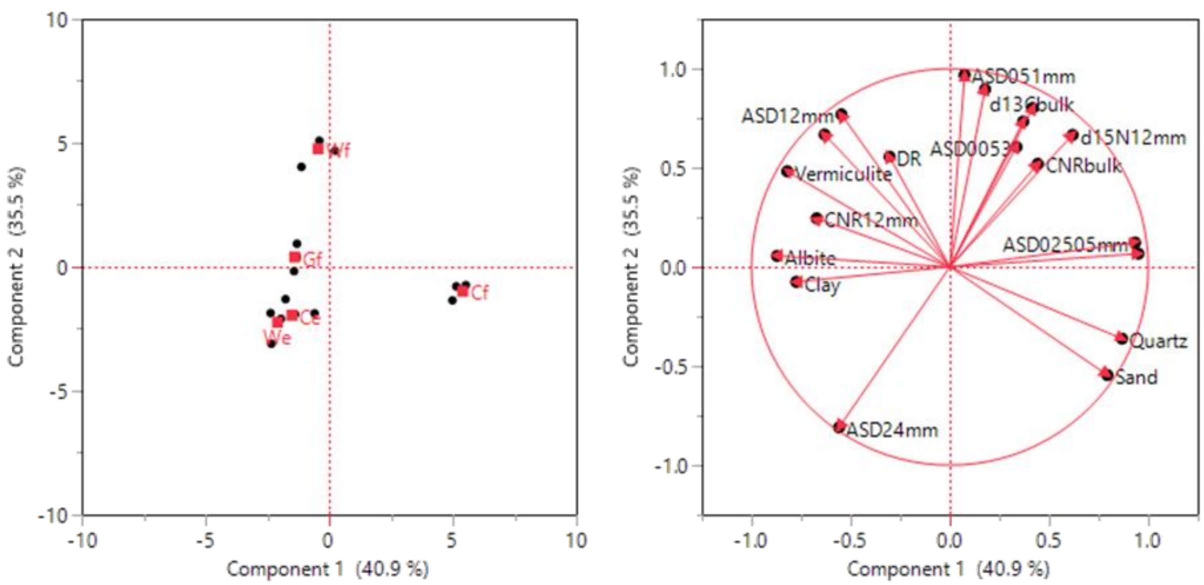

Figure 6. Principal Component Analysis of soil properties as impacted by different land-uses for 0–30 cm depth. C_e, eroded cornfield; W_e, eroded woodland; C_f, flat surface cornfield; W_f, flat surface woodland; G_f, flat surface grassland. ASD24mm, the percentile of aggregates between 2-4 mm diameter; ASD12mm, the percentile of aggregates between 1-2 mm diameter; ASD051mm, the percentile of aggregates between 0.5-1 mm diameter; ASD02505mm, the percentile of aggregates between 0.25-0.5 mm diameter; ASD0053025mm, the percentile of aggregates between 0.0053-0.25 mm diameter; ASD0053mm, the percentile of aggregates smaller than 0.0053 mm diameter; C:Nbulk, carbon, and nitrogen ratio in bulk soils; C:N12mm, carbon, and nitrogen ratio in 1-2 mm aggregates; d13Cbulk, $\delta^{13}C$ isotope ratio in bulk soils; d13C12mm, $\delta^{13}C$ isotope ratio in 1-2 mm aggregates; d15Nbulk, $^{15}N^{14}N$ isotope ratio in bulk soils; d15N12mm, $^{15}N^{14}N$ isotope ratio in 1-2 mm aggregates; Clay, clay content; Silt, silt content; Sand, sand content; DR, disaggregation reduction; Quartz, the percentile of quartz; Vermiculite, the percentile of clay minerals; Albite, the percentile of Albite.

In Cf, however, quartz and sand contents appear as the properties that distinguishes this land-use from other fields. In addition, clay content, albite content, and C:N in 1-2 mm aggregates seemed to explain a major portion of the variation in G_f. Overall, eroded land-uses appear to group together, while flat land-uses are also different from each other.

DISCUSSION

Land-use and erosion impacts on C: N, $\delta_{13}C$ and $\delta_{15}N$

The stability of C in soil plays a significant role by lengthening the turnover time, increasing the capacity of soil to sequester C, and hence enriching soil C content. However, SOC can vary because of conditions present in different land-uses and erosion status. For instance, W_f had higher C:N, $\delta_{13}C$, and $\delta_{15}N$ in both BS and 1-2 mm aggregates than G_f and C_f at any depth. It was also reported by other researchers that the C: N in forest land was greater compared to agricultural and grasslands (Puget and Lal, 2005; Tirgarsoltani et al., 2014). Changes in land-use from a natural state to a managed one are often cited as a cause for SOC stock decline. Guo and Gifford (2002) reported a 42% to 59% loss of SOC stocks due to conversion from forest and grassland to agriculture. Moreover, the addition of fresh plant materials under non-cultivated conditions is a possible reason that forest has higher C:N (Caravaca et al., 2002). Soils under agriculture have lower C:N than other ecosystems since agricultural management (i.e., tillage, planting, and harvesting) decrease C considerably more than they decrease N (Abera and Belachew, 2010). Further, crop tissue removal at harvest and conventional tillage practices may lead to SOC losses in agricultural fields (Kay, 1990). These observations agree with the findings of this work in that disturbance factors (i.e., erosion and cultivation) decreased C:N. Furthermore, Ma et al. (2016) mentioned that SOC and N stocks in deposition sites were the greatest, whereas SOC stocks at the eroded site were less. Since disturbance of soil can lead more of C lost compare to N, C: N ratio decreases under disturbing factors like erosion and tillage. Impacts of soil disturbance, such as deforestation, tillage, and erosion, on soil C: N, have increased the attention on the interactions between SOC and micro aggregates. If soil aggregates break down, SOC and N contents change, and hence C: N differentiates. A linear decrease in C: N as a result of the progress of litter decomposition (Vogel et al., 2014), can improve soil structure.

Photosynthesis discriminates against the heavier isotope (O'leary et al., 1992). Also, soil $\delta_{13}C$ is different compared to that of the atmosphere. The $_{13}C$ concentration of atmosphere is less than 1%, which means the $\delta_{13}C$ in the atmosphere is influenced by the addition of new C in the form of CO_2 (Yakir, 2011). The accumulation of $_{12}C$ in the atmosphere via soil CO_2 emissions, which is mainly $_{12}C$, decreases $_{12}C$ in soils and tends to increase $\delta_{13}C$. In addition, the $_{15}N$ isotope is stable and is lower in natural abundance than $_{14}N$ (Yu et al., 2019). In this study, $\delta_{13}C$ in BS was positively correlated with the relative mass of aggregates between 0.5 mm and 2 mm, hinting that the SOC in this aggregate fraction is more tightly related to microbial respiration than other fractions. It is thus important to track C and N biochemical cycles via stable isotope labeling ($_{13}C$, $_{15}N$) techniques (Vogel et al., 2014) to track the relationship between soil aggregation and SOC since $\delta_{13}C$ in soil increases due to CO_2 emission and $\delta_{13}C$ in the soil can be correlated with certain soil aggregate fractions.

Soil $\delta_{13}C$ and $\delta_{15}N$ in both BS and 1-2 mm aggregates were higher in W_f than those in C_f and G_f when only comparing among flat (non-eroded) land-uses. These findings overlap with what John et al. (2005) reported that $_{13}C$ values of surface soils were greater in forest and agriculture lands (which typically have more C4 plants) compared to those in grasslands (cool-season grasses are typically C3 plants). In addition, several $_{13}C$ isotope-focused studies reported high microbial activities, and high turnover of SOC in land-use with switchgrass (Chaudhary and Dick, 2016; Stewart et al., 2017), where the applied new C was lost in two forms, (i) completely got decomposed to produce CO_2 emission or (ii) in the form of DOC via convective flow (Kravchenko et al., 2019). This might be why $\delta_{13}C$ is lower under G_f. These findings may also explain why soil $\delta_{13}C$ increased as soil profile got deeper. Impacts from land cover decreases deeper in the soil profile, and hence changes in $\delta_{13}C$ at deeper depths are not impacted by land-use as much as upper depths. On the other hand, changes in $\delta_{15}N$ in this study were partially overlapping with previous work on the impacts of different land-use. Compton and Boone (2000) reported that plant uptake and loss of N might cause the removal of $_{14}N$ from organic matter, which made stable fractions of N (mineral-associated heavy fraction) enriched in $_{15}N$ in forest lands over a long timescale. This might be a reason $\delta_{15}N$ was higher in the present study.

In contrast, disturbance factors of soil erosion and tillage negatively affected $\delta_{13}C$ and $\delta_{15}N$ compared to non-disturbed fields. This might be due to the disturbance effects of erosion since the depletion of $_{15}N$ in pastured and cultivated land-uses is well documented (Compton and Boone, 2000). Stable isotopes might, however, not be completely understood as a result of SOC turnover in aggregates, since there was a coupled interaction between aggregate turnover and C-N storage in the aggregates (John et al., 2005). Our findings also show a relationship between aggregate size distribution, and C: N, $\delta_{13}C$, and $\delta_{15}N$. In this study, it is reported that C:N, $\delta_{13}C$, and $\delta_{15}N$ in BS were positively correlated with the relative mass of aggregates between 0.053 to 2 mm but negatively correlated with the relative mass of aggregates between 2 to 4 mm

Land-use and erosion impacts on aggregate size distribution and DR

Diversity in plant species might be one contributing factor in changing SOC quantity and quality where this variation shapes soil structure (Tirgarsoltani et al., 2014). Soil aggregate size distribution, a representative property of soil structure, can significant impact soil functions like root growth (Lipiec et al., 2007), water and oxygen availability, soil hydraulic properties, and solute transport processes (Dıaz-Zorita et al., 2002; Tirgarsoltani et al., 2014). However, the formation of different sizes of aggregates is significantly impacted by diverse land-uses over a long term period (> 30 years) with different erosion status and at various soil depths. In the present study, intensively managed land had a greater the proportion of small aggregates (< 0.5 mm). The response of different aggregate sizes was also documented where macro-aggregation was reported to be more sensitive to various conditions and disturbance factors (Franzluebbers and Arshad, 1997; Puget et al., 2000). However, the variations in aggregate size distribution due to the intensity of agricultural practices are not always observed if the effects of another disturbance factor, such as erosion, overwhelm them. Eroded soil had a higher amount of 2 – 4 mm aggregates and a lower amount of <2 mm aggregates at 0 – 30 cm depth. A dissimilar response in aggregate sizes for different land-uses and erosion status was somewhat expected since different mechanisms are responsible for the formation of aggregates of different sizes, and the mechanisms affecting their stability differ as well (Miedema, 1997). Increases in 2 – 4 mm aggregates in eroded soil might be explained by changes in particle size distribution that occur during the erosion process. However, these aggregates might not be as stable. In the present study, it was observed that the most intensely managed system among the three flat (non-eroded) fields, C_f, had low DR values of 1-2 mm aggregates at 0 – 30 cm depth, similar to the two eroded fields of W_e and C_e. Evaluating both aggregate size distribution and DR supports the interpretation of soil erosion effects on aggregation.

Association of Aggregate Size Distribution and DR with C: N, $\delta_{13}C$ and $\delta_{15}N$

The formation and stabilization of aggregates, and the disruption of aggregates by different levels of energy have been studied previously (Tisdall, 1996). Mechanisms involving soil physical structure can stabilize SOC by physically protecting it from decomposition through encapsulation in smaller pores (Six et al., 2002), or by physically keeping the soil in the same environment. During the decomposition of plant tissues, microorganisms form organic molecules that promoted the physical attachment of soil particles. The SOM produced in this process is not only protected within aggregates but can also function as a binding agent that holds particles together. These coupled mechanisms of aggregate formation can be different for aggregates of various sizes because different processes and binding agents are involved (Tisdall, 1996). Therefore, soil aggregate size distribution can be an indicator of C-sequestration.

Physically protected organic matter is mostly found in micro aggregates (Tisdall, 1996). In addition, macroaggregate protected C (1%–2%) can have greater mineralization rates than that of microaggregates (Elliott, 1986). As a result of POM decomposition, biologically processed organic substances can stabilize micro soil aggregates (Golchin et al., 1997). Factors that control the degree of SOM decomposition in different aggregate sizes include C:N, the chemical composition of SOM (Anderson and Paul, 1984), and the composition of C compound (e.g., lignin, cellulose, hemicellulose, etc.). The C: N tends to decrease as SOM decomposes since N tends to be reprocessed while C is mineralized with some loss to the atmosphere (Tisdall, 1996). In this study, the relative mass of 1-2 mm aggregates was positively correlated with C: N and δ_{13}C of 1-2 mm aggregates but not with δ_{15}N (Figure 5). Likewise, δ_{13}C was positively correlated with DR. This shows that both C: N and δ_{13}C were correlated with the formation and stabilization of aggregates, which in turn protect organic C. Given the nature of how aggregates of various sized form, aggregate size distribution is, therefore, an important factor for physical stability of SOC.

The role of particle size distribution and mineralogical composition in aggregation

Many soil physical properties, especially hydraulic properties, are influenced by particle size distribution and aggregation of soil. The particle size distribution primarily determines the size range of small pores, while the distribution of medium and large pores is mainly influenced by soil aggregates, which have sand, silt, and clay within them (Tisdall, 1996). The mineralization of SOM is dependent on the air and water equilibrium within the soil (Balesdent et al., 2000), which is controlled by intra- and inter-aggregate spaces. In this study, we found critical relationships between soil particle sizes and aggregates where silt content showed a positive correlation with 0.5 – 2 mm aggregates, and was negatively correlated with aggregates between 0.053 – 0.5 mm. In contrast, sand content showed positive correlation with aggregates between 0.053 – 0.5 mm and a negative correlation with 0.5 – 2 mm aggregates.

Findings from this study point to clay content as increasing aggregation more than silt and sand. However, another previously unrecognized interaction between silt content and 1-2 mm aggregates was found. We posit that silt content has a greater influence on the relative amount of 1-2 mm aggregates than clay. This relationship was noted with the high correlation (Figure 5) between the mass of 1-2 mm aggregates and silt content within 1-2 mm aggregates (81.3%), which was greater than the correlation between the mass of 1-2 mm aggregates and clay content within 1-2 mm aggregates (5.5%). In addition, changes in silt content for the different land-use and erosion state follows a similar trend to that of changes of 1-2 mm aggregates. The strong influence of silt particles can be partially attributed to the naturally high silt content of these soils relative to clay. Further, silt particles with a size diameter close to the clay range may behave as clay particles, while larger silt particles might play a positive role as a physical medium for aggregate structure. Although the role of soil particle size distribution on aggregation and aggregate stability has been well documented, the impact of clay versus silt particles has not been studied in depth. Aggregate formation and stability concepts tend to combine clay and silt particles together to explain the effect of particle size distribution. For example, Hassink (1997) and Tisdall and Oades (1982) documented that organic amendments primarily form SOM associations with clay particles, silt particles, and microaggregates (<250 mm), whereas macro-aggregation (>250 mm) occurs with the condition of saturated SOM binding capacity of clay and silt particles. Other studies had concluded that soil aggregates were more stable when there were greater amounts of clay and Fe in soil (Angst et al., 2017; Kemper and Koch, 1966; Zhao et al., 2017). However, in this study, DR values were positively correlated with silt content in flat (non-eroded) soils but not with clay content. This might be because the range of soil silt content was higher than clay, and sand contents and clay content was very low. Almajmaie et al. (2017) reported that aggregate stability was significantly and positively correlated with silt content but negatively correlated with quartz content. This is similar to the findings of this work on the correlation between DR and silt and quartz contents. Quartz was positively correlated with the relative mass of smaller aggregates, whereas albite and clay minerals were positively correlated with the relative mass of 1-2 mm aggregates, DR, and C:N of 1-2 mm aggregates, respectively, but were both negatively correlated with aggregates smaller than 0.5 mm.

CONCLUSIONS

In general, the more intensively managed system (i.e. C_f) had lower DR in 1-2 mm aggregates, and relative mass of aggregates smaller than 0.5 mm at 0 – 30 cm depth compared with the other flat non-eroded fields. Thus, intense managements develop a greater presence of smaller aggregates at 0 – 30 cm depth. However, the W_f land-use had significantly greater carbon and nitrogen ratio, $\delta_{13}C$, and $\delta_{15}N$ at 0 – 30 cm depth.

In addition, soil $\delta_{13}C$ was significantly higher deeper in the soil profile ($P \leq 0.01$), whereas the change in aggregate size distribution was not significantly related to soil depth. It was also found that the eroded land-uses (i.e. W_e and C_e) had a higher relative mass of 2 – 4 mm aggregates but lower DR ($P \leq 0.3$), C:N ($P \leq 0.2$), $\delta_{13}C$ ($P \leq 0.01$), and $\delta_{15}N$ ($P \leq 0.01$) of 1-2 mm aggregates at 0 – 30 cm depth. Similarly, eroded land-uses generally had a lower relative proportion of aggregates smaller than 2 mm aggregates in comparison to flat (non-eroded) land-uses at a depth of 0 – 30 cm.

Interestingly, the mass of 1-2 mm aggregates and DR were correlated to silt content across the five land-uses at all depths, but not so for clay content. Further, quartz was positively correlated with the mass of smaller aggregates, whereas albite and clay minerals were positively correlated with the relative mass of 1-2 mm aggregates, DR, and C: N of 1 – 2 mm aggregates at all depths. The C: N, $\delta_{13}C$, and $\delta_{15}N$ in BS were positively correlated with the relative mass of aggregates between 0.053- and 2-mm aggregates but negatively correlated with 2 – 4 mm aggregates.

Principal Component Analysis showed that eroded land soils grouped together while flat land soils were different from each other and from eroded land-uses. The relative mass of 1-2 mm aggregates was related to DR, C: N, and silt content, and seemed to be the principal property that was most different in W_f, where aggregate stability was higher than other land-uses.

Even though we found in this study that there is a strong association between SOC, soil minerals (clay minerals and albite), and the formation of different aggregate fractions, especially that of 1-2 mm aggregates, in the future it would be important to determine which aggregate fractions contain which forms of C. Similarly, conducting a timely and sensitive experiment on the relationship between aggregate turnover time and C turnover would be useful. It is also recommended to conduct future work on what form of SOC fraction is stored in which aggregate size classes.

Given the nature of how aggregates of different sizes form, soil aggregate size distribution was therefore an important indicator of soil physical stability of SOC. Soil mineral composition, the relative percentile of clay minerals and albite, played a critical role in improving soil aggregation. In addition, the physical stabilization of SOC and aggregate size distribution relies on the range of dominant soil particles where in this study, silt content which was about 70% on average, played a critical role.

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CHAPTER 3

THE RELATIONSHIP AMONG SOIL CARBON, HYDRAULIC PROPERTIES, AND SOIL STRUCTURE UNDER DIFFERENT LAND-USES

ABSTRACT

Aggregation plays important roles in soil, including carbon accumulation and protection, as well as affecting hydraulic properties. Soil organic C and aggregation affect each other, making their study important yet challenging. The mineralization of SOM is dependent on the air/water equilibrium within the soil, where soil structure can implicitly influence decomposition by affecting the microbial habitat between and within aggregates. Soil structure is the organization of soil particles bound together by organic and inorganic materials into different aggregate sizes and geometries. Thus, the relationships among soil structure influencing factors (e.g., soil water, air, and SOC) are important to understand. In this study, five long-term (>20 years) fields with different land-uses (agriculture, grass, and wooded) were selected on two different soil series (Plano and Griswold). Two of these fields were on sloping eroded landscape with 4 - 6% slope [eroded woodland (W_e), and eroded row crop (C_e)] and the other three were non-sloping with less than 1% slope [woodland (W_f), flat grassland (G_f), flat row crop (C_f)]. Soil erosion decreased soil water retention (SWR), fine-mesopores, and soil organic carbon (SOC) of the surface soil. This effect was translated deeper in the soil profile where SOC and carbon fractions in different aggregate sizes decreased with erosion. The lowest bulk density (ρ_b) was observed with G_f compared to W_f, C_f, W_e, and C_e by 2.1%, 5.3%, 15.8%, and 36.8% at the 0 to 5 cm depth. The SWR for G_f was greatest (i.e., higher moisture content values at different matric potentials) and had the greatest proportion of small soil pores. In addition, the SOC of both bulk

soil (BS) and 1 – 2 aggregate fraction (OTA) were greatest in W_f. The SOC of 1-2 mm aggregates was positively correlated with K_{sat}, whereas SOC in both BS and 1-2 mm aggregates were negatively correlated with pH, ρ_b, and CWEC. Further, CWEC and DOC showed a positive correlation with pH; however, they were negatively correlated with mesopores and SOC in both BS and 1-2 mm aggregates. In this study, as the intensity of disturbance on soil structure increased, under agriculture and with erosion, soil hydraulic properties and soil carbon content decreased. However, cold water extractable carbon and dissolved organic carbon were higher under greater disturbance intensity. The wooded land-use helped retain soil carbon content the most, whereas grassland had higher hydraulic properties and lower bulk density. Changes in soil structure related to carbon and hydraulic properties need to be evaluated for ranges of soil disturbance in short- and long-term time scales and in real-life conditions since general C content and C fractions like CWEC and DOC in different aggregate sizes shows different responses to land-use and erosion effects.

INTRODUCTION

Soil pore water is recognized as an important component for understanding environmental changes due to its influence on various mechanisms and feedback processes within the soil system (Green et al., 2019; Seneviratne et al., 2010). Soil water promotes plant transpiration and photosynthesis, and thus influences the water, energy, and biogeochemical cycles (Seneviratne et al., 2010). Soil moisture can be a limiting factor for C uptake due to its role in decreasing gross primary production (Green et al., 2019) via water stress (Humphrey et al., 2018; Zhao and Running, 2010), vegetation mortality in severe cases (Schwalm et al., 2017), and climate extremes (Seneviratne et al., 2010). Soil water can influence C stabilization through its role in physical protection because saturated and unsaturated conditions in soils create different micro-environmental conditions. Higher moisture contents under unsaturated conditions may decreases C mineralization and increase C accumulation (Huang and Hall, 2017).

Soil hydraulic properties depend on many factors, including aggregation and pore structure. For instance, soil aggregate size distribution and stability affect the sensitivity of soil to erosion and the regulation of plant-soil water dynamics (Kemper and Chepil, 1965; Tisdall, 1996). In addition, soil aggregation impacts hydraulic properties by creating larger pores than that between individual soil particles (Nimmo, 2004).

Soil structure is recognized as the organization of soil particles, bound together by organic and inorganic materials into aggregates of different dimensions and geometries (Tisdall, 1996). The complex nature of soil structure and its inter-relationship with important soil processes such as soil water and SOC warrants their study. Intra- and inter-aggregate spaces have different dynamics for air and water exchange. It is in these pore spaces where SOM mineralization occurs (Balesdent et al., 2000). Thus, soil structure can implicitly influence decomposition by affecting the microbial environment under which decomposition occurs, as well as directly affecting decomposition through its role in protecting SOM through encapsulation (Balesdent et al., 2000) within soil aggregates. Besides the understanding of how C is protected in microaggregates through physical encapsulation (Tisdall, 1996), how and which fractions of C (labile or stable) get lost due to the water movement in the soil is also critical to comprehend.

Loss of soil C fractions depends on various soil hydraulic properties, which are different depending on the particular land-use ecosystems and specific management practices. Soil management practices and soil degradation can noticeably alter the labile soil C fractions (Franko, 1997; Ozlu et al., 2019b). The alteration of SOC content due to changes in land-use has been well documented (Ogle et al., 2005). For instance, Don et al. (2011) and Houghton and Goodale (2004) reported a 25–30% decrease in C-stock due to land-use change from natural ecosystems to agriculture. Soil C composition can influence microbially linked soil properties (Weil et al., 2003), such as the stability of soil structure, which has been identified to be more closely related to active SOM fractions than to the total SOM content (Golchin et al., 1994).

The previous chapter attempted to provide a better understanding of the role of soil carbon and mineralogical composition in soil aggregate fractions. The relationship between soil structure and the ability to stabilize SOC are key elements in soil C dynamics (Six et al., 2002). The advancement of knowledge on soil structure and C dynamics requires a change in perspective of soil structure as a static parameter to a dynamic system (Golchin et al., 1994).

This chapter focuses on more dynamic C fraction measurements and their relationship to soil pore size distribution and structure.

The objective of this work was to determine relationships among soil physical structure, hydraulic properties, and traditional C content and fraction measurements. Different land-uses of a glacially developed silt loam that had experienced erosion, or not, were selected to achieve this goal. It was hypothesized that (i) overall SOC will be greater when there is a greater proportion of macropores, (ii) less intensively managed land-uses will have greater total SOC than agroecosystems; however, SOC fractions will be different with agroecosystems having more labile C (Cold water extractable carbon and dissolved organic carbon), (iii) soils under wooded management will have greater SOC than grass, but grass will have more labile C than woodland, and (iv) total SOC will be positively correlated with greater overall soil water retention, while labile C fractions may have a negative relationship with meso- and micro-pores.

MATERIALS AND METHODS

Study Site and Site Description

Five fields with three land-uses, including agriculture, grassland, and wooded land-use on two different soil series, were located at the Arlington Agricultural Research Station in Wisconsin. The two-soil series were Plano (Fine-silty, mixed, superactive, mesic Typic Argiudolls) and Griswold (Fine-loamy, mixed, superactive, mesic Typic Argiudolls). The Griswold series are similar to Plano, with the main distinction being that Griswold is present on sloped portions (4 - 6% slope) of the landscape and has experienced erosion while Plano is relatively flat (< 1% slope). The selected land-uses have been present for more than 20 years, and hereafter are referred to as flat wooded (W_f), flat grassland (G_f), flat row crop (C_f), eroded wood

(W_e), and eroded row crop (C_e). The C_f represents a long-term conventional-continuous corn rotation (*Zea mays* L.) within the Wisconsin Integrated Cropping Systems Trial. This field has received fertilizer applications, tillage, and herbicides. The G_f use has not received any fertilizer or tillage for about 30 years. The wooded uses have not received any inputs either.

Soil Sampling and Storage

Two sets of intact soil samples were collected from different land-uses during the spring of 2017. One set of the samples were collected in stainless steel liners (8 cm diameter and 5 cm height) from 0-5 and 30-35 cm depths to examine soil water retention (SWR), hydraulic conductivity (K_{sat}), bulk density (ρ_b), and pore size distribution. The second set of intact core samples was collected from 0 – 90 cm depth using a hydraulic system with 7.5 cm diameter and 100 cm height plastic cores. Samples were collected with three replications per land-use. Sampling locations withing a land-use were equidistant from each other on the vertices of an imaginary triangle. The sampling locations were random but far from the edge of the fields. Each intact soil core in the plastic liners was cut in half perpendicular to its base and separated into three soil depths: 0 - 30 cm, 30 - 60 cm, and 60 - 90cm. For all fields, surface cover was removed before samples were divided in three depths. Cores for the eroded land uses were not long enough to obtain samples beyond the 30 cm depth because there was a distinctive dense soil layer at around 50 cm of depth which prevented sampling. After air-drying to constant moisture content, one-half of the sample was used for aggregate fractionation into <0.053 mm, 0.053 - 0.25 mm, 0.25 - 0.5 mm, 0.5 – 1 mm, 1 – 2 mm (OTA), and 2 - 4 mm sizes. The other half was used as bulk soil (BS) for different analysis after grinding and passing through a 2-mm sieve. Soil carbon and soil pH were measured in both BS and 1-2 mm aggregates. The 1-2 mm aggregates are commonly used in aggregate stability analysis and thought to be representative of bulk soils. In this paper, 1-2 mm aggregate fraction was compared with bulk soils.

Soil Analysis

Soil pH

Soil pH of BS and 1-2 mm aggregates was analyzed in a 1:1 air-dried soil to deionized water ratio with an Orion Star (Thermo Fisher Scientific, Whatman, MA) pH/EC meter. Soil pH was reported as a controlling factor on aggregate size distribution in previous studies (Zhang et al., 2016) in which soil pH was positively correlated with the proportion of aggregates between 0.25 and 0.053 mm.

Soil Carbon Content

Dry combustion was performed to determine SOC content. About 8 – 10 mg of air-dried soil, ground to a fine powder, was placed into tin capsules. Soil samples were then run through a Flash EA 1112CN Automatic Elemental Analyzer (Thermo Fisher Scientific, Whatman, MA) to determine total C content in those samples. The SOC content was considered equal to total C content because inorganic C content in the studied soils were considered to be minor since soil pH was relatively low in these fields (Paul et al., 2001).

Soil Hydraulic Conductivity, Water Release, Pore Size Distribution, and Bulk Density

The same cores in the stainless-steel liners were used for analysis of the hydraulic conductivity of saturated soil (K_{sat}), soil water release curve (SWR), and bulk density (ρb). First, cores were saturated with tap water by capillarity (i.e., from the bottom up) for 24 hours to 48 hours until a water sheen was observed on top of the soil. The K_{sat} analysis was conducted with a constant head of 5 cm (model K_{sat}, Meter Group Inc., Pullman, WA).

After K_{sat} was determined, the same cores were used for SWR. Silk-screen nylon fabric was fixed to the bottom of the soil core, and then the core was saturated again with tap water by capillarity as described above. The SWR was analyzed at 0, -2.5, -5, -10, -15, and -20 kPa matric potential equivalent using a custom made tension table and at -30, -50, -100, -200, -300, and -500 kPa matric potential equivalent using a pressure plate extractor system (Soil Moisture Equipment Corp., Goleta, CA; Klute and Dirksen, 1986). Soil moisture content (w) was measured gravimetrically by oven drying the soil samples at 105 °C until constant weight at the end of each SWR run. The volumetric water content (θ) was calculated by multiplying w times ρb and dividing by the density of water. Soil pore size distribution was calculated using the capillary rise equation to determine effective pore size classes (Jury et al., 1991) from SWR data. Pore sizes were classified as macro- (>1000 μm), coarse meso- (60 – 1000 μm), fine meso-(10 – 60 μm), and micro-pores (<10 μm) depending on their average pore diameter.

Finally, the ρb was determined using the dry weight of soil contained in the stainless-steel liner after oven drying as described above at the end of SWR run. The mass of dry soil was divided by the volume of the stainless-steel liner to calculate the ρb (Grossman and Reinsch, 2002).

Water Extractable Carbon Contents in Different Aggregate Fractions

Chemical C fractions were determined using cold water extractable (Ghani et al., 2003; Silveira et al., 2008) and dissolved extraction approaches (Robertson et al., 1999). For dissolved organic C (DOC) analysis, a 1:3 soil to deionized water mass ratio was used. For cold water extractable C (CWEC), 3 g of aggregated soil (AS) and 30 mL distilled water (at room temperature) were placed into 50 mL polypropylene centrifuge tubes (1:10 water: soil ratio). Soil was mixed thoroughly with water on a vortexer for 10 sec and then moved to an end-over-end shaker for 30 minutes at 40 rpm for CWEC. The suspension after shaking was centrifuged at 3000 rpm for 25 minutes. Then, supernatant was filtered by using 0.45 µm syringe filter. Extracted solutions were then analyzed in a Shimadzu TOC – VCSH (Shimadzu Corporation, Kyoto, Japan) to determine CWEC in the solution. A similar process was applied for DOC. However, the only difference between DOC and CWEC methods was that soil-water mixture was shaken by end-over-end shaker for 24 hours at 40 rpm for DOC; however, shaking for 30 minutes at 40 rpm was done for CWEC.

Statistical analysis

Statistical analyses were performed to determine the impacts of (i) erosion, (ii) land-use, (iii) depth, and (iv) interaction of land-use x depth. Each of above-mentioned factors were set as fixed effects and replications as random effects in individual analysis. Duncan multiple range test analysis was used to determine differences between means when suitable using an $\alpha = 0.05$. A Person's correlation analysis (Wei et al., 2017) in R and multilinear discriminant analysis (JMP version 15, SAS Institute, Cary, NC) that included all soil properties in this study were performed to evaluate the impacts of land-use at the 0–30 cm depth.

Grassland (G_f) was not included during the analysis to evaluate erosion effects since only agriculture (C_e and C_f) and woodland (W_e and W_f) were represented in eroded and non-eroded ecosystems. However, soils from grassland were used to evaluate differences within non-sloping ecosystems, soil depth, and depth x land-use interaction. Therefore, the erosion comparison was conducted between C_f (flat, long-term corn), W_f (flat, long-term wood), C_e (eroded, long-term corn), W_e (eroded, long-term wood) land-uses only. Similarly, eroded land-uses(C_e and W_e) were not included in statistical analysis for depth effects, thus depth evaluation was performed among C_f (flat, long-term corn), W_f (flat, long-term wood), and G_f (flat, long-term grass) only.

RESULTS

Soil pH

Soil pH of BS was significantly affected by land-use throughout the soil profile, 0-30 cm ($P \leq 0.01$), 30-60 cm ($P \leq 0.01$), and 60-90 cm ($P \leq 0.01$) depths (Figure 1). Soil pH of BS was higher under C_f and W_e in comparison to those under G_f, W_f, and C_e at 0-30 cm depth whereas soil pH of BS was higher under C_f compared to those under G_f and W_f at 30-60 cm and 60-90 cm depths. A similar trend was observed for soil pH of 1-2 mm aggregates at all depths. However, land-use x depth interaction and effects of soil erosion were not significant for soil pH of both BS and 1-2 mm aggregates at 0-30 cm depth. Moreover, variation in pH due to changes in depth were statistically significant ($P<0.03$ for BS and $P<0.02$ for 1-2 mm aggregates). More specifically, soil pH ranged from 5.0 deeper in soil profile to 6.9 in surface soils.

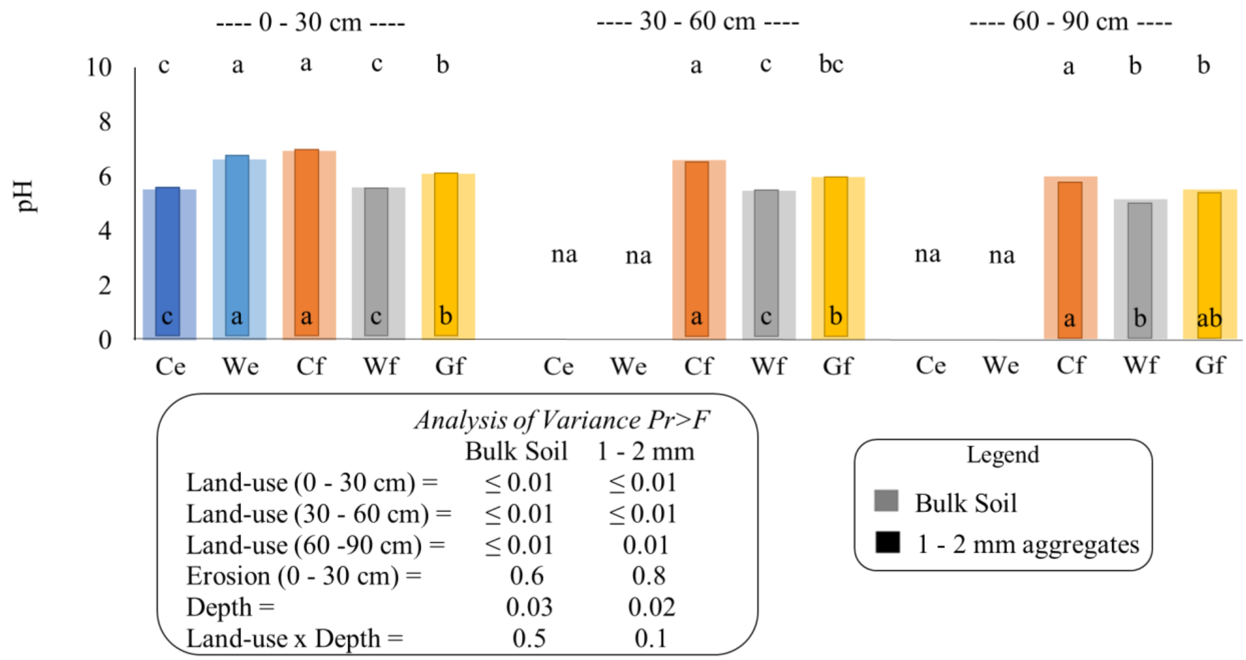


Figure 1. Soil pH of bulk soils and 1-2 mm aggregates for 0-30 cm, 30-60 cm, and 60-90 cm depths as influenced by different land-uses in Arlington, Wisconsin. C_e, eroded long-term cornfield; W_e, eroded long-term wood field; C_f, flat surface long-term cornfield; W_f, flat surface long-term wood field; G_f, flat surface long-term grassland. Data for 1-2 mm aggregated soils are not represented under eroded land-uses for 30–60 cm and 60-90 cm depths. Different superscript letters are significantly different at $\alpha = 0.05$. Lowercase letters above the bars indicate significance due to land-use in bulk soils, whereas lowercase letters within the bars refer to effects of land-use in 1 – 2 mm aggregates.

Soil bulk density and hydraulic conductivity of saturated soil

The ρ_b of non-eroded soil was significantly lower (P = 0.01) than that of eroded soil at 0-5 cm depth (Table 1). When comparing differences between land-uses, the lowest ρ_b was observed under G_f and W_f which was lower than that under C_f, W_e, and C_e by 5.3%, 15.8%, and 36.8%, respectively, at 0-5 cm depth. There was no significant difference in ρ_b between C_f and W_e. Although eroded land-uses had higher ρ_b compared to flat ones at 30-35 cm depth, these differences were not statistically significant. However, when looking at the overall effect of soil depth on ρ_b, the second lower depth (30-35 cm) had greater ρ_b than that at 0-5 cm. Land-use and the overall effect of erosion did not impact K_{sat} due to high variability. However, the K_{sat} was significantly lower in the 30-35 cm depth compared to that at 0-5 cm.

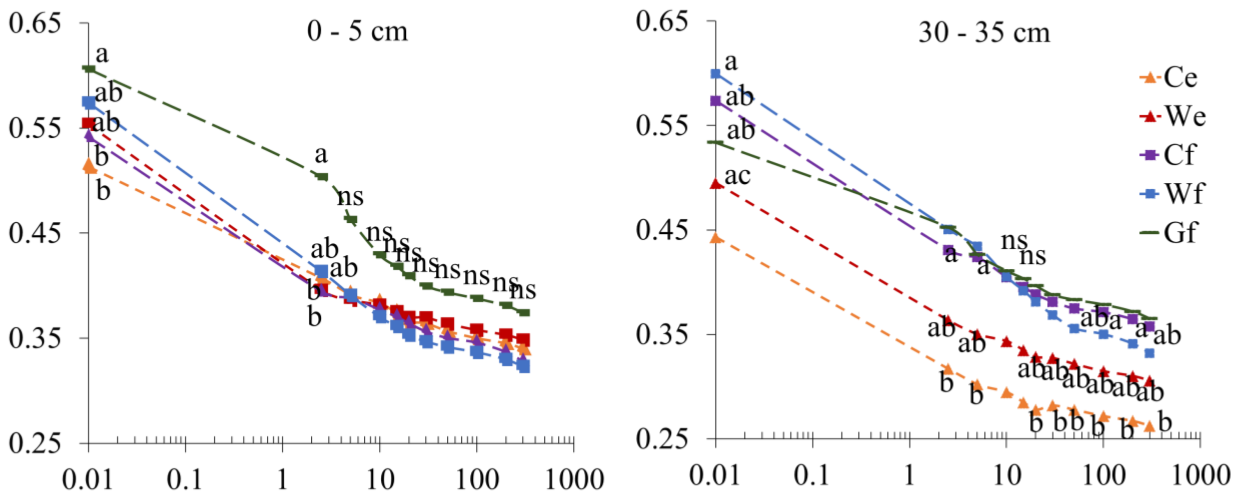
Table 1. Soil bulk density (g cm^{-3}) and hydraulic conductivity (cm d^{-1}) for 0-5 cm and 30-35 cm depths as influenced by different land-uses in Arlington, Wisconsin.

Land-use	Bulk Density	Hydraulic Conductivity
	-- 0-5 cm --	
C_e†	1.28[a††]	302[ns]
W_e	1.12[b]	861
C_f	1.10[b]	161
W_f	0.97[c]	363
G_f	0.95[c]	367
	-- 30-35 cm --	
C_e	1.34[ns]	41[ns]
W_e	1.38	32
C_f	1.17	261
W_f	1.22	164
G_f	1.34	24
	Analysis of Variance Pr>F	
Land-use (0-5 cm)	$\leq$ 0.01	0.10
Land-use (30-35 cm)	0.09	0.08
Erosion (0-5 cm)	0.01	0.10
Depth	$\leq$ 0.01	$\leq$ 0.01
Depth x Land-use	0.08	$\leq$ 0.01

†C_e, eroded long-term cornfield; W_e, eroded long-term wood field; C_f, flat surface long-term cornfield; W_f, flat surface long-term wood field; G_f, flat surface long-term grassland.
†† Means within the same column, followed by different superscript letters, are significantly different at α= 0.05.

Soil water retention and pore size distribution

The overall effect of depth was significant (P = 0.01) only at saturation, with 0-5 cm having greater water contents at this matric potential than at 30-35 cm (Fig. 2). The SWR was also significantly different for the Field x Depth interaction at 0, -2.5, -5, -10, -15, -20, and -30 kPa. In general, the SWR ranged from 0.34 $m^3 m^{-3}$ to 0.61 $m^3 m^{-3}$ at 0 - 10 cm depth and 0.26 $m^3 m^{-3}$ to 0.60 $m^3 m^{-3}$ at 30-35 cm depth from 0 to -500 kPa water potentials.



Analysis of Variance Pr > F

-kPa	0	2.5	5	10	15	20	30	50	100	200	300	500
Land-use (0 - 5 cm)	≤ 0.01	0.02	0.08	0.30	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Land-use (30 - 35 cm)	≤ 0.01	≤ 0.01	≤ 0.01	≤ 0.01	≤ 0.01	0.01	0.02	0.03	0.02	0.03	0.03	0.04
Depth	0.01	0.10	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Land-use x Depth	≤ 0.01	0.02	0.02	0.04	0.05	0.06	0.08	0.10	0.10	0.10	0.10	0.10

Figure 2. Soil water retention for 0-5 cm and 30-35 cm depths as influenced by different land-uses in Arlington, Wisconsin. C_e, eroded long-term cornfield; W_e, eroded long-term wood field; C_f, flat surface long-term cornfield; W_f, flat surface long-term wood field; G_f, flat surface long-term grassland. Different letters denote significant differences within a matric potential at α= 0.05. ns – not significant.

Soil water retention was different depending on land-use and erosion state at both soil depths (Fig. 2). At the first depth (0-5 cm), SWR was significantly different depending on land-use from 0 to -2.5 kPa matric potentials, and at most matric potentials at 30-35 cm depth. At the 0-5 cm depth there was no difference between G_f, W_f, and W_e, while C_f and C_e had lower water contents at 0 and -2.5 kPa. Differences between land-uses at the 30-35 cm varied depending on the matric potential, but generally G_f, W_f, C_f and W_e were significantly greater than C_e, although differences between W_e and C_e were not statistically significant. Summarizing, SWR data showed that non-eroded land-uses typically had higher moisture content at most matric potentials studied. There was no overall difference in soil pore size distribution with depth for any of the pore sizes (Table 2). However, the land-use x depth interaction was significant for fine-mesopores. In addition, pore size distribution was not influenced by changes in depth.

Significant differences in soil pore size distribution were only observed in fine mesopores at 0-5 cm depth, and in macropores, fine mesopores, and micropores at the 30-35 cm depth. In particular, G_f had higher fine mesopore volume at 0-5 cm depth than W_e by 3.8 times, but G_f was no different than the other land-uses. However, numerically the fine mesopore volume of G_f at this depth was greater than W_f, C_f, and C_e by 46%, 100%, and 140%. At the deeper depths, W_f had the greatest volume of fine mesopores, followed by G_f and C_f, and then by W_e and C_e. In the micropore fraction, G_f, W_f and C_f had statistically similar volumes; however, there was no difference between W_f, C_f, W_e and C_e. The macropore fraction at 30-35 cm depth was the largest for W_f, C_f, and W_e, while G_f, W_e and C_e were similar to each other. In general, the natural non-eroded land-uses had a greater total fraction of pores, which was reflected in ρ_b values.

Table 2. Pore size volume for different pore diameter ranges (m^3 m^{-3}) at 0-5 cm and 30-35 cm depths as influenced by different land-uses in Arlington, Wisconsin.

Land-use	Macro Pores	Coarse Mesopores	Fine Mesopores	Micro Pores
		-- 0-5 cm --		
C_e†	$0.11^{ns††}$	0.016^{ns}	0.027^{ab}	0.36^{ns}
W_e	0.16	0.009	0.017^{b}	0.37
C_f	0.15	0.006	0.032^{ab}	0.36
W_f	0.16	0.023	0.044^{ab}	0.35
G_f	0.10	0.041	0.064^{a}	0.40
		-- 30-35 cm --		
C_e	0.13^{ab}	0.015^{ns}	0.020^{c}	0.28^{b}
W_e	0.13^{ab}	0.013	0.023^{c}	0.33^{b}
C_f	0.14^{a}	0.007	0.043^{b}	0.38^{ab}
W_f	0.15^{a}	0.016	0.066^{a}	0.37^{ab}
G_f	0.08^{b}	0.026	0.039^{b}	0.39^{a}
		Analysis of Variance Pr>F		
Land-use (0-5 cm)	0.30	0.05	0.02	0.40
Land-use (30-35 cm)	0.01	0.06	≤ 0.01	0.02
Erosion (0-5 cm)	0.40	0.30	0.01	0.60
Depth	0.50	0.40	0.70	0.20
Depth x Land-use	0.80	0.60	≤ 0.01	0.07

† C_e, eroded long-term cornfield; W_e, eroded long-term wood field; C_f, flat surface long-term cornfield; W_f, flat surface long-term wood field; G_f, flat surface long-term grassland.
†† Means within the same sub-column, followed by different superscript letters, are significantly different at α= 0.05. ns - not significantly different.

Soil carbon content

Data for SOC content under different land-use and erosion for BS and 1-2 mm aggregates in the 0-30 cm, 30-60 cm, and 60-90 cm depths are shown in Table 3. Depth overall had a

Table 3. Soil carbon content (g kg dry soil $^{-1}$) of bulk soils and 1 – 2 mm aggregates for 0-30 cm, 30-60 cm, and 60-90 cm depths as influenced by different land-uses in Arlington, Wisconsin.

Land-use	Bulk	1 - 2 mm
	---- 0 - 30 cm ----	
C_e†	23.2^{c}††	28.0^{c}
W_e	19.4^{d}	21.7^{d}
C_f	23.4^{bc}	32.0^{bc}
W_f	45.9^{a}	38.3^{a}
G_f	25.1^{b}	35.3^{ab}
	---- 30 - 60 cm ----	
C_e	-	-
W_e	-	-
C_f	24.6^{a}	31.3^{ns}
W_f	15.3^{b}	17.9
G_f	11.1^{b}	15.6
	---- 60 - 90 cm ----	
C_e	-	-
W_e	-	-
C_f	3.8^{b}	3.8^{b}
W_f	4.9^{a}	8.0^{a}
G_f	5.1^{a}	6.5^{a}
	Analysis of Variance Pr>F	
Land-use (0 -30 cm)	$\leq$ 0.01	$\leq$ 0.01
Land-use (30 -60 cm)	$\leq$ 0.01	0.07
Land-use (60 -90 cm)	0.20	$\leq$ 0.01
Erosion (0 - 30 cm)	0.03	0.40
Depth	$\leq$ 0.01	$\leq$ 0.01
Depth x Land-use	$\leq$ 0.01	$\leq$ 0.01

†C_e, eroded long-term cornfield; W_e, eroded long-term wood field; C_f, flat surface long-term cornfield; W_f, flat surface long-term wood field; G_f, flat surface long-term grassland.
††Means within the same column, followed by different superscript letters are significantly different at α= 0.05. ns – not significantly different.

significant effect on SOC in both BS (P≤0.01) and 1-2 mm aggregates (P≤0.01). Erosion also significantly affected SOC of BS (P=0.03), but not 1-2 mm aggregates (P=0.40). There was a significant land-use x depth interaction effect of SOC of BS and 1-2 mm aggregates (P≤0.01, respectively). Comparing land-uses, the highest SOC concentrations in BS at the 0-30 cm depth were observed with W_f which was significantly higher than G_f, C_f, C_e, and W_e by 83%, 96%, 98% and 137% times. Deeper in the profile, C_f had greater BS SOC at 30-60 cm than G_f and W_f, but at 60-90 cm depth the natural land-uses had significantly greater SOC than C_f. Focusing on SOC of 1-2 mm aggregates, the trend was less clear. At the surface depth, W_f had significantly greater SOC in the 1-2 mm aggregates than G_f and C_f. Similarly, there were no differences in SOC of 1-2 mm aggregates between C_f and C_e, while W_e had the lowest concentration of this depth (0-30 cm). There were no differences in SOC in 1-2 mm aggregates between land-uses at 30-60 cm. At the 60-90 cm depth, the W_f and G_f land-uses had significantly greater SOC of 1-2 mm aggregates than C_f.

Water extractable carbon contents in different aggregate size fractions

Depth significantly decreased the CWEC for all aggregate size fractions (Table 4). However, erosion had no significant effect on CWEC for any of the aggregate sizes studied at the 0-30 cm depth. The impact of land-use on CWEC varied depending on depth and aggregate size fraction, but in general C_f had highest CWEC.

Table 4. Cold water-extractable carbon (mg kg $^{-1}$) in different aggregate fractions for 0-30 cm, 30-60 cm, and 60-90 cm depths as influenced by different land-uses in Arlington, Wisconsin.

Land-use	---------------------- Aggregate Fractions ----------------------				
	2-4 mm	1 - 2 mm	0.5-1 mm	0.25-0.5 mm	0.053-0.25 mm
			-- 0 - 30 cm --		
C_e†	101$_{cd}$††	136$_c$	113$_{ns}$	158$_{ns}$	119$_b$
W_e	134$_{ab}$	235$_a$	145	131	186$_a$
C_f	141$_a$	199$_b$	168	164	204$_a$
W_f	106$_c$	143$_c$	138	109	134$_b$
G_f	124$_b$	141$_c$	130	171	141$_b$
			-- 30 - 60 cm --		
C_e	-	-	-	-	-
W_e	-	-	-	-	-
C_f	109$_{ns}$	147$_{ns}$	167$_a$	130$_a$	136$_{ns}$
W_f	96	97	105$_b$	95$_b$	127
G_f	113	105	106$_b$	94$_b$	146
			-- 60 - 90 cm --		
C_e	-	-	-	-	-
W_e	-	-	-	-	-
C_f	94$_a$	111$_{ns}$	110$_{ns}$	112$_a$	149$_{ns}$
W_f	67$_b$	116	67	61$_b$	104
G_f	52$_c$	59	110	64$_b$	119
			Analysis of Variance Pr>F		
Land-use (0 -30 cm)	0.02	≤ 0.01	0.10	0.30	≤ 0.01
Land-use (30 -60 cm)	0.60	0.20	0.03	≤ 0.01	0.50
Land-use (60 -90 cm)	≤ 0.01	0.20	0.07	0.02	0.10
Erosion (0 - 30 cm)	0.60	0.60	0.10	0.70	0.50
Depth	≤ 0.01	≤ 0.01	0.01	≤ 0.01	0.04
Depth x Land-use	0.02	0.40	0.07	0.02	0.09

†C_e, eroded long-term cornfield; W_e, eroded long-term wood field; C_f, flat surface long-term cornfield; W_f, flat surface long-term wood field; G_f, flat surface long-term grassland.
††Means within the same column, followed by different superscript letters are significantly different at α= 0.05. ns – not significantly different.

The DOC significantly decreased deeper in profile for the larger aggregate fractions (2-4 and 1-2 mm; Table 5). Differences in DOC due to erosion were only significant for 2-4 mm ($P \leq 0.01$) and 0.5-1 mm ($P \leq 0.01$) sized aggregates, but trends were not consistent. Similar to

CWEC, the C_f had greatest DOC concentrations, but more often there were no significant differences between land-uses at the different depths.

Table 5. Dissolved organic carbon (mg kg $^{-1}$) in different aggregate fractions for 0-30 cm, 30-60 cm, and 60-90 cm depths as influenced by different land-uses in Arlington, Wisconsin.

Land-use	--------------------- Aggregate Fractions ---------------------				
	2-4 mm	1 - 2 mm	0.5-1 mm	0.25-0.5 mm	0.053-0.25 mm
			-- 0 - 30 cm --		
C_e†	182^{d}††	185^{ns}	279^{ns}	236^{ns}	287^{ns}
W_e	205^{c}	182	301	246	212
C_f	258^{a}	196	251	164	252
W_f	225^{b}	149	215	281	249
G_f	203^{c}	158	173	228	180
			-- 30 - 60 cm --		
C_e	-	-	-	-	-
W_e	-	-	-	-	-
C_f	161^{a}	142^{ns}	144^{ns}	223^{ns}	254^{ns}
W_f	111^{b}	118	83	115	145
G_f	77^{b}	99	119	209	204
			-- 60 - 90 cm --		
C_e	-	-	-	-	-
W_e	-	-	-	-	-
C_f	157^{a}	149^{a}	230^{a}	186^{ns}	200^{ns}
W_f	61^{b}	59^{b}	96^{b}	195	199
G_f	61^{b}	60^{b}	91^{b}	270	236
			Analysis of Variance Pr>F		
Land-use (0 -30 cm)	≤ 0.01	0.10	0.10	0.50	0.07
Land-use (30 -60 cm)	0.02	0.20	0.10	0.20	0.30
Land-use (60 -90 cm)	≤ 0.01	≤ 0.01	≤ 0.01	0.20	0.20
Erosion (0 - 30 cm)	≤ 0.01	0.5	≤ 0.01	0.70	0.90
Depth	≤ 0.01	≤ 0.01	0.10	0.50	0.50
Depth x Land-use	≤ 0.01	0.07	0.08	0.60	0.50

†C_e, eroded long-term cornfield; W_e, eroded long-term woodland; C_f, flat surface long-term cornfield; W_f, flat surface long-term wood field; G_f, flat surface long-term grassland.
††Means within the same column, followed by different superscript letters are significantly different at α= 0.05. ns – not significantly different.

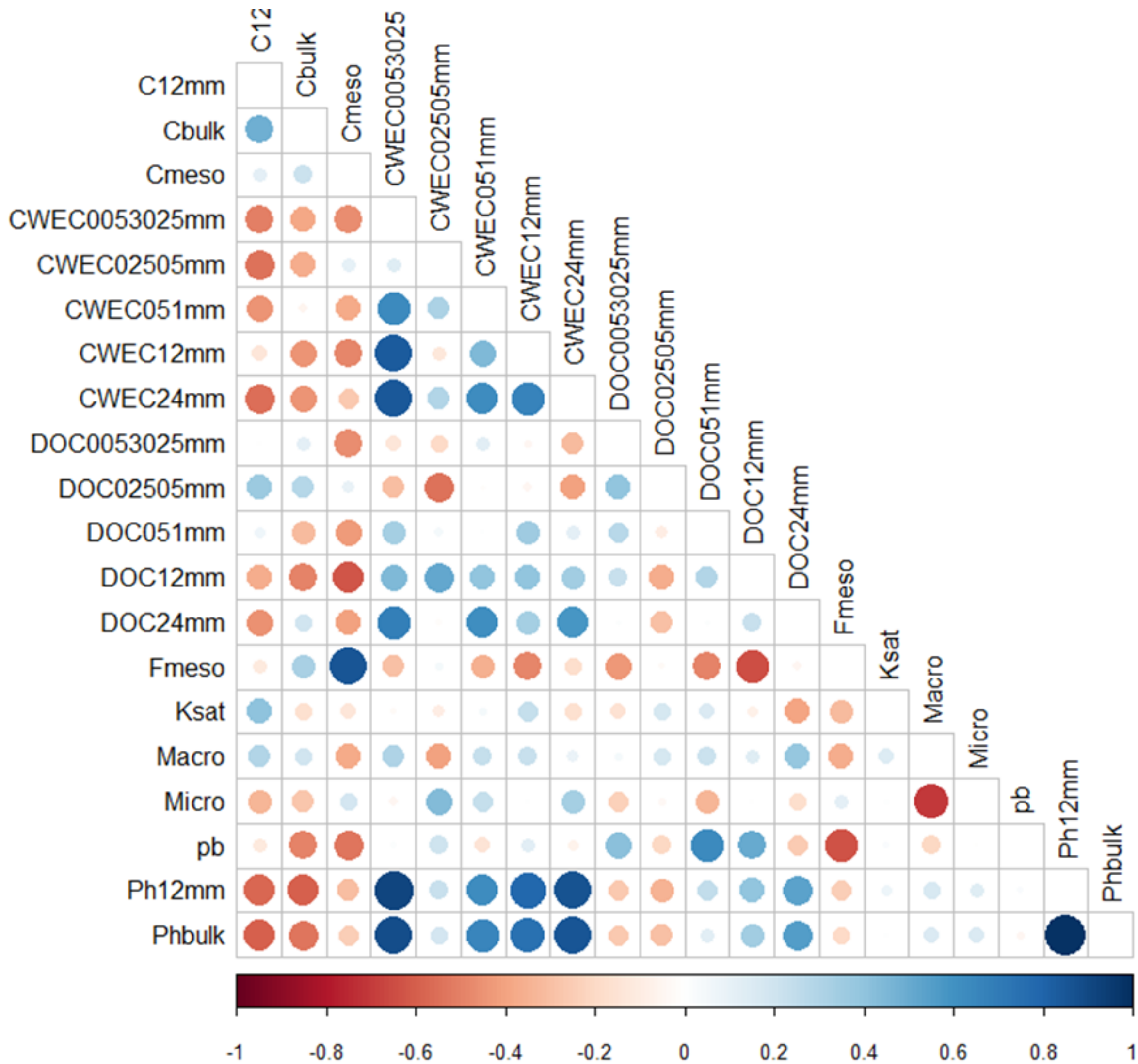


Figure 3. Pearson's correlation analysis of soil properties as impacted by different land-uses for 0–30 cm depth. The color intensity of the chart denotes the magnitude of the relationship. K_{sat}, hydraulic conductivity; pb, bulk density; Macro, macropores; Fmeso, fine mesopores; Cmeso, Coarse mesopores; Micro, micropores; C12mm, the carbon content of 1-2 mm aggregates; Cbulk, C content of bulk soil; Ph12mm, pH of 1-2 mm aggregates; Phbulk, pH of bulk soil, CWEC24mm; cold-water extractable carbon in 2-4 mm aggregates, CWEC12mm; cold-water extractable carbon in 1-2 mm aggregates, CWEC051mm; cold-water extractable carbon in 0.5-1 mm aggregates, CWEC02505mm; cold-water extractable carbon in 0.25-0.5 mm aggregates, CWEC0053025mm; cold-water extractable carbon in 0.053-0.25 mm aggregates, DOC24mm; dissolved organic carbon in 2-4 mm aggregates, DOC12mm; dissolved organic carbon in 1-2 mm aggregates, DOC051mm; dissolved organic carbon in 0.5-1 mm aggregates, DOC02505mm; dissolved organic carbon in 0.25-0.5 mm aggregates, DOC0053025mm; dissolved organic carbon in 0.053-0.25 mm aggregates.

Correlation between soil properties and multiple linear discrimination of study treatments

Pearson's correlation analysis showed that the proportion of soil macropores was positively correlated with DOC in 2-4 mm aggregates but negatively correlated with CWEC in 0.25-05 mm aggregates (Figure 3). In addition, the proportion of both coarse and fine mesopores were positively correlated with SOC in BS but negatively correlated with *pb*, and C fractions in all aggregate size fractions except those between 0.25 and 0.5 mm. Moreover, the proportion of soil micro pores was positively correlated with CWEC in 0.25-0.5 mm, 0.5-1 mm, and 2-4 mm aggregates but negatively correlated with SOC in both BS and 1-2 mm aggregates.

Finally, a multiple linear discriminant analysis was performed to evaluate land-use impact on all soil properties used in this chapter (Figure 4). Results of the multiple linear discriminant analysis grouped different land uses that are represented with circles. The distance between circles represents the likelihood that factors are related, thus circles representing different land uses that are further apart are less similar. The multiple linear discriminant analysis showed that all land-use fields are significantly different to each other considering all soil properties evaluated in this chapter. Eroded fields grouped together where non-eroded forest (W_f) was the most significantly different to the eroded fields. Soil pH and fine mesopores had a significant contribution to differentiate C_f. In addition, C_e was most affected by changes in pore size distribution whereas C in BS made the most difference in W_f.

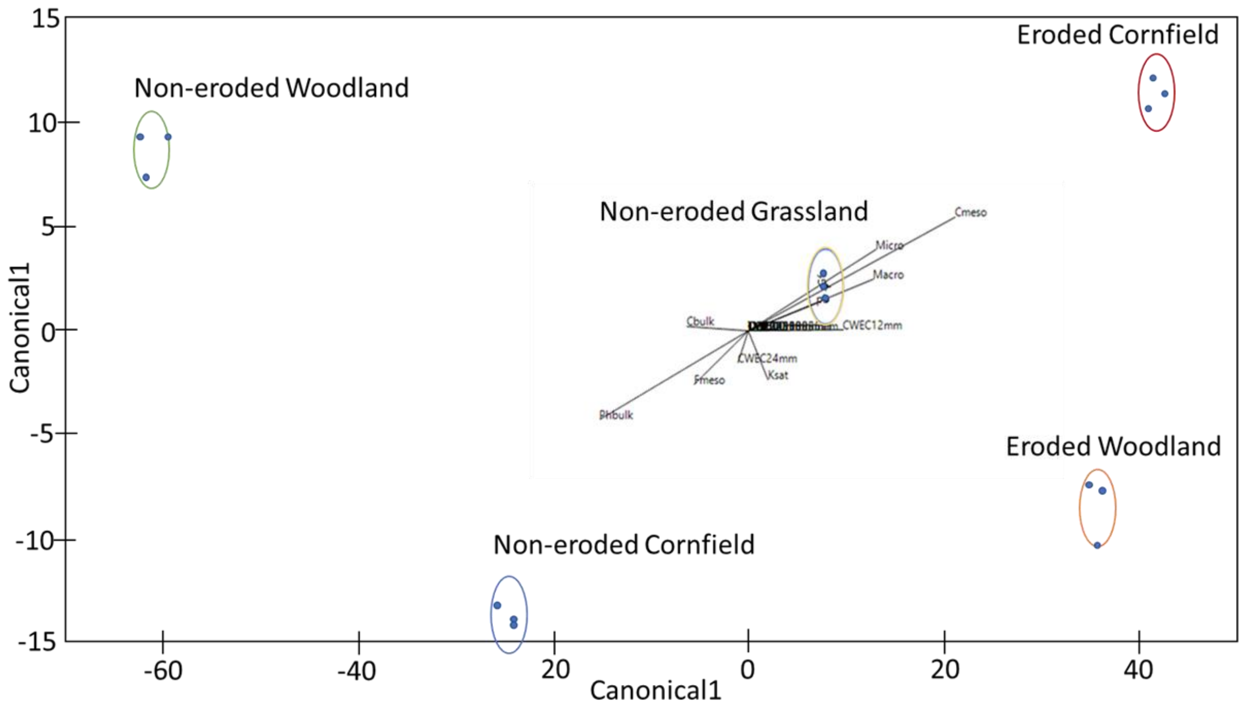


Figure 4. Multiple linear discriminant analysis of soil properties as correlated with different land-uses for 0–30 cm depth. C_e, eroded long-term cornfield; W_e, eroded long-term woodland; C_f, flat surface long-term cornfield; W_f, flat surface long-term wood field; G_f, flat surface long-term grassland.

DISCUSSION

Soil pH and associations with soil hydraulic properties under impacts of land-use and erosion

Aggregates can break down by slaking and clay dispersion (Russell, 1971) which are dependent on surface charge of soil particles (Bolan et al., 1996). Soil pH and the valency of major cations filling exchange sites are among factors that influence surface charge of soil particles (Arora and Coleman, 1979; Shainberg et al., 1989). Moreover, soil pH interaction with soil hydraulic conductivity was presented by Suarez et al. (1984). Suarez et al. (1984) reported that K_{sat} at pH of 9 were lower than at pH of 6 for a montmorillonitic and a kaolinitic soil, however, for a low SOC and high silt content vermiculitic soil (as in the present study), pH changes may not show large impact on K_{sat}. In this study, soil pH ranged from 5.0 deeper in the soil profile to 6.9 on the surface depth. There were no significant differences in K_{sat} due to land-use or erosion effect. Between eroded land-uses, C_e had lower pH than W_e, whereas, W_f had lower pH than C_f and G_f. These differences between eroded and non-eroded land-uses could also be attributed to differences in management between these systems. Further, land-use significantly influenced the soil pH of both BS and 1-2 mm aggregates throughout the soil profile (0 to 90 cm depth). Among flat surfaces C_f had greater pH than G_f and W_f. Changes in pH due to management and fertility practices in agricultural soils were previously reported in several studies in northern great plains (Ozlu and Kumar, 2018; Sandhu, 2016). Northern forest soils have been documented to have more acidic soils (Ross et al., 2008) where many studies reported liming effect under different agricultural management practices (Ozlu, 2016; Sandhu, 2016). These may explain why agriculture have higher pH than W_f and G_f.

Soil bulk density and hydraulic conductivity as influenced by land-use and erosion

The measurement of soil ρ_b integrates various aspects such as the state of soil structure, compaction, water content and movement, soil porosity and space to store C. Soil ρ_b was greater in eroded soil by 19% compared to non-eroded fields. Ghebreiyessus et al. (1994) noted that erosion and the duration of erosion had a positive relationship with ρ_b. Therefore, long-term impact of erosion as it is in the present study, increases soil ρ_b compared to non-eroded lands-uses. In addition, (Frye et al., 1982) reported an increase of ρ_b of fine-loam-mixed mesic Typic Paleudalfs soils under impacts of erosion, and also stated an association between higher ρ_b and lower water content (by 4 to 5%) and SOC. In this study, SOC of BS was negatively correlated with ρ_b. On the other hand, Lowery et al. (1995) reported that although erosion can change ρ_b of upper soil layers (Ap horizon), ρ_b deeper in a soil profile may not change (AB, B, BC, and C horizons). However, in this study, soil ρ_b was greater at 30-35 cm depth than 0-5 cm depth.

Among non-sloping fields at 0-5 cm depth, soil ρ_b was the lowest in G_f compared to W_f and C_f by 2%, 14%. In contrast, there were no significant differences in ρ_b due to land-use effects at 30-35 cm depth. The changes in ρ_b under different land-use can be because of numerous factors. In agricultural fields ρ_b can increase due to management practices like tillage, harvesting, planting, and intensive addition of low C fertilizers. Lower bulk density in grassland might be due to higher SOC, root structure, and less compaction. Soil organic C plays a critical role in improving soil aggregation and porosity which in turn can influence soil ρ_b. Previous studies reported a linear negative relationship between SOC and ρ_b (Ozlu et al., 2019), soil aggregation, and porosity where inorganic fertilizers increased ρ_b compared to manure additions (Ozlu and Kumar, 2018). In the present study, ρ_b had a negative correlation with SOC in BS, coarse mesopores, and fine mesopores, but positively correlated with DOC in different aggregate size fractions. Moreover, greater ρ_b of the two corn systems can be attributed to the use of farming machinery which can cause compaction and destroy soil structure. This is similar to the findings of Don et al. (2011) in which the ρ_b of agricultural fields was found to be greater than that of grassland and forest. Our results from woodland and grassland with lower ρ_b but higher C content under no disturbance due to management practices supports above statements.

However, differences in ρ_b did not translate to differences in K_{sat}. There was great variability in K_{sat} values, highlighting the difficulty of using this property as a reliable factor to draw some information on the porosity of soil. Nevertheless, K_{sat} was positively correlated with C in 1-2 mm aggregates and negatively correlated with DOC in the 2 – 4 mm aggregate size fraction. Positive correlation of K_{sat} and SOC is well known (Bayramin et al., 2009; Benjamin et al., 2008). In this study, K_{sat} was positively correlated with SOC in 1-2 mm aggregates.

Soil water retention and pore size distribution as influenced by land-use and erosion

Soil water retention, a complex function of soil structure (Rawls et al., 1991; Wösten et al., 2001), is a critical indicator for soil pore size distribution and crop productivity. Soil water content under some matric potentials showed a negative impact of soil erosion. However, the interaction between land-use and depth (*Land-use x Depth*) were significant at 0, -2.5, -5, -10, and -15 kPa. The lower SWR with erosion might be due to the greater ρ_b and lower SOC. The role of SOC on improving SWR has been documented (Ontl and Schulte, 2012; Rawls et al., 2003). Improving SOM can directly improve soil hydraulic properties due to its lower bulk density and indirectly influence SWR through its role in creating different pore sizes. The influences of SOC on soil structure, adsorption properties, and hence SWR might be related to climate change and adjustments in management practices (Rawls et al., 2003). Soil organic C plays an important role in SWR because of its influence on the creation of meso and micropores which can retain water at greater matric potentials than macropores.

In addition, C_f had significantly lower SWR compared to those of W_f, and G_f for 0 and -2.5 kPa at 0-5 cm depth, and for 0, -2.5, -5 kPa at 30-35 cm depth. Decreases in water content at higher potentials might be related to the impacts of macropores on water availability and air-filled porosity (Allbrook, 1986; Bruand and Cousin, 1995; Dickerson, 1976; McNabb and Froehlich, 1984; Startsev and McNabb, 2001; Warkentin, 1971). Since agricultural fields are more disturbed, the aggregation and pore size distribution might negatively impact SWR. The effect of disturbance, due to intensity in management, lead considerable impacts of SOC on SWR in medium- and fine textured soils (Bauer and Black, 1981). Similarly, Startsev and McNabb (2001) reported that harvesting equipment can create soil compaction and negatively impact SWR via the alteration in pore space and changes in the quality of the root environment.

Conversely, SWR might be higher in woodland and grassland due to the effect of their root system and accumulation of SOC as observed in this study. The G_f had greater SWR for 0 and -2.5 kPa at 0-5 cm depth but for the 30-35 cm depth this was not observed for the same matric potentials. In addition, lower disturbance, higher SOC content, better quality of root structure, lower compaction, and distribution of soil pores are factors that can lead to better SWR in grassland and woodland compared to agriculturally managed soils. However, at matric potentials lower than -5 kPa there was a shift in SWR under different land-uses. This might be caused by changes in soil texture of eroded soil. A land-use like grassland, with greater SOC content and better root environment but lower ρ_b, had higher SWR. Some studies related this change in SWR between higher and lower potentials to size of pores and ρ_b. As mentioned above, decreases in SWR at higher potentials can be attributed to macropores which impact plant water availability and air-filled porosity (Allbrook, 1986; Bruand and Cousin, 1995; Dickerson, 1976; McNabb and Froehlich, 1984; Warkentin, 1971), but here it is also reported that SWR at lower potentials might increase or not be affected by an increase in smaller pores from soil compaction (Hill and Sumner, 1967; Startsev and McNabb, 2001). Changes in these pore sizes due to compaction can also impact aggregate structure of soils. Nanzyo et al. (1993) reported that SOM promoted the SWR capacity of an Andisol since it contributed stable aggregate formation, creating more mesopores and micropores, which in turn maintained capillary and hygroscopic moisture. This effect might also explain changes observed in this study in which G_f compared to other land-uses for the range of matric potentials evaluated had greater water contents at 0-5 cm depth, but significant differences were limited to some matric potentials. Moreover, at 30-35 cm depth the water contents at different pressures were lower in the eroded agroecosystem, but for 0-5 cm these differences were not clear.

Pores of different sizes and shapes can physically protect C (Quigley et al., 2018). In these pores, the soil controls water movement and related mechanisms within the soil pore structures. Previous studies reported that different size and spatial configurations of pores due to differences in aggregation were characterized by aggregate size distributions and provided micro-environments to physically protect C in the soil matrix (Ekschmitt et al., 2008; Ekschmitt et al., 2005; Kravchenko and Guber, 2017; Quigley et al., 2018; Rabot et al., 2018; Young et al., 2001). The relationship between soil structure and the ability of a soil to stabilize SOM in different pore sizes is an important element for soil C dynamics (Six et al., 2002). In this study, soil erosion effects on pore size distribution at 0-5 cm depth were not significant except for fine mesopores, which were negatively impacted by erosion. Among eroded fields, the agricultural management had a greater proportion of fine mesopores than that of woodland by 59%. In a previous section of this chapter, it was reported that C_e had lower SOC and higher ρ_b. It can be possible that the fine mesopore fraction in C_e was created as a result of a loss of larger pores from equipment traffic or other causes. Except for this difference, fine mesopores were lower in more disturbed and intensely managed land-uses, such as those eroded and under agricultural management. Among non-sloping land uses, the proportion of fine mesopores at 0-5 cm depth were higher in G_f than W_f and C_f by 45% and 100%. A similar result was also observed for fine mesopores at 30-35 cm depth. Greater fine mesopores in grassland compared to croplands were also reported by Dai et al. (2019). Similarly, previous studies reported lower pores of 37.5–97.5 μm in conventionally managed agricultural fields (Wang et al., 2012). Higher relative percentile of smaller pores (fine-mesopores and micropores) may be a result of better aggregation by cementing of soil particles from greater SOM levels and in turn increased water infiltration (Ozlu et al., 2019; Singh Brar et al., 2015). These observations are supported by micropores results of this study where micropores were also higher in G_f compared to C_f and W_f at 30-35 cm depth. The association between SOC content and proportion of pores between 15 – 37.5 μm was also reported by Ananyeva et al. (2013) where native systems had greater heterogeneity of pore size distribution, higher C and higher variability in intra-aggregate C content compared to agricultural managed systems.

Pearson's correlation analysis also showed that the proportion of soil macropores was positively correlated with DOC in 2-4 mm aggregates but negatively correlated with CWEC in 0.25-05 mm aggregates. Since macropores can connect to the soil surface, they can provide greater water infiltration rates, but the intensity and amount of rainfall can collapse soil pores or breakdown soil aggregates and in turn increase runoff (Moss, 1991) and soil erosion (Holz et al., 2015). However, at 30-35 cm depth macropores in eroded soil were less. Neither soil depth nor the land-use x depth interaction had significant impacts on the proportion of macropores. The W_f had a greater amount of macropores compared to other land-uses. Previous studies (Zhang et al., 2017) also reported greater proportion of macropores in forests compared to grassland and agriculture, which might be associated with stable and greater vegetation cover, higher gravel content, greater SOM, but lower ρ_b, and less field traffic. Greater proportion of macropores in woodland and grassland can also be attributed to greater faunal (e.g. earthworms and ants) abundance and activity in soils (Lavelle, 1988).

Soil carbon content, and associations with soil hydraulic properties under impacts of land-use and erosion

Soil organic C is the most studied attribute of soil and can be influenced by land-use (Zhang et al., 2007), erosion level, and soil management practices. Identification of C storage in native ecosystems is important to determine overall C sequestration potential of ecosystems and hence current research efforts are focused on C storage studies globally (Batjes, 2002; Bernoux et al., 2002; Krogh et al., 2003; Lacelle et al., 1997; Zhang et al., 2007). In this study, soil erosion significantly decreased SOC of both BS and in 1-2 mm aggregates. Also, SOC decreased deeper in the soil profile. A study was carried out in Tibet over 50 years to evaluate dynamics of soil erosion determined that SOC was influenced by land-use changes, with SOC of eroded sloping landscapes been 27% lower than that of non-sloping fields (Xiaojun et al., 2010). The W_f had higher SOC content in both BS and in 1-2 mm aggregates than SOC of other land uses at 0-30 cm depth. At 30-60 cm depth, C_f had higher SOC in both BS and in 1-2 mm aggregates compared to other land uses. However, trends in SOC at 60-90 cm depth was opposite of the trend at 30-60 cm depth where G_f and W_f had the higher SOC than C_f. Decreases in SOC while moving deeper in the soil profile was documented by Zhang et al. (2007) where greater SOC was reported in forests compared to grassland and agriculture. Similarly, Tirgarsoltani et al. (2014) reported that agriculture had lower carbon and nitrogen ratio than forest and rangeland. Furthermore, Pearson's correlation analysis (Figure 3) showed that SOC of BS and in 1-2 mm aggregates were negatively correlated with soil pH, ρ_b, and CWEC, while SOC of 1-2 mm aggregates was positively correlated with K_{sat}.

Water extractable carbon contents in different aggregate fractions

Soil erosion had no impacts on CWEC and DOC. The CWEC and DOC in different aggregate fractions were decreased with soil depth. Results from Scheuner and Makeschin (2005) overlaps with our findings that CWEC decreased with soil depth. In addition, Scheuner and Makeschin (2005) reported that water extractable C and POC were dominant energy sources for microbial metabolism in an O horizon (Scheuner and Makeschin, 2005). Other researchers reported no difference in water extractable C due to depth change. Corre et al. (1999) and Cook and Allan (1992) reported that CWEC varied depending on soil physical, chemical, and biological properties of a soil type, but not due to forest type, vegetation age or type. However, in this study the CWEC and DOC of all aggregate fractions were greater in non-eroded agricultural land use, while non-eroded forest soil showed greater CWEC in 1-2 mm aggregates. Ćirić et al. (2016) reported significant differences of water extractable C depending on land-use. Hamkalo and Bedernichek (2014) reported that SOC amounts contributed to greater CWEC and labile water extractable C fractions in forests compared to agricultural soils. In addition, CWEC in different aggregate sizes was positively correlated with soil pH. However, CWEC was negatively correlated with fine mesopores, SOC, and TN in both BS and 1-2 mm aggregates. Moreover, DOC in different aggregate sizes was positively correlated with ρ_b and pH. Similar to CWEC, DOC was negatively correlated with fine mesopores, SOC, and TN in both BS and in 1-2 mm aggregates. Ćirić et al. (2016) reported a positive correlation between CWEC and mean weight aggregate diameter, SOC in soil particles smaller than 53 µm, and SOC in macroaggregates. Soils with relatively low CWEC may have higher SOC stability since CWEC is one of the most active C fractions and it can easily be lost. Ćirić et al. (2016) stated that SOC in Mollisols was more stable since water extractable organic C was lower than in soils with less SOC.

CONCLUSION

Eroded land uses had lower soil water retention and fine-mesopores but greater bulk densities at 0-5 cm depth. In addition, eroded land uses had lower carbon content in bulk soil and the 1 – 2 mm aggregate size fraction compared to non-eroded land uses at 0-30 cm depth.

Among non-eroded land uses, the more intensively managed agricultural system (C_f) had greater bulk density and fine mesopores at 0-5 cm depth. The C_f land use also had higher pH in both bulk soil and 1-2 mm aggregates, and water extractable carbon fractions in different aggregate sizes at all depths compared to W_f and G_f. However, C_f had lower soil water retention at 0-5 cm and 30-35 cm depths, and lower C content at the 0-30 and 60-90 cm depths. The W_f land use had higher carbon content in bulk soil and 1 – 2 aggregate size fractions compared to all other land uses. Moreover, the bulk density in G_f was lowest compared to those of other land uses at the 0-5 cm depth, whereas G_f had higher moisture content under different matric potentials and more of the smaller pores [fine meso pores (0-5 cm and 30-35 cm) and micropores (only at 30-35 cm depth)].

There was an inverse relationship between soil depth and hydraulic conductivity, carbon content of bulk soil and the 1 – 2 mm aggregate fraction, cold-water extractable carbon and dissolved organic carbon of all soil aggregate size fractions, but differences were not always significant. Furthermore, carbon content of the 1 – 2 mm aggregate fraction was positively correlated with hydraulic conductivity and fine-mesopores, whereas carbon content in both bulk soil and 1 – 2 mm aggregate fraction were negatively correlated with pH, bulk density, and cold water extractable carbon. Further, cold water extractable carbon and dissolved organic carbon in different aggregate sizes had a positive correlation with pH, but were negatively correlated with macropores, mesopores, hydraulic conductivity, and carbon content in bulk soil and 1 – 2 mm aggregate fraction.

The multiple linear discriminant analysis showed that all land uses were significantly different from each other when considering all properties studied in this chapter. Eroded fields grouped together where non-eroded wooded (W_f) was the most significantly different to eroded land-uses.

Results show an overall decrease in soil hydraulic properties and carbon content as the intensity of disturbance on soil structure increases, like under agriculture and erosion. However, all fractions of carbon in soils may not follow the same trend of that of total carbon content. Cold water extractable carbon and dissolved organic carbon were higher in soils with more disturbances. Wooded was the land-use that helped build carbon content the most, whereas grassland had better hydraulic properties. These differences might be attributed to different plant tissue carbon turnover rates and root structures.

Changes in soil structure related to carbon and hydraulic properties need to be evaluated for different land-uses in short- and long-term time scales and in real-life conditions, since the impact of soil disturbances can be relatively continuous over large time scales like erosion, or they can occur multiple times a year with possibly short- and long-term implications. Devising studies that incorporate short- and long-term time scales can help reveal the status of soil structure at one point in time and also inform on the re-formation process of soil structure.

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CHAPTER 4

SOIL AGGREGATE RE-FORMATION DYNAMICS AFTER DISTURBANCE

ABSTRACT

Aggregate re-formation after a disturbance is important for maintaining soil hydraulic properties and carbon (C) stabilization. A study investigating the re-formation of aggregates after disturbance by spring tillage was conducted at a site located on a south-facing (6%) slope with a silt-loam soil [Saybrook (Fine-silty, mixed, superactive, mesic Oxyaquic Argiudolls) and Ringwood (Fine-loamy, mixed, superactive, mesic Typic Argiudolls) series association] at the University of Wisconsin-Madison Arlington Agricultural Research Station. Study treatments were conventional tillage (CT) and no-tillage (NT) with (SM) and without (NM) dairy solid manure winter application in a completely randomized design. Soils under NT had a higher proportion of larger aggregates (>1 mm), whereas the proportion of smaller (<1 mm) aggregates were greater under CT. Soil organic carbon (SOC), total nitrogen (TN), bulk density (ρ_b), soil water retention (SWR), and micropores of NT treatments were higher compared to CT systems at 0-5 cm depth during 2018 and 2019. However, the impacts of manure application on soil properties were not significant, except for those of SOC, TN, and electrical conductivity (EC). Harvesting in 2018 decreased the relative proportion of 2-4 mm and 0.5-1 mm aggregates, EC, hydraulic conductivity of saturated soil (K_{sat}), and soil pores. These results indicate that the immediate effects of tillage and harvest are to decrease larger aggregates and reduce total porosity, mainly due to an increase in ρ_b and lower C content. Conversely, aggregates smaller than 2 mm were mainly influenced by the long-term effects of the management operations. It appears that larger soil aggregates can recover on an annual basis but aggregates smaller than 2 mm do not. There is a need to monitor aggregates, including their size distribution and pore

structures, in long term studies to identify aggregate turnover time and rate, which in turn will augment our understanding of aggregate formation and related C stabilization.

INTRODUCTION

Soil are a complex and dynamic system affected by heterogeneity in climate, organisms, topography, parent material, and time. Soil formation is a result of various processes and mechanisms that are interrelated to aggregate formation, stabilization, and disruption. Two main approaches for studying soil aggregation used in the past were (i) the disruption of aggregates by different amounts of energy, and (ii) the formation and stabilization of aggregates (Tisdall, 1996). The turnover of SOM and formation/stabilization of aggregates are tightly linked. The formation of aggregates begins with the availability of organic C (e.g. plant tissue, manure, etc.) as a source of energy for soil microbes. During the decomposition of plant tissues, microorganisms form organic molecules that promote the physical attachment of soil particles. These organic molecules can be binding agents and protected within the aggregates. However, microbial disturbance affects the production of binding agents, thus potentially causing aggregate disruption or de-stabilization. Agricultural practices, such as intensive tillage, can cause disruption of aggregates, interrupt microbial activities, and lead to soil colloid and particle dispersion. However, mechanisms in this aggregate formation model can be different for aggregates of varying sizes (Logan and Kilps, 1995). For instance, mechanisms responsible for microaggregate formation are different than macro aggregate formation because different processes and binding agents are involved (Wagai et al., 2018).

Soil aggregate size distribution and aggregate stability affect the sensitivity of land to erosion and regulate plant-soil water dynamics (Kemper and Chepil, 1965; Tisdall, 1996). One theory explains aggregate structure as micro-aggregates (20–53 μm) bound into macro-aggregates (> 212 μm), in which forces within micro-aggregates are greater than those among micro-aggregates (Edwards and Bremner, 1967). For instance, larger pores are usually between larger aggregates than smaller aggregates (Dexter, 1988). Less stable macro-aggregates can break into micro-aggregates because of water action and other disruptive forces (Emerson and Greenland, 1990). There is some evidence that physically protected organic matter is found mostly in micro-aggregates (Tisdall, 1996). Factors that control the degree of SOM decomposition in different aggregate sizes vary, but the composition of SOM is an important one (Anderson and Paul, 1984). Similarly, Elliott (1986) reported higher mineralization rates of macro-aggregate protected C. Soil tillage management and land-use affect microbial activities through their impacts on pore size distribution and connectivity of pores since these affect the oxygen diffusion rate, water movement and nutrient supply, and hence microbial activities (Dungait et al., 2012) and community structures (Young et al., 2008). Depending on soil texture and environmental factors, micro-aggregates can encapsulate decomposing organic C and physically protect this C from decomposition (Lehmann and Kleber, 2015; Lützow et al., 2006). The role micro-aggregates play in protecting carbon may be different to that of macro-aggregates since microaggregates given their geometry and size might block C decomposition early in the aggregate formation process (Golchin et al., 1997; Rabbi et al., 2016; Sollins et al., 1996).

Soil management practices influence C stabilization and formation of stable aggregates by altering these mechanisms. For example, management practices, such as tillage, can expose SOC that was within aggregates, thus making this C more susceptible to decomposition (Zheng et al., 2018). Mechanisms that can stabilize SOC are (1) physical protection from decomposition through encapsulation in smaller pores, (2) association with silt and clay particles, and (3) biochemical stabilization through the recalcitrant SOM compounds (Six et al., 2002). Soil management practices may also broadly impact SOM dynamics through differences in soil temperature and moisture regimes, the integration of SOM with the soil matrix, and periodic disruption of soil aggregates (Balesdent et al., 2000).

In this study, the physical stabilization of soil C and aggregation over short and long periods of time were investigated. To achieve this goal, the re-formation of aggregates after tillage disruption was studied by examining soil before and after a tillage event. Further, differences in aggregation between long-term no-tillage and conventional tillage were investigated to provide an insight into long-term differences. Additionally, the impact of aggregate disruption and re-formation on soil hydraulic properties and different soil C fractions at different scales (macro, meso, and micro) was investigated. The hypotheses underlying this work are:

I. Soil aggregate disturbance by tillage primarily reduces the proportion of macro-aggregates (>2-mm).
II. The hydraulic conductivity of saturated soil is proportionally related to aggregate size.
III. Meso- and micro- aggregates (53–212 and 20–53 µm, respectively) reform faster than macro- aggregates after disturbance by tillage.

The objectives for this work were to 1) compare the impact of tillage on soil aggregate size distribution, hydraulic properties, and SOC, 2) evaluate the re-formation of aggregates after tillage during a growing season, and 3) determine the dynamics of SOC during the aggregate re-formation process.

MATERIALS AND METHODS

Experimental Site and Site Description

The experimental site was located at the University of Wisconsin-Madison Arlington Agricultural Research Station (43° 17' 55.8" N 89° 21' 54.5" W). Before the current experiment, the field was under alfalfa production for four years. Since 2015, the site was planted in continuous corn for silage with a 76-cm row spacing. The study site was on a south-facing slope

(6%) and silt-loam soil [Saybrook (Fine-silty, mixed, superactive, mesic Oxyaquic Argiudolls) and Ringwood (Fine-loamy, mixed, superactive, mesic Typic Argiudolls) series association]. The elevation was 319 m with a humid continental climate having relatively humid summers and cold, snowy winters. The mean annual air temperature in the winter was -14.6 °C and 25.7 °C in the summer, and the mean annual precipitation was 870 mm from 2015 to 2018. This study was conducted in conjunction with another study initiated in the fall of 2014 to investigate the effect of tillage on runoff from dairy manure application during the winter (Stock, 2018).

Study Treatments

Treatments include (i) conventional tillage with solid manure application (CTSM), (ii) conventional tillage with no manure (CTNM), (iii) no-tillage with solid manure application (NTSM), and (iv) no-tillage with no manure (NTNM). The CT treatment consists of a chisel plow in the fall, and a soil finisher in the spring, with tillage passes done perpendicular to the slope. Plots were arranged in pairs according to tillage to facilitate field operations and manure applications were randomized within pairs. For the SM treatment, solid dairy manure was applied fresh manually each year in January at a rate of 2.2-ton ha^{-1} on a dry basis onto frozen and/or snow-covered ground. Treatments were replicated three times. Each plot was 4.6 m wide by 15.2 m long.

Soil Sampling and Processing

Two sets of intact soil core samples were collected from two depths and four times during the growing seasons of 2018 (after spring tillage before planting, during the growing season, before harvest, and after harvest) and 2019 (before spring tillage, after spring tillage before planting, during the growing season, and before harvest). The first set of samples was conducted by using stainless steel rings (5 cm height and 8 cm diameter) from 0-5 and 15-20 cm soil depths to examine soil water release (SWR), hydraulic conductivity of saturated soil (K_{sat}), bulk density (ρ_b), and pore size distribution. The second set of undisturbed core samples was collected using 7.5 cm diameter by 15 cm long plastic cores from 0-15 and 15-30 cm soil depths. Samples from plastic cores were divided vertically into two sub-samples in the laboratory. One subsample was used for dry aggregate fractionation, and the second subsample was ground to pass through a 2-mm sieve for other analyses (soil pH, electrical conductivity, soil organic C, and total nitrogen).

Sample Analysis

Aggregate Size Distribution

The dry-sieve procedure was performed to determine the aggregate size distribution (Nimmo and Perkins, 2002). The first half of the intact (undisturbed) core samples (air dried soil samples) were dropped from 1 meter to disperse the physical body of aggregated soil equally. Aggregates within a sample were physically dispersed by a similar force since the same mass of soil was dropped from the same height. The resulting separated aggregates were then transferred to a mechanical shaker device and sieved for 30 seconds through a nest of sieves. The square openings for each sieve had diameters of 4 mm, 2 mm, 1 mm, 0.5 mm, 0.25 mm, 0.053 mm, respectively. Therefore, the aggregates from this procedure were divided in six fractions, <0.053 mm, 0.053-0.25 mm, 0.25-0.5 mm, 0.5-1 mm, 1-2 mm, and 2-4 mm. The mass of each sieved aggregate size fraction was used to determine the percentage of each aggregate fraction relative to that of the total soil-sample mass.

Soil Carbon Content, Nitrogen Content, and Carbon and Nitrogen Ratio

For total soil C and N contents, a portion of soil was taken from the ground and 2 mm sieved soil subsample. This portion of soil samples were fine powdered using a handheld coffee grinder, and 8-10 mg were packed into tin capsules for TC and TN analysis by dry combustion. A Flash EA 1112CN Automatic Elemental Analyzer (Thermo Fisher Scientific, Whatman, MA) was used to determine C and N contents. The SOC was assumed to be equal to total C because soil inorganic C is insignificant in these soils since soil pH is relatively low (Paul et al., 2001). The C and N ratio (C: N) was calculated using the result of SOC and the N contents.

Soil pH and Electrical Conductivity

Soil pH and EC for 0-15 cm and 15-30 cm depth were determined in a mixture of 1:1 (pH) and 1:2 (EC) soil (air-dried, grinded and 2 mm sieved) and deionized water using an Orion Star pH / EC meter (Thermo Fisher Scientific, Whatman, MA).

Hydraulic Conductivity of Saturated Soil

For K_{sat} measurements, the 0-5 and 15-20 cm soil cores were saturated with tap water by capillarity for a duration ranging from 24 hours to 48 hours until a sheen of water was seen on the soil surface. The K_{sat} was measured with a constant head (5 cm) approach using a K_{sat} instrument (Meter Group Inc., Pullman, WA).

Soil Water Retention and Pore Size Distribution

The SWR analysis for 0-15 cm and 15-30 cm depths were processed using the same cores after K_{sat} analysis. A nylon fabric cloth was placed at the bottom of each ring, and then these rings were saturated again with tap water by capillarity for another 24 hours to 48 hours. The

SWR was tested using 0, -2.5, -5, -10, -15, -20, -30, -50, -100, -200, -300, and -500 kPa matric potentials with a tension table and a pressure plate apparatus (Klute and Dirksen, 1986). Soil water content was determined gravimetrically after oven drying the soil samples at 105 °C. The volumetric water content was then calculated by multiplying the gravimetric water content by the ρ_b divided by the density of water (1,000 kg m^{-3}). The soil pore size distribution was calculated using the capillary rise equation to determine the effective pore size diameter (Jury et al., 1991) from the SWR data and classified as macro- (>1000 μm), coarse meso- (60-1000 μm), fine meso- (10-60 μm), and micro-pores (<10 μm).

Soil Bulk Density

The bulk density of soil (ρb) was determined using the core method (Grossman and Reinsch, 2002) for the 0-5 cm and 15-20 cm soil depths, using the stainless-steel ring samples after K_{sat} and SWR measurements.

Statistical Analysis

The aggregate size distribution, pH, EC, ρ_b, K_{sat}, SWR, and pore size distribution were evaluated at different depths, different tillage and manure application combinations (CTNM, CTSM, NTNM, and NTSM), and different sampling times. The SOC, TN content, and C: N of soil under different tillage and manure application combinations (CTNM, CTSM, NTNM, and NTSM) from the samples collected during the growing season of 2018 were compared. Soil aggregate size distribution, pH, EC, SOC, TN content, and C:N analysis were performed for two different soil depths 0-15 cm and 15-30 cm, while ρ_b, K_{sat}, SWR, and pore size distribution were analyzed at 0-5 cm and 15-20 cm. An analysis of variance and a Duncan multiple range test analysis in R software was used to determine the impacts of different (i) treatments, (ii) depths, and (iii) time on variables of interest. Differences between treatment means are denoted with different letters when there were statistically significant differences at the significance level of $\alpha = 0.05$.

RESULTS

Aggregate Size Distribution

Aggregate size distribution results showed that soils of this study in general have greater proportion of 2-4 aggregates where decreasing in size of aggregates followed by decreasing in the proportion of these aggregate sizes as shown on Figure 1.a and Figure 1.b. The relative mass of 2-4 mm and 1-2 mm aggregates was greater for NT treatments compared to those under CT. Manure had no impact on these aggregate sizes for 0-15 cm depth for all sampling times in 2018 and 2019. The proportion of 2-4 mm aggregates were lower after spring tillage before planting compared to those of during growing season. The only significant differences between treatments at 0 -15 cm depth were observed for the during growing season sampling in 2018, where NTSM had a greater proportion of 1-2 mm aggregates compared to that of NTNM, CTNM, and CTSM by 6.6%, 13.7%, and 14.7%, respectively. At 15-30 cm depth (Figure 1.b), neither tillage nor manure application showed significant impacts on the relative mass of 1-2 mm and 2-4 mm aggregates (Appendix-c, Tables S1-S6). Relative mass of 1-2 and 2-4 mm aggregates were significantly greater at 15-30 cm than at 0-15 cm for almost all timepoints, except there were no significant differences for 2-4 mm aggregates at before harvest of 2018 and after tillage of 2019, and 1-2 mm aggregates after spring tillage before planting of 2018. The 0-15 cm depth had significantly lower 2-4 mm aggregates compared to those of 15-30 cm depth.

Further, the relative mass of 2-4 mm aggregates increased in 2018 from spring after tillage before planting and to the time before harvest at both depths (Table 2), while the proportion of 1-2 mm aggregates decreased.

The proportion of aggregates between 0.5-1 mm size at 0-15 cm depth ranged from 15.1% to 22.5% between treatments, but differences were not significant in any treatments in 2018. Similarly, there were no significant differences in 0.5-1 mm aggregates at 15-30 cm depth in both 2018 and 2019. However, at 0-15 cm depth in 2019, CT significantly increased the relative mass of 0.5-1 mm aggregates compared to NT treatments. Further, the relative mass of 0.053-0.25 mm and 0.25-0.5 mm aggregates at 0-15 cm depth were significantly greater with CT compared to NT.

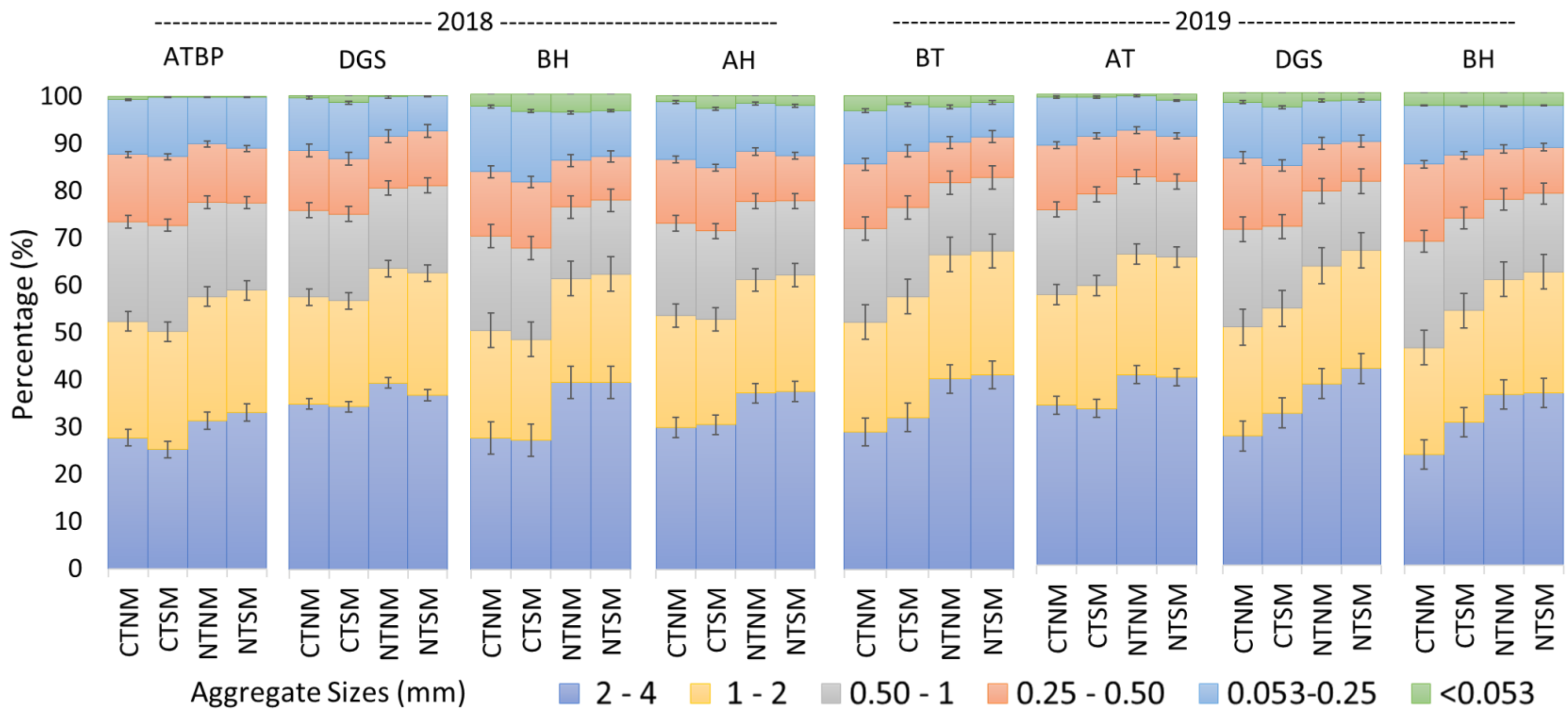

Figure 1.a. Aggregate size distribution at 0-15 cm soil depth as affected by tillage and manure applications for different soil sampling times in 2018 and 2019. CTNM, chisel tillage no manure application; CTSM, chisel tillage with manure application; NTNM, no-till with no manure application; NTSM, no-till with manure application; ATBP, after tillage before planting; BT, before tillage; AT, after tillage; DGS, during growing season; BH, before harvest; AH, after harvest.

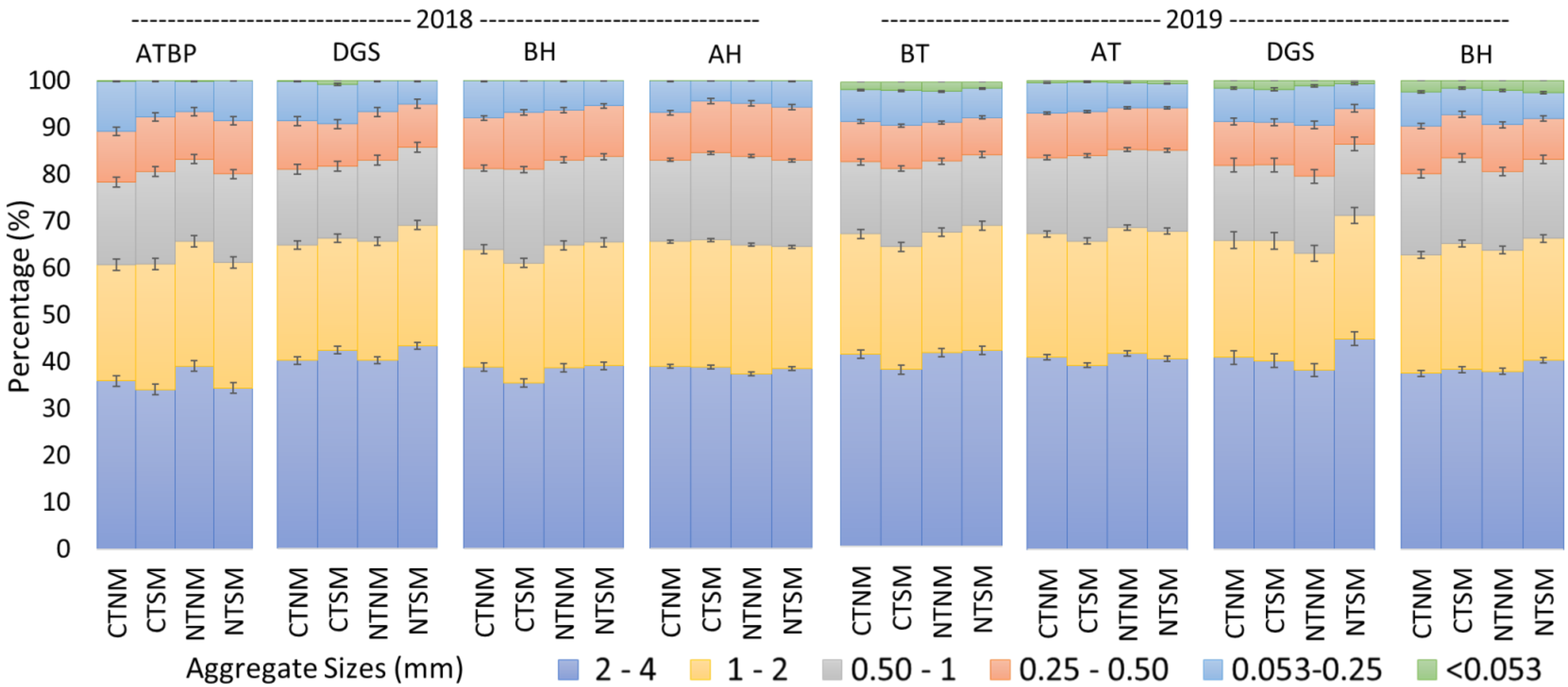

Figure 1.b. Aggregate size distribution at 15-30 cm soil depth as affected by tillage and manure applications for different soil sampling times in 2018 and 2019. CTNM, chisel tillage no manure application; CTSM, chisel tillage with manure application; NTNM, no-till with no manure application; NTSM, no-till with manure application; ATBP, after tillage before planting; BT, before tillage; AT, after tillage; DGS, during growing season; BH, before harvest; AH, after harvest.

The greatest relative mass of 0.053-0.25 mm aggregates was higher with CT systems compared to those of NT plots by 51% for 0-15 cm depth sampled during the 2018 growing season. In addition, the only significant difference for aggregates smaller than 0.053 mm for 0-15 cm and 15-30 cm depths at any sampling time were noted for the 15-30 cm depth during the 2018 growing season sampling where CTSM had a significantly greater (P = 0.01) proportion of these aggregates. Generally, samples from deeper in the soil profile had less of the aggregates smaller than 1 mm.

Overall, aggregate size distribution results show that the aggregate size range over the sampling period varied mainly by tillage. No-tillage resulted in a higher proportion of larger aggregates. Manure application had no effects on aggregate size distribution at any sampling timings in either 2018 or 2019. Soil depth significantly influenced aggregate size distribution, where the upper soil depth studied had a higher relative mass of aggregates smaller than 1 mm, while soil from deeper in the profile had a greater proportion of larger (1< mm) aggregates.

Carbon and Nitrogen Contents and Carbon-Nitrogen Ratio

The SOC under CTNM was significantly (P=0.01) lower than CTSM, NTNM, and NTSM by 19%, 16%, and 23%, respectively, at 0-15 cm depth during growing season of 2018 (Figure 2). There were no significant differences in SOC for the 15-30 cm depth (not shown). Similar trends were observed for TN content at both depths – decreased N in CTNM for 0-15 cm, and no differences across treatments for 15-30 cm. Further, these differences did not translate to differences in C:N ratio between treatments. The data indicate that manure application increased SOC and N contents a 0-15 cm depth when CT was used, but it did not make a difference with NT. However, these differences were only observed for the upper soil layer studied.

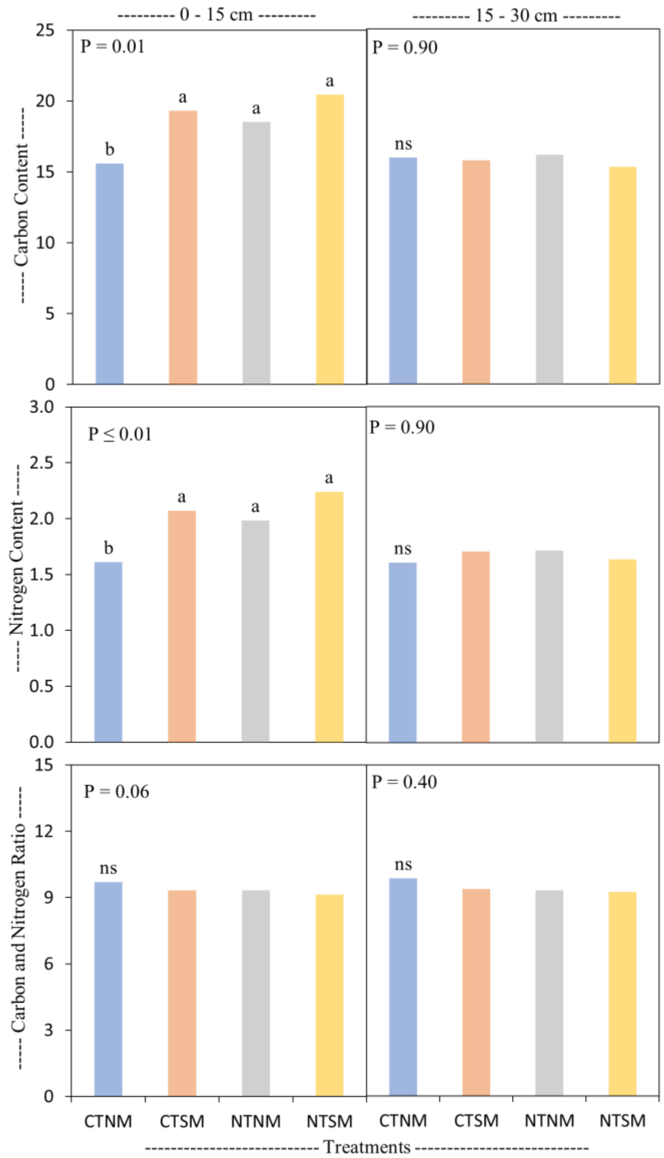

Figure 2. Soil organic carbon (g kg $^{-1}$), nitrogen (g kg $^{-1}$), and carbon and nitrogen ratio of 0 – 15 and 15 – 30 cm soil depth for tillage and manure application treatments for samples collected during the growing season of 2018. CTNM, chisel tillage no manure application; CTSM, chisel tillage with manure application; NTNM, no-till with no manure application; NTSM, no-till with manure application.

Soil pH and Electrical Conductivity

Soil pH at 0-15 cm depth, ranged from 7.0 under NTSM before harvest of 2018 to 7.6 under CTNM before harvest of 2019 (Figure 3). The trends in pH values varied depending on depth, sampling time and year, but overall, NT treatments tended to have lower pH values than CT, especially for the 0-15 cm depth. There were some timepoints for which there were no significant differences in pH. It appears that pH was not an important factor since there were small differences which might be likely due to the management nature of these agroecosystems.

Soil EC did not vary much between treatments, with only three sampling timings having significant differences between treatments of the eight total times sampled (Figure 4). Soil EC was higher with CTSM in 2018 before harvest at 0 -15 cm depth compared to CTNM and NTSM, but it was no different to NTNM. During this same sampling time, CT treatments had significantly greater EC than the NT ones at 15-30 cm depth. In 2019, differences in EC before harvest for 0-15 cm depth were slightly different than 2018, in which NTSM had the highest EC value compared to CTNM and CTSM, but there was no difference between NTNM and NTSM. Both NT treatments had significantly greater EC than CTNM and CTSM after harvest for 0-15 cm depth. There was no general EC trend in the 15-30 cm depth in 2019, with CTNM and NTNM having greater EC values. Annual differences and management aspects probably had an overriding effect on EC values.

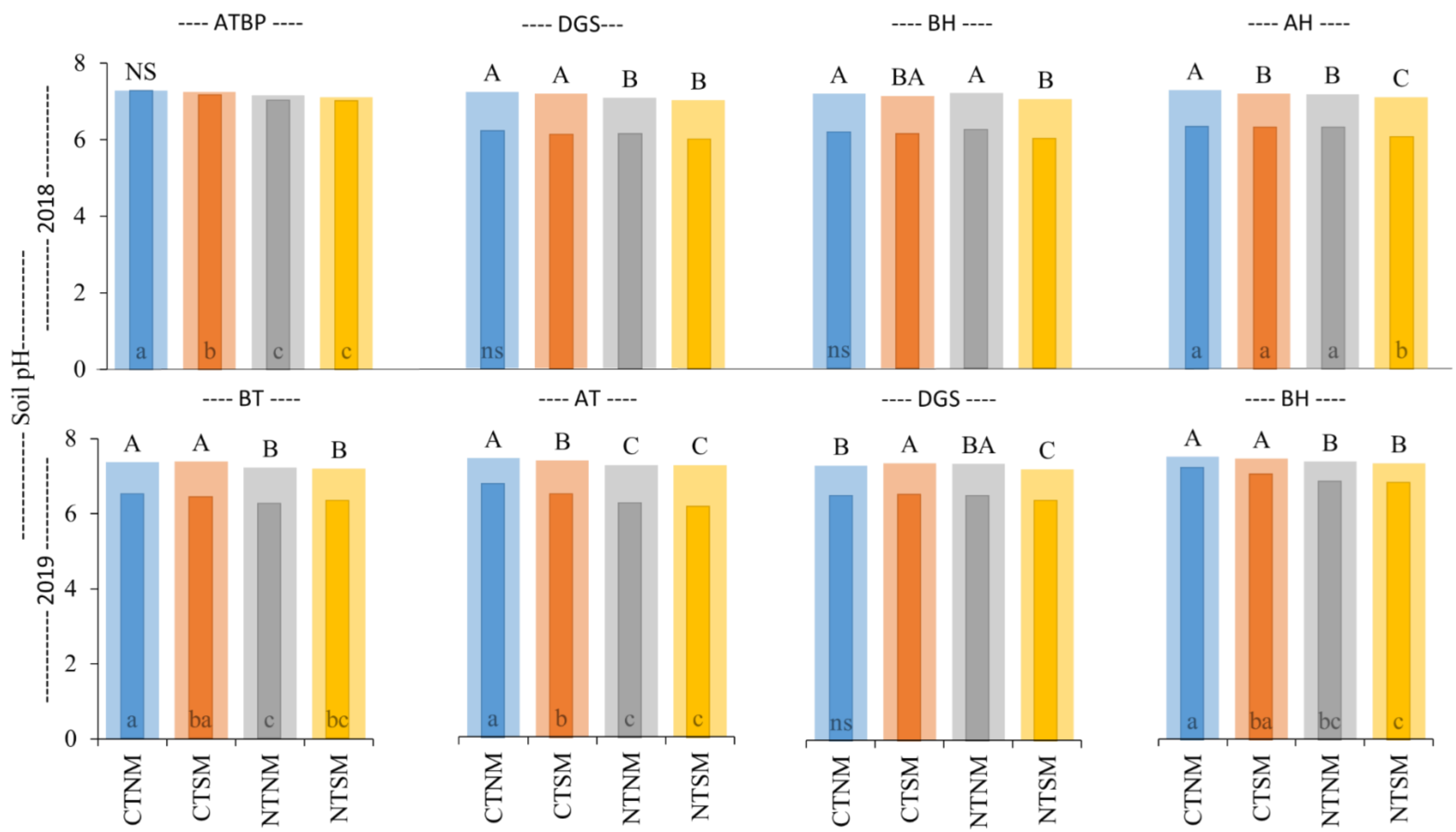

Figure 3. Soil pH of 0 – 15 and 15 – 30 cm soil depth for two tillage and manure application treatments at different soil sampling times in 2018 (spring, summer, before harvest, and after harvest), and 2019 (before tillage, after tillage, summer, and harvest). CTNM, chisel tillage no manure application; CTSM, chisel tillage with manure application; NTNM, no-till with no manure application; NTSM, no-till with manure application. ns, no significant difference; ATBP, after tillage before planting; BT, before tillage; AT, after tillage; DGS, during growing season; BH, before harvest; AH, after harvest. Lighter colored and thicker columns represent 0 – 15 cm where darker colored thinner columns represent 15 – 30 cm soil depth. Different letters denote statistical differences between means of the treatments at alpha = 0.05 with uppercase letters representing 0-15 cm depth and lowercase letter representing 15-30 cm.

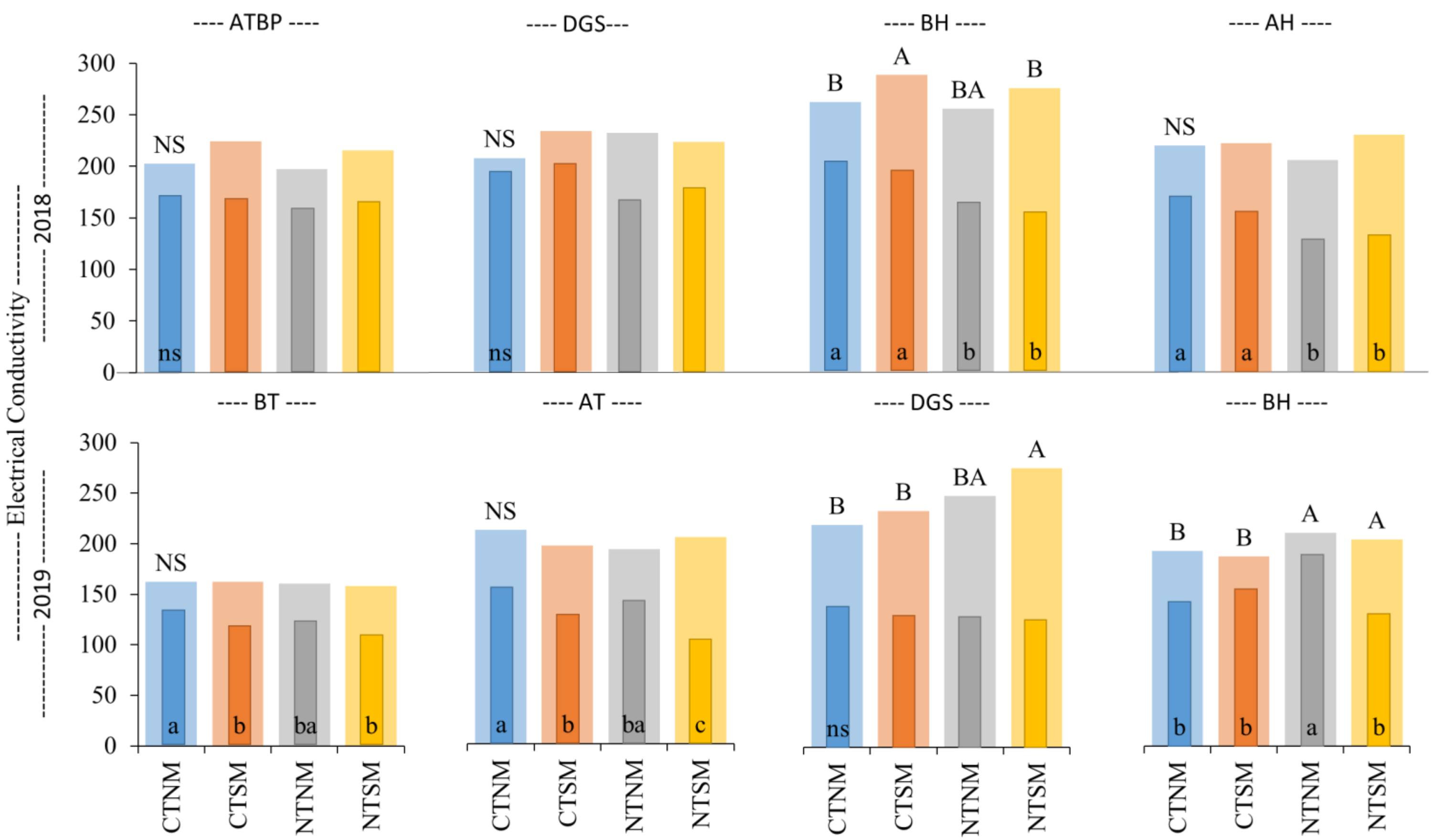

Figure 4. Soil electrical conductivity (µS cm -1) of 0 – 15 and 15 – 30 cm soil depth for two tillage and manure application treatments at different soil sampling times in 2018 (spring, summer, before harvest, and after harvest), and 2019 (before tillage, after tillage, summer, and harvest). CTNM, chisel tillage no manure application; CTSM, chisel tillage with manure application; NTNM, no-till with no manure application; NTSM, no-till with manure application. ns, no significant difference; ATBP, after tillage before planting; BT, before tillage; AT, after tillage; DGS, during growing season; BH, before harvest; AH, after harvest. Lighter colored and thicker columns represent 0 – 15 cm where darker colored thinner columns represent 15 – 30 cm soil depth. Different letters denote statistical difference between means of the treatments at alpha = 0.05 with uppercase letters representing 0-15 cm depth and lowercase letters representing 15-30 cm depth.

Soil Bulk Density and Hydraulic Conductivity

The soil ρ_b was similar across treatments during most of this study, with 12 of the 16 sampling dates x depth combinations having no significant differences (Figure 5a and 5b). No tillage had significantly greater ρ_b values at 0-5 cm in 2018 before planting, but there was no difference in ρ_b when treatments were sampled again during the growing season (Figure 5a). However, before harvest ρ_b was greatest for NTNM, which was no different to CTSM and NTSM. Bulk density for CTNM was statistically similar to those of CTSM and NTSM. There were no differences in ρ_b after harvest in 2018. At the 15-20 cm depth in 2018, the only significant differences were observed in the after-harvest sampling with CTNM having greater ρ_b relative to CTSM, but it was similar to NTNM and NTSM. In 2019, the only significant difference in ρ_b was detected at 0-5 cm depth for the during growing season sampling in which NTNM and NTSM had greater ρ_b than CTSM but similar to CTNM.

K_{sat} at 0-15 and 15-30 cm depth was not significantly different across treatments for all timings of sampling in 2018 and 2019, with the exception of those at the 15-20 cm depth after spring tillage before planting of 2018 (Figure 6). The K_{sat} of CTSM was greater than NTNM and NTSM, but not different to CTNM for the before planting time in 2018. However, there were no differences in K_{sat} between CTNM, NTNM and NTSM. The values of K_{sat} were similar between depths.

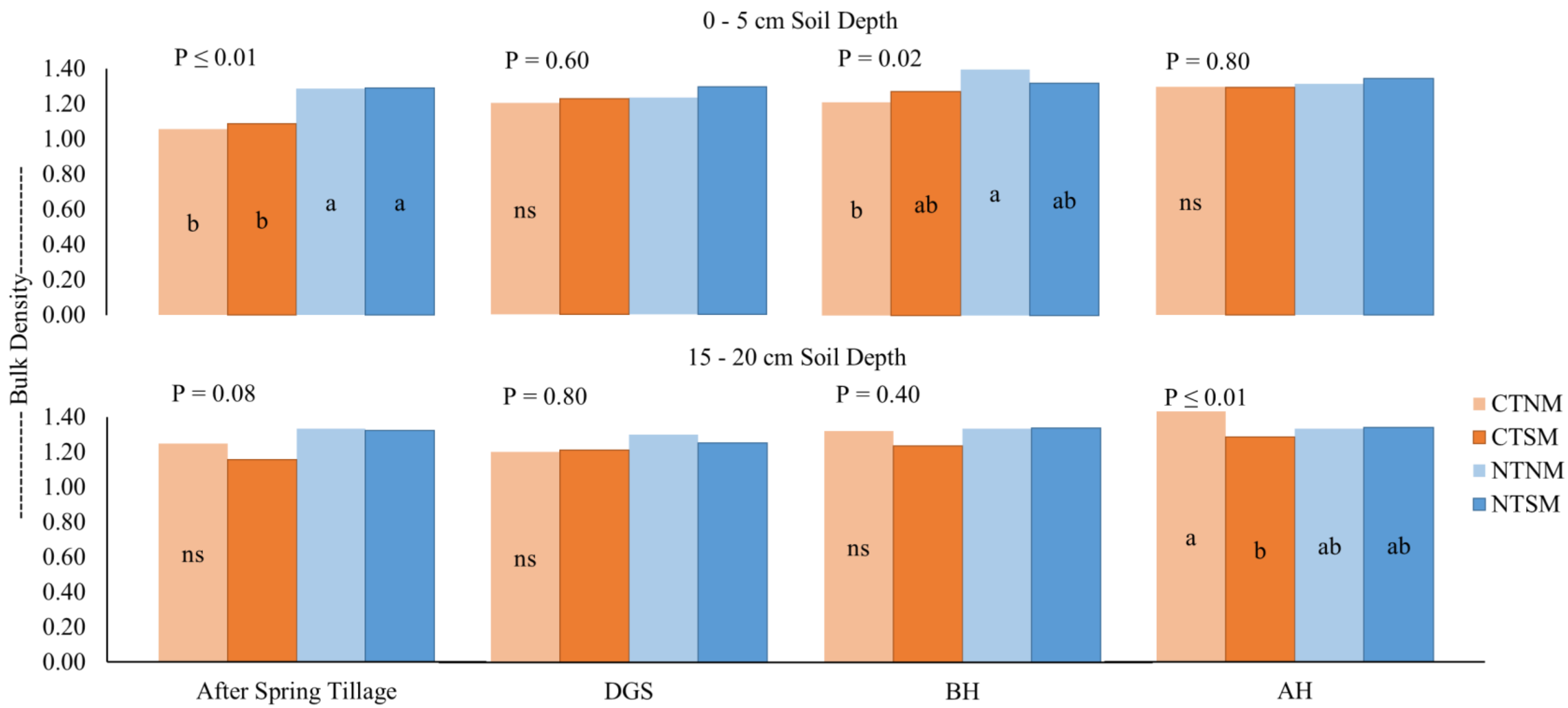

Figure 5.a. Soil bulk density (gr cm $^{-3}$) of 0-5 and 15-20 cm soil depth for two tillage and manure application treatments at different soil sampling times of spring, summer, before harvest, and after harvest in 2018. CTNM, chisel tillage no manure application; CTSM, chisel tillage with manure application; NTNM, no-till with no manure application; NTSM, no-till with manure application; ATBP, after tillage before planting; DGS, during growing season; BH, before harvest; AH, after harvest.

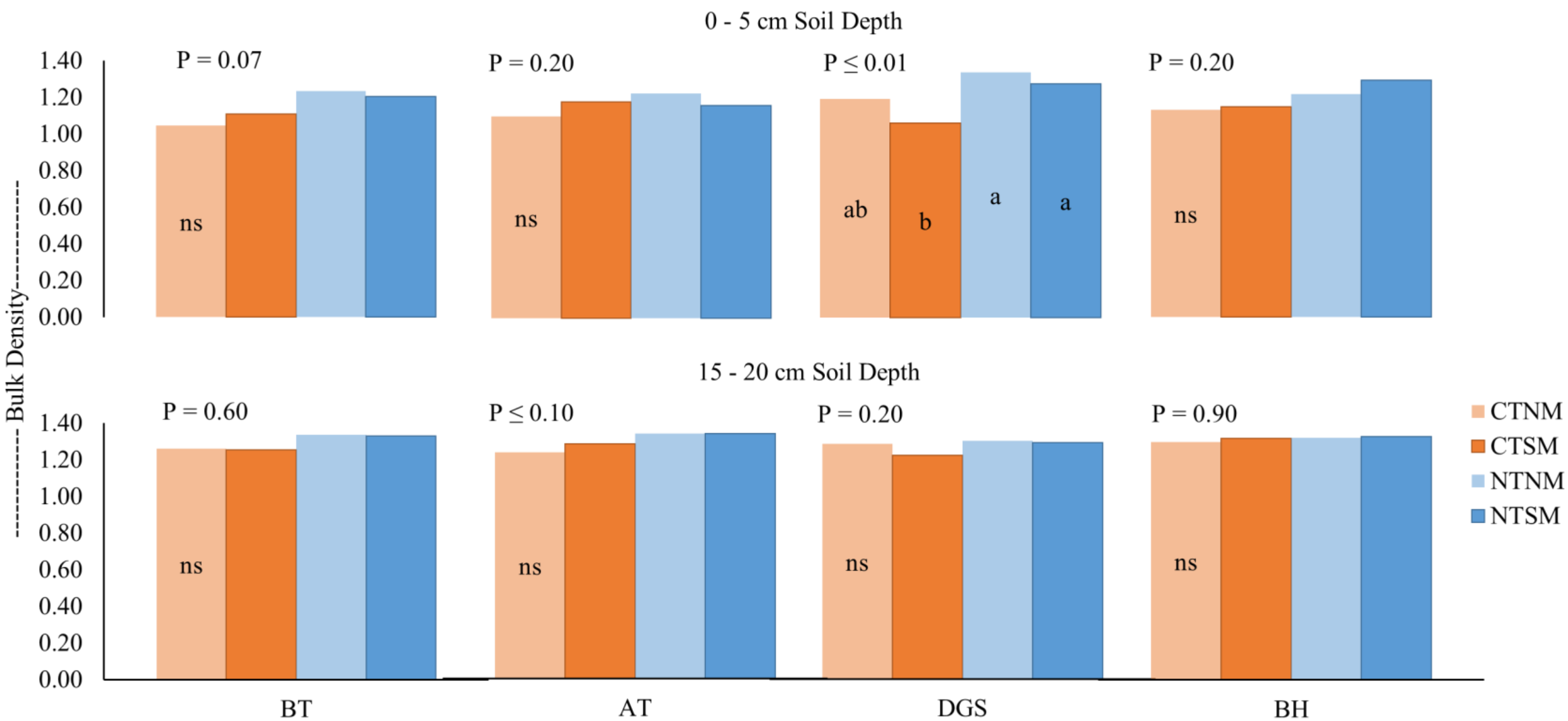

Figure 5.b. Soil bulk density (gr cm $^{-3}$) of 0-5 and 15-20 cm soil depth for two tillage and manure application treatments at different soil sampling times of before tillage, after tillage, summer, and harvest in 2019. CTNM, chisel tillage no manure application; CTSM, chisel tillage with manure application; NTNM, no-till with no manure application; NTSM, no-till with manure application; BT, before tillage; AT, after tillage; DGS, during growing season; BH, before harvest.

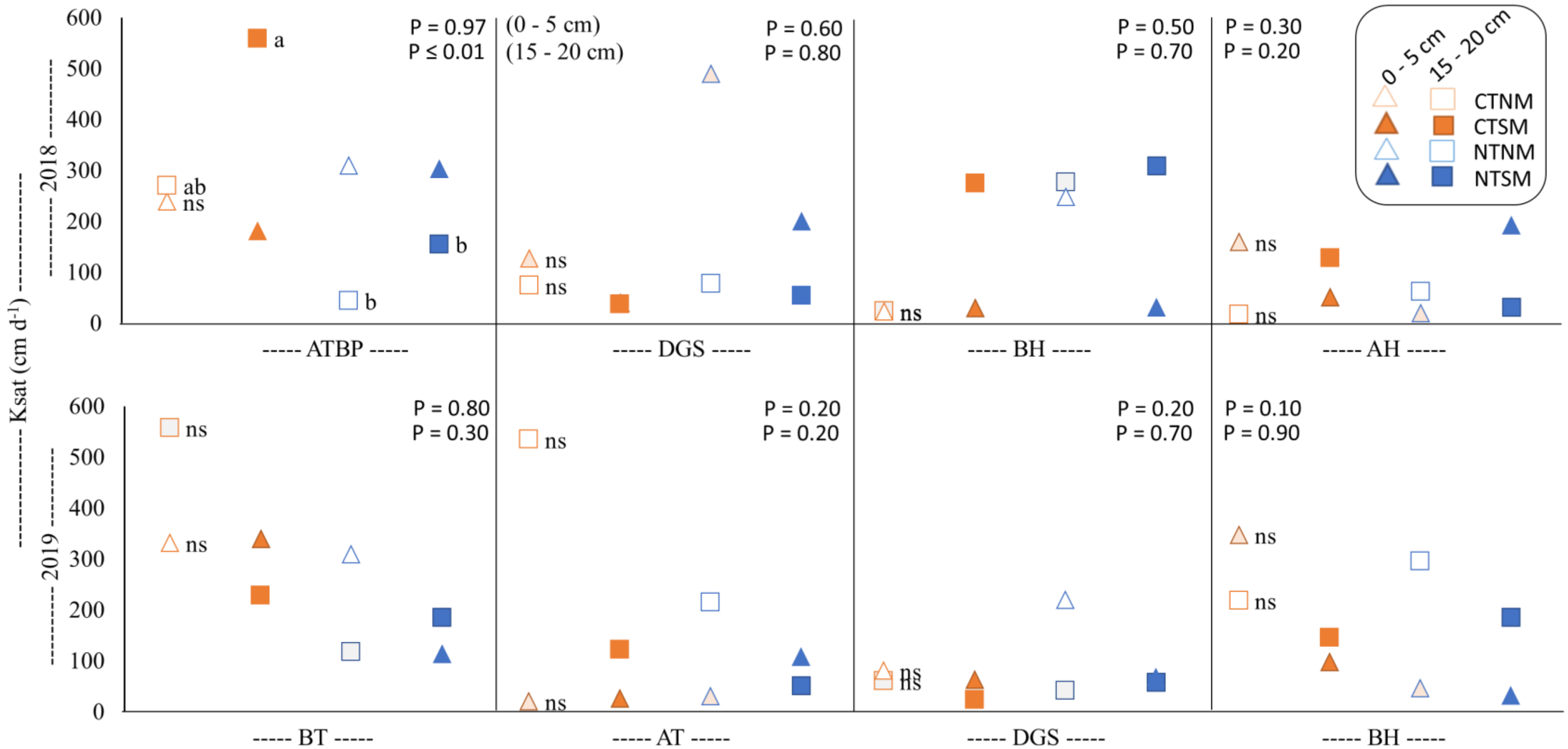

Figure 6. Soil hydraulic conductivity (cm d^{-1}) of 0-5 and 15-20 cm soil depths for two tillage and manure application treatments at different soil sampling times in 2018 (spring, summer, before harvest, and after harvest), and 2019 (before tillage, after tillage, summer, and harvest). CTNM, chisel tillage no manure application; CTSM, chisel tillage with manure application; NTNM, no-till with no manure application; NTSM, no-till with manure application; ATBP, after tillage before planting; BT, before tillage; AT, after tillage; DGS, during growing season; BH, before harvest; AH, after harvest.

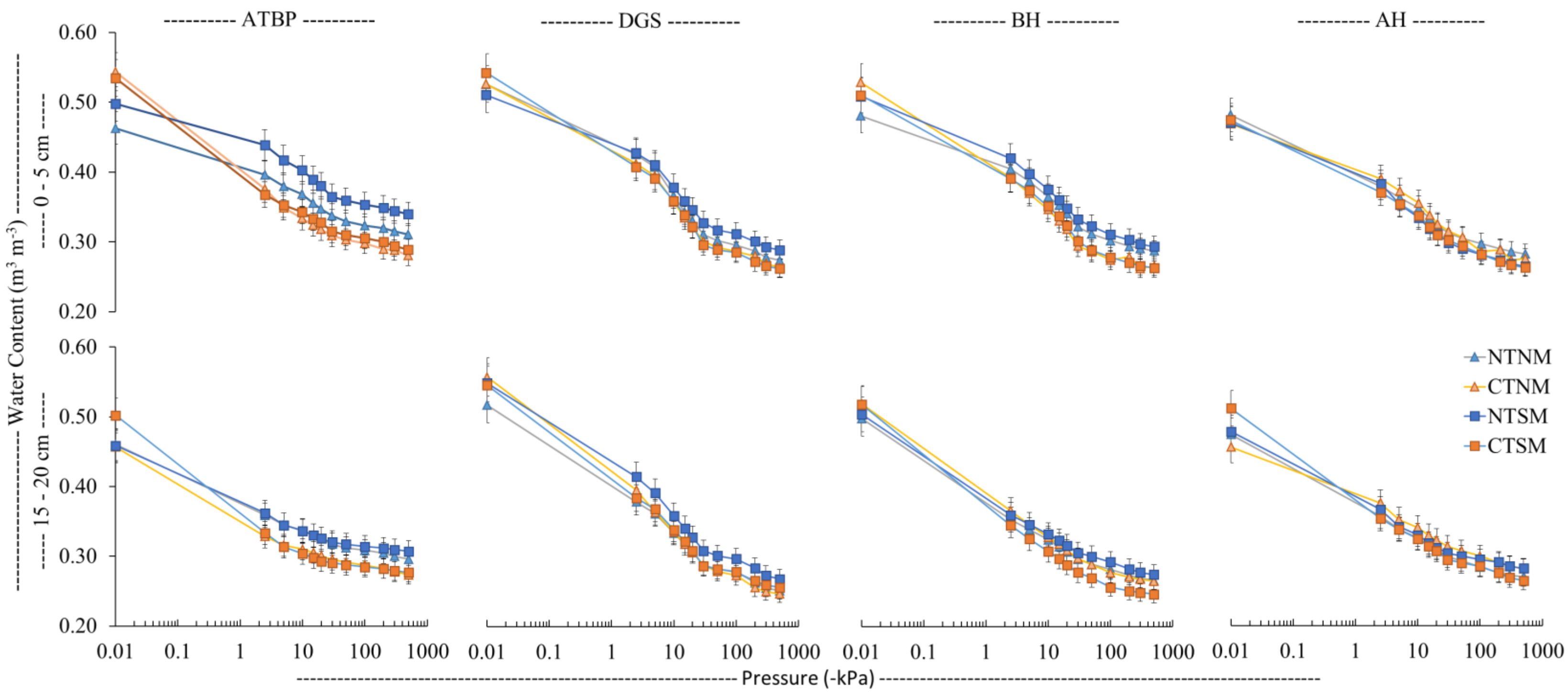

Figure 7.a. Soil water content for different matric potentials of 0-5 and 15-20 cm soil depths for two tillage and manure application treatments at different soil sampling times of spring, summer, before harvest, and after harvest in 2018. CTNM, chisel tillage no manure application; CTSM, chisel tillage with manure application; NTNM, no-till with no manure application; NTSM, no-till with manure application; ATBP, after tillage before planting; DGS, during growing season; BH, before harvest; AH, after harvest.

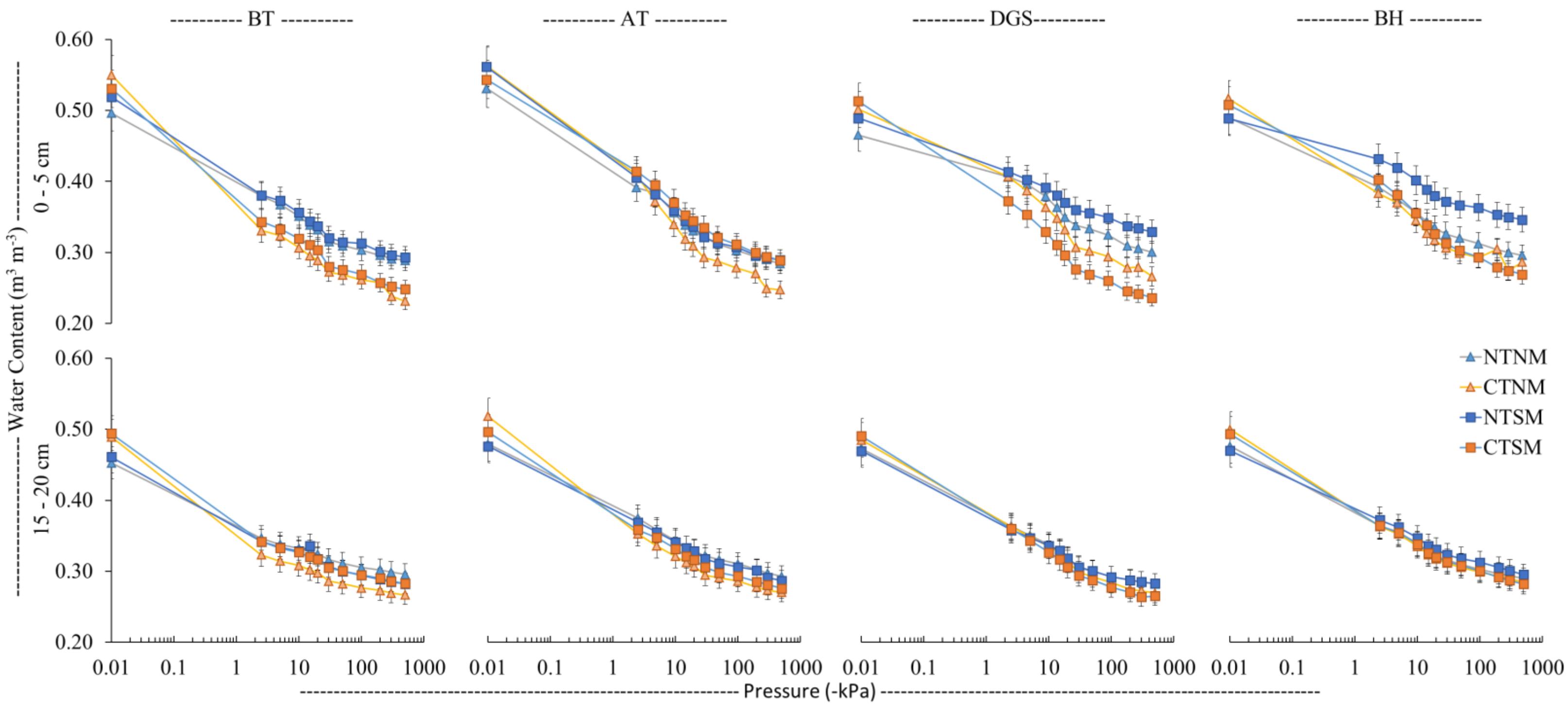

Figure 7.b. Soil water content under different matric potentials of 0-5 and 15-20 cm soil depths under impacts of tillage and manure applications at soil sampling times of before tillage, after tillage, summer, and harvest in 2019. CTNM, chisel tillage no manure application; CTSM, chisel tillage with manure application; NTNM, no-till with no manure application; NTSM, no-till with manure application; BT, before tillage; AT, after tillage; DGS, during growing season; BH, before harvest.

Soil Water Retention

The SWR was affected by tillage and manure treatment combinations as well as sampling time (Figure 7.a and 7.b). In general, differences were more marked in 2019 than 2018. In 2018, the soil water content at saturation was typically greater for CT treatments, but as the matric potential increased, the NT treatments had greater soil water content values. This implies that the pore space of CT was larger and quickly drained as the matric potential increased. A similar trend was observed in 2019 (Figure 7.b). Differences in treatments were more pronounced in the surface depth than at 15-20 cm.

Pore Size Distribution

Differences in pore size distribution across the pore sizes studied were minor. Soil macropores were not significantly different except at 0-5 cm depth before planting and 15-20 cm after harvest in 2018, before spring tillage in 2019, and during the 2019 growing season (Table 1.a). At 0-5 cm depth before planting in 2018, CTNM and CTSM had more macropore volume than NTNM and NTSM by 2.5 times and 2.8 times, respectively. A similar trend was observed for 0-5 cm depth before tillage in 2019 where CTNM had greater macro-porosity than NTNM and NTSM. However, within the growing season, CTNM had statistically the same macro-porosity as all other treatments and CTSM had greater values than NTNM and NTSM. The only statistically significant difference in macropore volume at 15-20 cm depth in 2018 was for the after-harvest sampling where CTNM had greater values relative to CTSM but similar to NTNM and NTSM.

Overall, coarse and fine mesopore volumes under different treatments were not significantly different, with the exception of 0-5 cm coarse mesopores after harvest in 2018 and coarse and fine mesopores within the 2019 growing season sampling time (Table 1.b and 1.c). Coarse mesopores at 0-5 cm depth after harvest in 2018 were higher in NTSM compared to those of CTNM, NTNM, and CTSM by 76.5%, 87.5%, and 87.5%. Coarse and fine mesopore volumes at 0-5 cm depth during the 2019 growing season were greater for CTNM and CTSM compared to

NTNM and NTSM, and further, fine mesopores were lowest for NTSM compared to NTNM.

Table 1.a. Soil macropores ($m^3 m^{-3}$) of 0-5 and 15-20 cm soil depths for two tillage and manure managements for different sampling times in 2018 and 2019.

Treatment	------------------ 2018 ------------------				------------------ 2019 ------------------			
	ATBP	DGS	BH	AH	BT	AT	DGS	BH
				---- 0 - 5 cm ----				
CTNM†	0.168^{a††}	0.114^{ns}	0.137^{ns}	0.079^{ns}	0.219^{a}	0.153^{ns}	0.095^{ab}	0.134^{ns}
CTSM	0.167^{a}	0.134	0.120	0.104	0.188^{ab}	0.129	0.140^{a}	0.106
NTNM	0.067^{b}	0.100	0.076	0.103	0.117^{b}	0.140	0.059^{b}	0.099
NTSM	0.059^{b}	0.082	0.089	0.087	0.138^{b}	0.156	0.076^{b}	0.057
				---- 15 - 20 cm ----				
CTNM	0.128^{ns}	0.161^{ns}	0.153^{ns}	0.180^{a}	0.166^{ns}	0.165^{ns}	0.122^{ns}	0.137^{ns}
CTSM	0.169	0.161	0.173	0.158^{b}	0.152	0.138	0.131	0.129
NTNM	0.101	0.138	0.145	0.117^{ab}	0.106	0.104	0.109	0.112
NTSM	0.097	0.133	0.145	0.112^{ab}	0.119	0.107	0.111	0.098
				Analysis of Variance				
Treatment (0 -15 cm)	≤ 0.01	0.50	0.06	0.80	0.03	0.80	0.02	0.20
Treatment (15 -30 cm)	0.20	0.90	0.70	0.03	0.40	0.08	0.50	0.40
Depth	0.70	0.03	≤ 0.01	0.10	0.20	0.30	0.04	0.20

†CTNM, chisel tillage no manure application; CTSM, chisel tillage with manure application; NTNM, no-till with no manure application; NTSM, no-till with manure application; ATBP, after tillage before planting; BT, before tillage; AT, after tillage; DGS, during growing season; BH, before harvest; AH, after harvest. ††Means within the same column, followed by different superscript letters are significantly different at α= 0.05.

Table 1.b. Soil coarse mesopores ($m^3 m^{-3}$) of 0-5 and 15-20 cm soil depths for two tillage and manure managements for different sampling times in 2018 and 2019.

Treatment	------------------ 2018 ------------------				------------------ 2019 ------------------			
	ATBP	DGS	BH	AH	BT	AT	DGS	BH
				---- 0 - 5 cm ----				
CTNM†	0.027[ns]††	0.018[ns]	0.022[ns]	0.017[b]	0.007[ns]	0.038[ns]	0.020[a]	0.013[ns]
CTSM	0.015	0.016	0.017	0.016[b]	0.010	0.019	0.019[a]	0.021
NTNM	0.016	0.018	0.018	0.016[b]	0.012	0.007	0.011[b]	0.016
NTSM	0.021	0.017	0.022	0.030[a]	0.008	0.023	0.011[b]	0.012
				---- 15 - 20 cm ----				
CTNM	0.013[ns]	0.031[ns]	0.020[ns]	0.025[ns]	0.009[ns]	0.017[ns]	0.014[ns]	0.010[ns]
CTSM	0.020	0.016	0.020	0.016	0.009	0.011	0.016	0.010
NTNM	0.014	0.016	0.015	0.019	0.009	0.017	0.013	0.009
NTSM	0.017	0.023	0.013	0.024	0.008	0.014	0.011	0.010
				Analysis of Variance				
Treatment (0 -15 cm)	0.20	0.97	0.60	≤ 0.01	0.80	0.40	≤ 0.01	0.30
Treatment (15 -30 cm)	0.40	0.06	0.40	0.50	0.80	0.80	0.03	0.70
Depth	0.20	0.10	≤ 0.01	0.70	0.70	0.30	0.30	≤ 0.01

†CTNM, chisel tillage no manure application; CTSM, chisel tillage with manure application; NTNM, no-till with no manure application; NTSM, no-till with manure application; ATBP, after tillage before planting; BT, before tillage; AT, after tillage; DGS, during growing season; BH, before harvest; AH, after harvest. ††Means within the same column, followed by different superscript letters are significantly different at α= 0.05.

Table 1.c. Soil fine-mesopores ($m^3 m^{-3}$) of 0-5 and 15-20 cm soil depths for two tillage and manure managements for different sampling times in 2018 and 2019.

Treatment	------------------ 2018 ------------------				------------------ 2019 ------------------			
	ATBP	DGS	BH	AH	BT	AT	DGS	BH
				---- 0 - 5 cm ----				
CTNM†	0.040[ns††]	0.093[ns]	0.076[ns]	0.058[ns]	0.051[ns]	0.079[ns]	0.080[a]	0.064[ns]
CTSM	0.038	0.095	0.073	0.052	0.053	0.060	0.077[a]	0.068
NTNM	0.042	0.096	0.065	0.051	0.052	0.062	0.058[b]	0.049
NTSM	0.053	0.083	0.065	0.055	0.052	0.061	0.043[c]	0.048
				---- 15 - 20 cm ----				
CTNM	0.020[ns]	0.075[ns]	0.048[ns]	0.038[ns]	0.028[ns]	0.041[ns]	0.050[ns]	0.041[ns]
CTSM	0.023	0.081	0.048	0.043	0.028	0.042	0.050	0.041
NTNM	0.028	0.073	0.042	0.040	0.022	0.036	0.045	0.040
NTSM	0.024	0.083	0.041	0.038	0.027	0.038	0.041	0.039
				Analysis of Variance				
Treatment (0 -15 cm)	0.40	0.10	0.20	0.07	0.99	0.09	≤ 0.01	0.50
Treatment (15 -30 cm)	0.40	0.60	0.40	0.40	0.20	0.60	0.20	0.90
Depth	≤ 0.01	≤ 0.01	≤ 0.01	≤ 0.01	≤ 0.01	≤ 0.01	≤ 0.01	≤ 0.01

†CTNM, chisel tillage no manure application; CTSM, chisel tillage with manure application; NTNM, no-till with no manure application; NTSM, no-till with manure application; ATBP, after tillage before planting; BT, before tillage; AT, after tillage; DGS, during growing season; BH, before harvest; AH, after harvest. ††Means within the same column, followed by different superscript letters are significantly different at $\alpha = 0.05$.

Table 1.d. Soil micropores ($m^3 m^{-3}$) of 0-5 and 15-20 cm soil depths for two tillage and manure managements for different sampling times in 2018 and 2019.

Treatments	------------------ 2018 ------------------				------------------ 2019 ------------------			
	ATBP	DGS	BH	AH	BT	AT	DGS	BH
				---- 0 - 5 cm ----				
CTNM†	$0.309^{b\dagger\dagger}$	0.300^{ns}	0.295^{ns}	0.315^{ns}	0.272^{ns}	0.293^{ns}	0.307^{bc}	0.306^{ns}
CTSM	0.315^{ab}	0.294	0.302	0.301	0.280	0.335	0.276^{c}	0.313
NTNM	0.338^{ab}	0.309	0.323	0.311	0.315	0.322	0.338^{ab}	0.326
NTSM	0.364^{a}	0.326	0.333	0.298	0.321	0.322	0.360^{a}	0.372
				---- 15 - 20 cm ----				
CTNM	0.295^{ns}	0.288^{ns}	0.298^{ns}	0.314^{ns}	0.286^{ns}	0.294^{ns}	0.299^{ab}	0.311^{ns}
CTSM	0.290	0.286	0.277	0.294	0.305	0.306	0.294^{a}	0.313
NTNM	0.317	0.288	0.296	0.298	0.316	0.322	0.305^{ab}	0.316
NTSM	0.320	0.308	0.306	0.304	0.307	0.317	0.306^{b}	0.323
				Analysis of Variance				
Treatment (0 -15 cm)	0.05	0.40	0.10	0.90	0.05	0.50	≤ 0.01	0.06
Treatment (15 -30 cm)	0.10	0.90	0.10	0.30	0.30	0.20	0.60	0.80
Depth	0.02	0.30	≤ 0.01	0.70	0.50	0.50	0.10	0.20

†CTNM, chisel tillage no manure application; CTSM, chisel tillage with manure application; NTNM, no-till with no manure application; NTSM, no-till with manure application; ATBP, after tillage before planting; BT, before tillage; AT, after tillage; DGS, during growing season; BH, before harvest; AH, after harvest. ††Means within the same column, followed by different superscript letters are significantly different at $\alpha = 0.05$.

Micropores appear to have a similar but inverse trend to macropores (Table 1.d). Broadly, the NT treatments appear to have greater volume of macropores than CT, however significant differences were observed in a few sampling times and depths. For 0-5 cm depth, micropore volumes were greater for NTSM, NTNM and CTSM when compared to CTNM before planting in 2018. Further, differences between CTNM, CTSM and NTNM were not significantly different. Somewhat similar, micro-porosity during the 2019 growing season sampling time was significantly greater for NTMN and NTSM compared to CTSM, but there were no differences between NTNM and CTNM, and between CTNM and CTSM. At the 15-20 cm depth for the same sampling time, CTSM had greater micropore volume than NTSM, but CTSM was no different to CTNM and NTNM. Further, CTNM, NTNM and NTSM had similar micro-porosity.

DISCUSSION

Association Between Aggregate size distribution and Other Soil Properties as Affected by Tillage and Manure

The re-formation of soil aggregates has been studied in the context of soil physical processes such as wetting and drying or freezing and thawing cycles in order to improve the understanding of soil structure (Chaney and Swift, 1986). Long-term impacts of agricultural practices on the formation of aggregates are important since physical changes due to agricultural managements may occur faster (Mikha et al., 2013). These changes can result in dispersion of soil aggregates and aggregate re-formation, which is important to fulfill an objective of sustainable agriculture to improve the development of well-structured soils before or after soil structure disruption. Agricultural practices such as tillage, harvest, and traffic operations are some of the factors involved in the degradation of soil physical structure through aggregation and soil compaction (Kay, 1990).

It has been reported in previous work that soils under NT management had significantly greater aggregate mean weight diameter and available water compared to CT (Mahboubi et al., 1993). In this study, NT soil also had a higher proportion of larger aggregates (>1 mm), ρ_b, and micropores at 0-5 cm depth. Similarly, soil under NT had higher water content values for different matric potentials ranging from -2.5 kPa to -500 kPa, for all sampling dates except for the ones after harvest in 2018 and after spring tillage in 2019, where there were no differences. Conversely, CT systems had a greater proportion of smaller (<1 mm) aggregates, pH, EC, C: N (differences were not significant), and water content (only at saturated conditions) during 2018 and 2019. These differences in aggregate size distribution were expected with NT having a greater proportion of larger aggregates than CT since soil in CT systems are physically disturbed at least once a year. In addition, SOC may accumulate in bigger aggregates under non-disturbed conditions, which may indicate future development of SOC in smaller aggregates (Beare et al., 1994; Gale and Cambardella, 2000; Oades, 1984). Increases in macro aggregation were reported to be an indicator of C sequestration by Six et al. (2000). In addition, previous studies have reported that NT maintains SOM, aggregate stability (Rhoton, 2000), soil temperatures, soil moisture (Benegas and Kokubun, 1998), and improve water infiltration rates, SWR, K_{sat} (Bhattacharyya et al., 2006), and soil structure (Bhattacharyya et al., 2012; Martino and Shaykewich, 1994). In this study the effects of NT were similar to these previous studies but not with all soil properties.

The addition of organic amendments such as manure have been found to improve soil structure and increase SOC (Ozlu and Kumar, 2018a). To increase the C storage in soils and provide better soil structure, management practices applied to soil need to deliver a better C sequestration rate over time. Long-term increases in SOC levels might be possible with the addition of better quality and quantity of organic amendments like manuring or residue return, among others, and less disturbance by tillage or other field operations over time (Havlin et al., 1990; Peterson et al., 1998). However, increasing C sequestration in soils by improving soil management practices depends highly on the stabilization of SOC in soils. One way to stabilize SOC is to develop aggregates which can use soil particles to encapsulate SOC in pores in soil aggregates. Although in this work manure application had no effects on aggregate size distribution, coarse-mesopores, fine mesopores, ρ_b, and K_{sat} at both depths or any sampling times for both 2018 and 2019, it increased EC, and slightly increased microaggregates. These findings are similar to previous studies at low manure application rates (Blair et al., 2006; Eghball, 2002; Eguchi et al., 2016; Liang et al., 2012; Ozlu, 2016).

Besides the above-mentioned relationship between aggregate size distribution and other soil properties under treatment effects, pore size distribution, which is a key component in C-stabilization mechanisms associated with soil aggregation, was controlled by other soil properties. The proportion of macropores were negatively correlated with ρ_b, but ρ_b was positively correlated with micropores at both 0-15 cm and 15-30 cm depths (Figure 8). This supports the statements above that some portion of smaller pores might be created due to soil densification. An increase in ρ_b indicates a decrease in total pore space and higher proportion of micropores (Kozlowski and Pallardy, 1997). On the other hand, the proportions of coarse mesopores and fine mesopores were positively correlated with EC at 15-30 cm depth, whereas micropores were negatively correlated with EC. The development of different pore sizes was a result of different mechanisms and these mechanisms do not necessarily have positive impacts on the general concept of soil structure and its functionality. For instance, an increase in soil ρ_b results in a decrease in the proportion of macropores, which may negatively influence soil air and water balance and crop production. In addition, increases in ρ_b may decrease macropores that are essential for water infiltration, nutrient availability, and root development (Kim et al., 2010; Kozlowski and Pallardy, 1997).

Evaluation of Soil Depth Effects

Previous studies focusing on tillage impacts on pore size distribution and total porosity suggested the evaluation of properties at different depths to capture variability within the soil profile (Kay and VandenBygaart, 2002). In this study, soils at 0-15 cm depth had greater SOC, TN, pH, EC, mesopores, micropores, and relative mass of aggregates smaller than 1 mm than soils at 15-30 cm. In previous studies, it was documented that TN (Yagmur et al., 2017), SOC, EC, and water-stable aggregates were higher in upper soil layers (Ozlu and Kumar, 2018). In contrast, soils at 15-30 cm depth had a higher relative proportion of larger (> 1 mm) aggregates and macropores. A higher proportion of aggregates bigger than 1 mm was overall negatively associated with ρ_b. In this study soil depth had no impact on C: N, ρ_b, K_{sat}, and SWR. Even though differences in 0-15 cm and 15-30 cm depth were significant for the above-mentioned properties, associations between individual soil properties showed similar correlations in both depths (Figure 8).

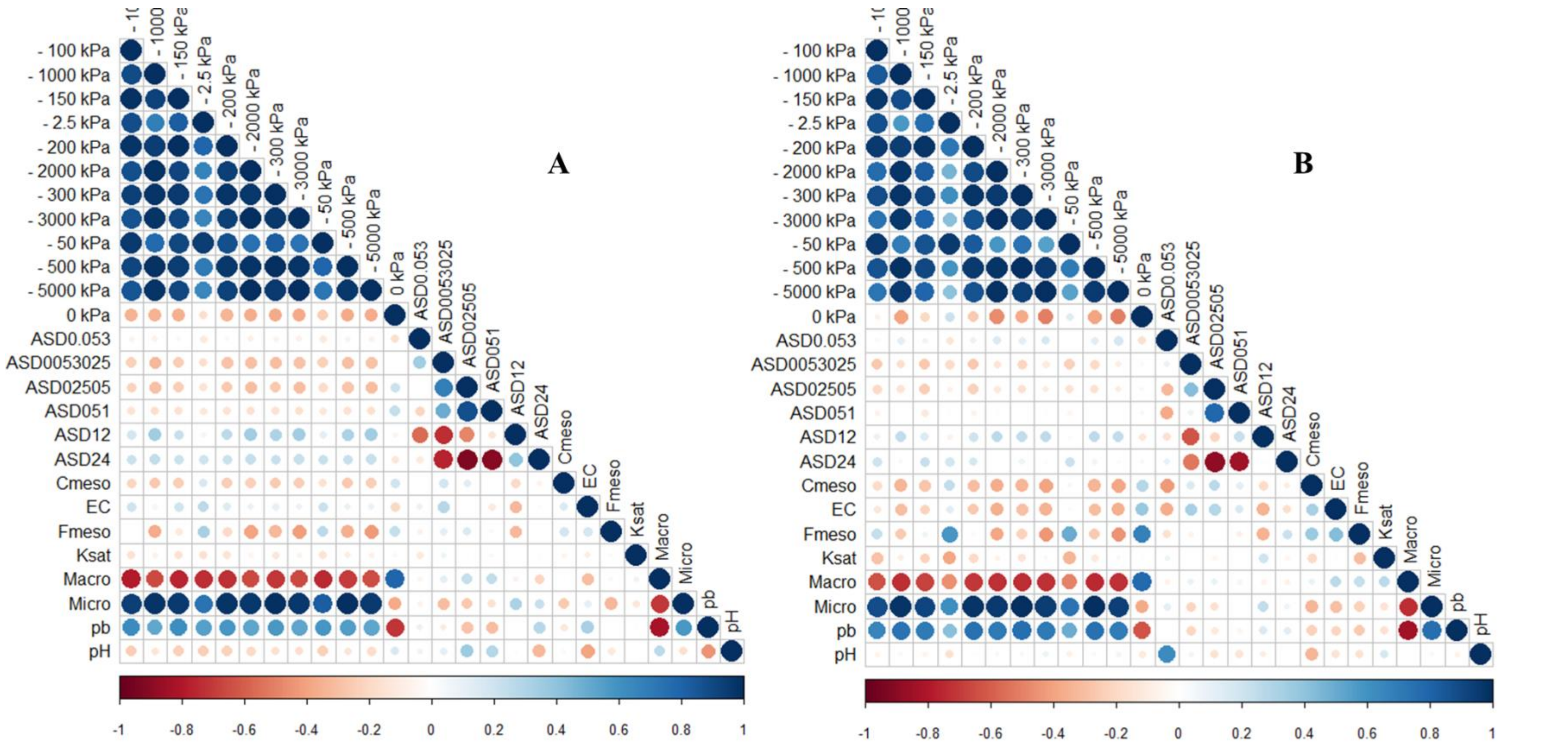

Figure 8. Pearson's correlation analysis of 0-15 (A) and 15-30 (B) cm depths for two tillage and manure application treatments in 2018 and 2019. EC, electrical conductivity; pH, soil pH; *pb*, bulk density; K_{sat}, hydraulic conductivity; ASD0.053, proportion of aggregates smaller than 0.053 mm; ASD0053025, proportion of 0.053-0.25 mm aggregates, ; ASD0.250.5, proportion of 0.25-0.5 mm aggregates; ASD0.51, proportion of 0.5-1 mm aggregates; ASD12, proportion of 1-2 mm aggregates; ASD24, proportion of 2-4 mm aggregates; 0 kPa, moisture content at 0 kPa; - 2.5 kPa, moisture content at -2.5 kPa; - 50 kPa, moisture content at -5 kPa; - 100 kPa, moisture content at -10 kPa; - 150 kPa, moisture content at -15 kPa; - 200 kPa, moisture content at -20 kPa; - 300 kPa, moisture content at -30 kPa; - 500 kPa, moisture content at -50 kPa; - 1000 kPa, moisture content at -100 kPa; - 2000 kPa, moisture content at -200 kPa; - 3000 kPa, moisture content at -300 kPa; - 5000 kPa, moisture content at -5000 kPa; Macro, proportion of macropores; Cmeso, proportion of coarse meso pores; Fmeso, proportion of fine meso pores; Micro, proportion of micro pores.

Short Term Effects of Aggregate Disruption in an Agroecosystem

Soil properties varied over time, before and after spring tillage, during the growing season, and before and after harvest (Table 2). In this study, soil ρ_b at 0-5 cm depth increased during the growing season in 2018, whereas pH, the mass of 1-2 mm and 0.5-1 mm aggregates decreased (Table S1). Previous studies reported variations in soil aggregation during the growing season (Bullock et al., 1988; Carter, 1988) and reported significant changes especially in aggregate stability (Perfect et al., 1990). Perfect et al. (1990) stated that changes in aggregation during the growing season can be as large as treatment effects in agricultural experiments where soil moisture, temperature, root structure, microbial biomass are significant predictors of soil structure during a growing season. Similarly, greater aggregate associated SOC and higher proportion of macro aggregates were reported under NT than those in conventional tillage (Mikha and Rice, 2004). Also, ρ_b, coarse-mesopores, fine-mesopores, and micropores at 0-5 cm depth were higher after tillage compared to before tillage in 2019, whereas K_{sat}, macropores, and the relative mass of 2-4 mm aggregates showed an opposite trend (Table S1). The EC, K_{sat}, macropores, coarse-mesopores, fine-mesopores, micropores, and relative mass of 2-4 mm and 0.5-1 mm aggregates, at 0-5 cm depth were lower immediately after harvesting relative to before harvest in 2018. However, soil pH and ρ_b after harvest were higher than that of before harvesting in 2018. Harvesting may lead to higher ρ_b, but lower volumetric water content due to field traffic of machinery during crop harvest operations (Williamson and Neilsen, 2000) (Blanco-Canqui et al., 2017).

Table 2. Effects of time on soil properties at 0 – 30 cm depth for two tillage and manure application treatments in 2018 and 2019.

Properties	P-value	---------- 2018 ----------				---------- 2019 ----------			
		ATBP	DGS	BH	AH	BT	AT	DGS	BH
pH	≤ 0.01	c††	d	d	c	b	b	b	a
EC	≤ 0.01	c	b	a	c	e	d	c	dc
pb	≤ 0.01	b	b	a	a	b	b	b	b
K_{sat}	0.03	ba	bc	bac	c	a	bac	c	bac
ASD0.053	≤ 0.01	d	dc	b	c	ba	dc	b	a
ASD00530.25	≤ 0.01	a	bc	ba	bc	dc	d	bc	c
ASD0.250.5	≤ 0.01	a	b	a	b	a	b	a	b
ASD0.51	0.02	a	bc	bac	c	bc	bc	ba	bac
ASD12	≤ 0.01	c	ba	d	bac	e	bc	d	a
ASD24	≤ 0.01	e	bc	dc	a	de	ba	e	bc
0 kPa	≤ 0.01	b	e	a	b	c	dc	dc	de
- 2.5 kPa	≤ 0.01	dc	f	a	c	ba	e	b	de
- 5 kPa	≤ 0.01	dc	f	a	d	ba	fe	bc	de
- 10 kPa	≤ 0.01	bc	e	ba	dc	a	de	ba	dce
- 15 kPa	≤ 0.01	ba	c	a	bc	a	c	a	bc
- 20 kPa	≤ 0.01	ba	d	ba	dc	a	d	bac	bdc
- 30 kPa	0.03	ba	bac	ba	bc	a	c	a	bac
- 50 kPa	0.05	a	ba	ba	b	a	b	a	ba
- 100 kPa	0.06	ns							
- 200 kPa	0.09	ns							
- 300 kPa	0.06	ns							
- 500 kPa	0.08	ns							
Macro	≤ 0.01	a	ba	ba	ba	cd	ba	d	bc
CMeso	0.03	bc	c	a	ba	ba	bac	ba	bac
FMeso	≤ 0.01	d	f	a	c	b	de	c	e
Micro	0.03	ba	bac	ba	bc	a	c	a	bac

††Different superscript letters are significantly different at α = 0.05. ATBP, after tillage before planting; BT, before tillage; AT, after tillage; DGS, during growing season; BH, before harvest; AH, after harvest; EC, electrical conductivity; pH, soil pH; *pb*, bulk density; K_{sat}, hydraulic conductivity; ASD0.053, proportion of aggregates smaller than 0.053 mm; ASD0053025, proportion of 0.053-0.25 mm aggregates, ; ASD0.250.5, proportion of 0.25-0.5 mm aggregates; ASD0.51, proportion of 0.5-1 mm aggregates; ASD12, proportion of 1-2 mm aggregates; ASD24, proportion of 2-4 mm aggregates; 0 kPa, moisture content at 0 kPa; - 2.5 kPa, moisture content at -2.5 kPa; - 50 kPa, moisture content at -5 kPa; - 100 kPa, moisture content at -10 kPa; - 150 kPa, moisture content at -15 kPa; - 200 kPa, moisture content at -20 kPa; - 300 kPa, moisture content at -30 kPa; - 500 kPa, moisture content at -50 kPa; - 1000 kPa, moisture content at -100 kPa; - 2000 kPa, moisture content at -200 kPa; - 3000 kPa, moisture content at -300 kPa; - 5000 kPa, moisture content at -5000 kPa; Macro, proportion of macropores; Cmeso, proportion of coarse meso pores; Fmeso, proportion of fine meso pores; Micro, proportion of micro pores.

Overall, short term effects of aggregate disruption in agroecosystems influenced aggregate size distribution and other related soil properties, including increases in ρ_b and a decreased in pH. In addition, harvesting and tillage negatively influenced aggregation and soil pore size distribution due to field traffic, disturbing soil aggregates, and removing crops and crop residue.

Aggregate Turnover Time

Moving averages have been used to determine efficiency and temporal changes (Tiao and Guttman, 1980). Figure 9 presents a moving average of aggregates between 2 to 4 mm diameters. These aggregate sizes at 0-15 cm depth decreased under CT systems with or without manure application because of spring tillage in 2018. However, those under NT systems continuously increased over time in both 2018 and 2019. Aggregates that were disrupted during the 2018 spring tillage operation were able to recover over winter before the next tillage operation in 2019. However, re-formed aggregates decreased again following spring tillage in 2019. Aggregates between 2-4 mm appear to re-form on an annual basis but cannot be maintained if disrupted by tillage again. Aggregates between 2 mm and 0.053 mm were different depending on tillage practice, and these differences can be attributed to the long-term impacts of tillage management. This might be because macro aggregates can form before micro aggregates. It was documented that SOC may accumulate in bigger aggregates under non-disturbed conditions, which may indicate future development of SOC in smaller aggregates since SOC first built-in macroaggregates and then forms new micro-aggregates (Beare et al., 1994; Gale and Cambardella, 2000; Oades, 1984).

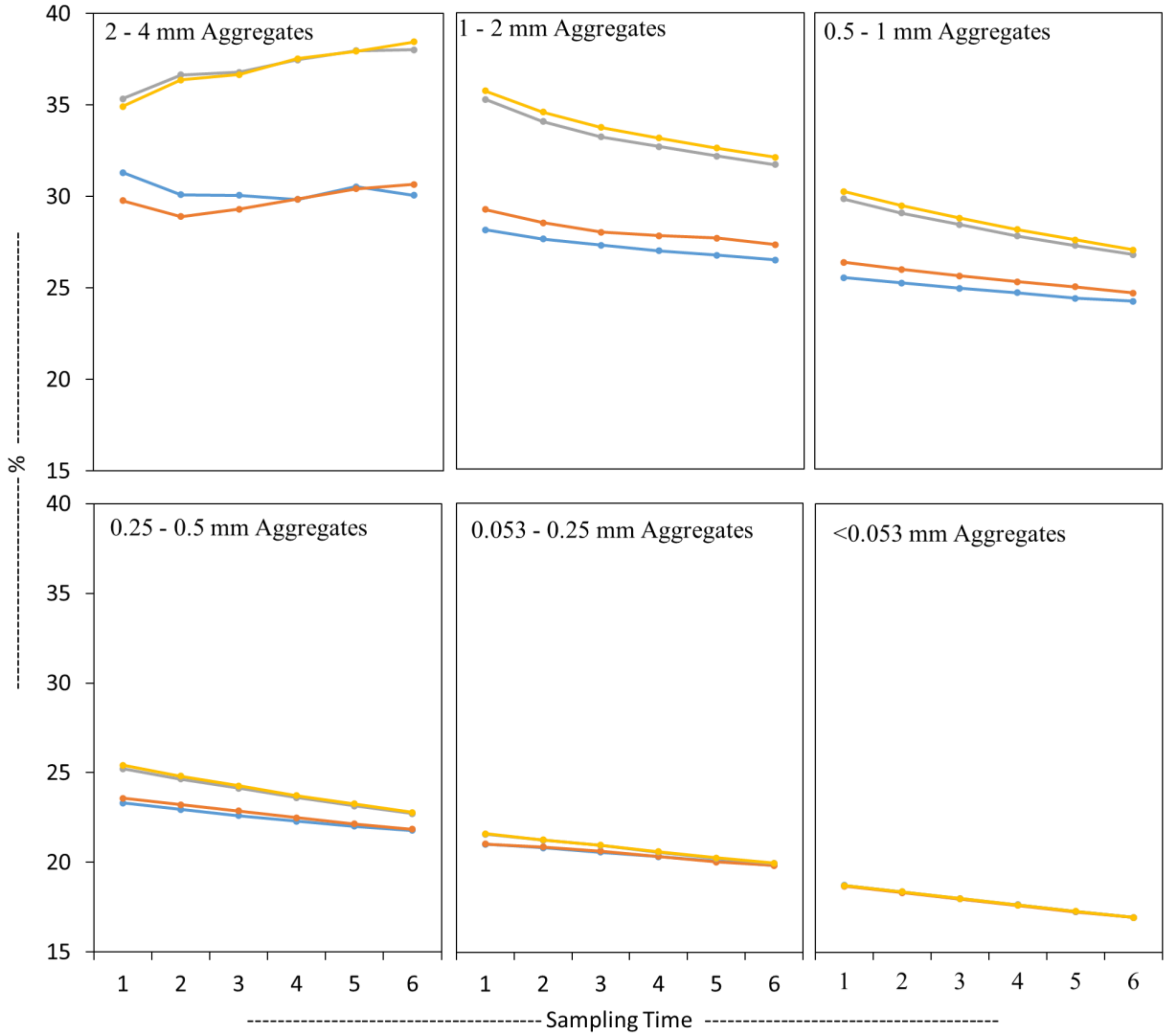

Figure 9. Moving averages of aggregate size distribution for two tillages and manure applications at 0-15 cm depth in both 2018 and 2019. CTNM, chisel tillage no manure application; CTSM, chisel tillage with manure application; NTNM, no-till with no manure application; NTSM, no-till with manure application.

CONCLUSION

In order to evaluate the re-formation of aggregates and creation of pore spaces that can encapsulate SOC, this study assessed related soil physical properties in five sections, (i) management treatments effect, (ii) correlation between soil properties, (iii) depth effect, (iv) time after tillage perturbation, and (v) aggregate turnover.

Soils managed under NT systems developed larger aggregates (>1mm) while CT had a greater proportion of smaller aggregates (<1mm). This greater proportion of larger aggregates under NT management was generally developed associated with higher SOC, TN, and ρ_b, which also led to more micropores. However, disturbed aggregates in CT had higher EC and retained more water at saturated conditions only, which shows that soils under CT management usually hold water in macropores which can easily drain as the matric potential increases. EC was positively correlated with mesopores but negatively correlated with micro pores. Soil at the surface depth showed greater impacts from disturbance because this soil had a greater proportion of aggregates smaller than <1 mm, micropores and mesopores.

The growing season negatively influenced the proportion of soil aggregates between 0.5-2 mm and increased ρ_b. Similarly, the immediate effects of tillage and harvesting decreased larger sized aggregates and pores, and resulted in lower K_{sat} and higher ρ_b. Aggregates between 2 mm and 4 mm were able to re-form on an annual basis but cannot be maintained if disrupted by tillage again. However, differences in aggregates between 2 mm and 0.053 mm were mainly attributed to the long-term impacts of tillage management.

These results indicate that immediate effects of growing season, tillage and harvest negatively influence soil aggregates and pore structures mainly due to higher bulk density and lower SOC content. Aggregates smaller than 2 mm were mainly influenced by long-term effects of tillage. Larger soil aggregates can recover on an annual basis but aggregates smaller than 2 mm do not. There is a need to monitor aggregation, size distribution of aggregates, and pore structures in long term studies which can help identify aggregate turnover time and rate which in turn will help our understanding of aggregate formation and related C stabilization.

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CHAPTER 5

GENERAL CONCLUSIONS

In this study, we evaluated the dynamics of soil aggregate formation in different management and ecosystems. The association between soil aggregate formation and soil mineralogy, soil hydraulic properties, and SOC were studied. Another part of this work focused on soil aggregate re-formation and the turnover of aggregates under short- and long-term impacts from management practices. The following conclusions can be drawn from this work.

The work conducted in Chapter 2 concluded that soil aggregate size distribution was an important indicator of the physical stability of SOC, where the clay minerals and albite play a critical role in improving soil aggregation. In addition, aggregate size distribution and associated SOC were strongly related to soil silt content, which was the dominant soil particle in the land uses studied. The carbon and nitrogen ratio, $\delta_{13}C$, and $\delta_{15}N$ were positively correlated with the proportion of aggregates between 0.053- and 2-mm aggregates but negatively correlated with 2-4 mm aggregates.

In the surface 30 cm of soil, eroded land-uses had a lower proportion of aggregates smaller than 2 mm but a higher relative mass of 2-4 mm aggregates, and lower disaggregation reduction, carbon, and nitrogen ratio, $\delta_{13}C$, and $\delta_{15}N$ in 1-2 mm aggregates. Like erosion, the more intensively managed systems had greater proportion of smaller aggregates, whereas wooded had significantly higher carbon and nitrogen ratio, $\delta_{13}C$, and $\delta_{15}N$.

When considering all soil properties in Chapter 2, the response of soil properties to eroded land-uses was similar to each other, while the response of soil properties within non-eroded land uses varied according to the intensity of management. Overall, the increasing in intensity of disturbance by management practices or erosion negatively influenced soil aggregation, SOC and hydraulic properties.

Soil hydraulic properties were introduced in Chapter 3 to further investigate relationships among soil physical structure, hydraulic properties, and traditional C content and fraction measurements. Soil hydraulic properties and soil carbon content were negatively affected by the intensity of soil disturbance, which included the effects of agricultural management and erosion. However, cold water extractable carbon and dissolved organic carbon did not follow the same trend as the overall carbon content. These carbon fractions in different aggregate sizes were higher with greater disturbance (i.e. tillage and erosion), however, soil organic carbon content was lower. In general, eroded land-uses had lower soil water retention and fine-mesopores, but higher bulk density at 0-5 cm depth. Also, eroded fields had lower carbon content in bulk soil and 1-2 mm aggregate fraction at 0-30 cm depth. In addition, the wooded land-use had the greatest carbon content, whereas grassland had better hydraulic properties compared to other land-uses. Among non-sloping land-uses, agriculture had higher bulk density at 0-5 cm depth, electrical conductivity, and fine mesopores at the 0-30 and 30-60 cm depths; however, agriculture had lower hydraulic conductivity and soil water release at 0-5 cm and 30-35 cm depths. Moreover, moving deeper into the soil profile also decreased soil hydraulic properties and carbon fractions of all soil aggregate size fractions.

The carbon content of 1-2 mm aggregate fraction was positively correlated with hydraulic conductivity and fine-mesopores but negatively correlated with soil pH, electrical conductivity, and bulk density. Carbon fractions in different aggregate sizes showed a positive correlation with soil pH and electrical conductivity, but a negative association with macropores, mesopores, hydraulic conductivity, and carbon and nitrogen contents. When considering the overall impacts of land-uses, multiple linear discriminant analysis showed that eroded fields grouped together, with the non-eroded wooded was most significantly different to the eroded land-uses. Overall decrease in soil hydraulic properties and carbon content as the intensity of disturbance on soil structure increases, like under agriculture and erosion.

Finally, in Chapter 4 the reformation of aggregates after a tillage disturbance was considered to investigate short- and long-term effects. In this chapter conventional tillage and no-tillage in agroecosystems receiving, or not, solid dairy manure were compared. Aggregates between 2-4 mm can reform on an annual basis but cannot be maintained if tillage operations persist. Aggregates of 2-4 mm in no-tillage systems continuously increased over time in both years. In this study, the process of aggregate disturbance to recovery was introduced as aggregate turnover time.

Soils under no-tillage had a greater proportion of aggregates bigger than 1 mm, whereas the proportion of aggregates smaller than 1 mm was higher with the conventionally tilled system. Compared to conventional tillage systems, no-tillage increased soil organic carbon, total nitrogen, bulk density, soil water retention, and the relative proportion of micropores at 0-5 cm depth. In contrast, the conventional tillage system increased soil pH, electrical conductivity, the relative proportion of fine mesopores, and the carbon and nitrogen ratio. Manure application had no significant impacts on soil properties evaluated in this study, except for SOC, TN, and electrical conductivity which increased with manure application.

The relative mass of larger aggregates was positively correlated with bulk density, electrical conductivity, and the proportion of micropores, but negatively correlated with pH and micropores. In contrast, the relative mass of smaller aggregates had an opposite correlation than larger aggregates. Bulk density appeared to be related to aggregate size distribution and soil water characteristics.

The immediate effect of harvesting in 2018 decreased the relative proportion of 2-4 mm and 0.5-1 mm aggregates, electrical conductivity, hydraulic conductivity, macropores, coarse-mesopores, fine-mesopores, and micropores. There was a decrease in hydraulic conductivity, macropores, and the proportion of 2-4 mm aggregates after spring tillage. Overall, larger soil aggregates can recover on an annual basis but aggregates smaller than 2 mm do not.

The combined work presented here further highlights the need for future research on the association of soil organic carbon and aggregate formation. During this study, we found that even though there is a strong association between soil carbon, soil minerals, and the formation of aggregates of different sizes, it would be important to determine what forms of organic carbon are present in different aggregate sizes. Modeling efforts considering soil minerals and specific surface areas might help elucidate the carbon storage capacity of soils in different ecosystems. Similarly, detailed investigations considering time scale to identify the relationship between aggregate turnover time and carbon turnover are needed.

APPENDIX A
CHAPTER 2 SUPPLEMENTARY INFORMATION

Table S.1. Soil carbon: nitrogen ratio of bulk soils and 1-2 mm aggregates for 0-30 cm, 30-60 cm, and 60-90 cm depths as influenced by different land-uses in Arlington, Wisconsin.

Field	Bulk Soils	1 - 2 mm aggregates
	------------- *0 - 30 cm* -------------	
C_e†	10.1^{b}††	12.0^{ab}
W_e	11.6^{ab}	10.6^{b}
C_f	13.0^{a}	12.8^{a}
W_f	13.0^{a}	13.0^{a}
G_f	12.2^{ab}	12.9^{a}
	------------- *30 - 60 cm* -------------	
C_e	-	-
W_e	-	-
C_f	13.0^{ns}	13.7^{ns}
W_f	10.1	11.0
G_f	11.7	12.5
	------------- *60 - 90 cm* -------------	
C_e	-	-
W_e	-	-
C_f	14.0^{a}	12.4^{ns}
W_f	7.5^{b}	12.9
G_f	7.4^{b}	10.9
	Analysis of Variance Pr>F	
0 -30 cm	0.02	0.04
30 -60 cm	0.2	0.1
60 -90 cm	0.01	0.2

†C_e, eroded cornfield; W_e, eroded woodland; C_f, flat surface cornfield; W_f, flat surface woodland; G_f, flat surface grassland. ††Means within the same column, followed by different superscript letters are significantly different at α= 0.05.

Table S.2. The particle size distribution of 1 – 2 mm aggregates for 0-30 cm depth as influenced by different land-uses in Arlington, Wisconsin.

Field	Clay	Silt	Sand
		--- 0 - 30 cm (%) ---	
C_e†	12.4b††	70.9b	16.8b
W_e	16.4a	66.2c	17.4ab
C_f	9.9c	60.0d	30.1a
W_f	13.1b	76.5a	10.5c
G_f	13.5b	71.4b	15.2c
		Analysis of Variance Pr>F	
Field	0.01	0.01	0.01

†C_e, eroded cornfield; W_e, eroded woodland; C_f, flat surface cornfield; W_f, flat surface woodland; G_f, flat surface grassland. ††Means within the same column, followed by different superscript letters are significantly different at $\alpha = 0.05$.

Table S.3. Disaggregation reduction 1-2 mm aggregates for 0-30 cm depth as influenced by different land-uses in Arlington, Wisconsin.

Field	DR	MWD 1	MWD 2
C_e†	155.5$_{ab}$††	189.8$_{ns}$	34.3$_b$
W_e	144.4$_b$	185.1	40.7$_b$
C_f	143.1$_b$	276.3	133.2$_a$
W_f	184.4$_a$	207.0	22.6$_b$
G_f	196.4$_a$	234.8	38.4$_b$
	Analysis of Variance Pr>F		
Field	0.02	0.6	0.01

†C_e, eroded cornfield; W_e, eroded woodland; C_f, flat surface cornfield; W_f, flat surface woodland; G_f, flat surface grassland. ††Means within the same column, followed by different superscript letters are significantly different at α= 0.05.

Table S.4. X-ray diffraction (%) of bulk soils for 0-30 cm soil depth as influenced by different land-uses in Arlington, Wisconsin. Means within the same column, followed by different superscript letters, are significantly different at α= 0.05. Lower cases indicate significance due to land-use impacts

Field	Vermiculite	SuO2-Quartz	Albite
	-------------- % --------------		
C_e†	13.3^{b}††	80.4^{ns}	6.3^{bc}
W_e	15.7^{ab}	76.1	8.2^{b}
C_f	6.5^{c}	90.2	3.4^{c}
W_f	18.7^{b}	74.3	7.0^{b}
G_f	14.7^{b}	78.2	7.2^{b}
	Analysis of Variance Pr>F		
Field	0.01	0.01	0.01

†C_e, eroded cornfield; W_e, eroded woodland; C_f, flat surface cornfield; W_f, flat surface woodland; G_f, flat surface grassland. ††Means within the same column, followed by different superscript letters are significantly different at α= 0.05.

APPENDIX B
CHAPTER 3 SUPPLEMENTARY INFORMATION

Table S.1. Soil pH and electrical conductivity of bulk soils and 1-2 mm aggregates for 0-30 cm, 30-60 cm, and 60-90 cm depths as influenced by different land-uses in Arlington, Wisconsin.

Land-use	pH		EC	
	Bulk	1 - 2 mm	Bulk	1 - 2 mm
	0 - 30 cm			
C_e†	5.5^{c}††	5.5^{c}	123^{ns}	89^{b}
W_e	6.6^{a}	6.7^{a}	166	168^{ab}
C_f	6.9^{a}	6.9^{a}	176	230^{a}
W_f	5.6^{c}	5.5^{c}	100	115^{b}
G_f	6.1^{b}	6.1^{b}	148	187^{ab}
	30 - 60 cm			
C_e				
W_e				
C_f	6.6^{a}	6.5^{a}	100^{a}	109^{a}
W_f	5.5^{c}	5.4^{b}	39^{c}	56^{b}
G_f	6.0^{bc}	5.9^{ab}	50^{b}	68^{ab}
	60 - 90 cm			
C_e				
W_e				
C_f	6.0^{a}	5.8^{a}	61^{a}	72^{ns}
W_f	5.1^{b}	5.0^{b}	29^{b}	53
G_f	5.5^{b}	5.4^{ab}	30^{b}	69
	Analysis of Variance Pr>F			
Land-use (0 -30 cm)	0.01	0.01	0.08	0.04
Land-use (30 -60 cm)	0.01	0.01	0.04	0.05
Land-use (60 -90 cm)	0.01	0.01	0.01	0.40
Erosion (0 - 30 cm)	0.60	0.80	0.80	0.30
Depth	0.03	0.02	0.01	0.01
Depth x Land-use	0.50	0.10	0.20	0.30

†C_e, eroded long-term cornfield; W_e, eroded long-term wood field; C_f, flat surface long-term cornfield; W_f, flat surface long-term wood field; G_f, flat surface long-term grassland.
††Means within the same column, followed by different superscript letters are significantly different at $\alpha = 0.05$.

Table S.2. Soil Water Retention (m^3 m^{-3}) for 0 – 5 cm and 30 – 35 cm depths as influenced by different land-uses in Arlington, Wisconsin.

-Kpa	0.01	2.5	5	10	15	20	30	50	100	200	300	500
						-- 0 - 5 cm --						
C_e†	0.51_{b}	0.41_{ab}	0.39_{ns}	0.38_{ns}	0.37_{ns}	0.37_{ns}	0.36_{ns}	0.36_{ns}	0.35_{ns}	0.35_{ns}	0.34_{ns}	0.34_{ns}
W_e	0.55_{ab}	0.40_{b}	0.39	0.38	0.38	0.37	0.37	0.36	0.36	0.35	0.35	0.34
C_f	0.54_{b}	0.40_{b}	0.39	0.38	0.37	0.36	0.36	0.35	0.35	0.34	0.33	0.32
W_f	0.57_{ab}	0.41_{ab}	0.39	0.37	0.36	0.35	0.35	0.34	0.34	0.33	0.32	0.32
G_f	0.61_{a}	0.50_{a}	0.46	0.43	0.42	0.41	0.40	0.39	0.39	0.38	0.37	0.37
						-- 30 - 35 cm --						
C_e	0.44_{c}	0.32_{b}	0.30_{b}	0.30_{ns}	0.29_{ns}	0.28_{b}	0.28_{b}	0.28_{b}	0.27_{b}	0.27_{b}	0.26_{b}	0.26_{b}
W_e	0.50_{ac}	0.36_{ab}	0.35_{ab}	0.34	0.34	0.33_{ab}	0.33_{ab}	0.32_{ab}	0.32_{ab}	0.31_{ab}	0.31_{ab}	0.30_{ab}
C_f	0.57_{ab}	0.43_{a}	0.42_{a}	0.41	0.40	0.39_{a}	0.38_{a}	0.38_{ab}	0.37_{a}	0.36_{a}	0.36_{ab}	0.35_{ab}
W_f	0.60_{a}	0.45_{a}	0.43_{a}	0.41	0.39	0.38_{a}	0.37_{ab}	0.36_{ab}	0.35_{ab}	0.34_{ab}	0.33_{ab}	0.32_{ab}
G_f	0.53_{ab}	0.45_{a}	0.43_{a}	0.41	0.40	0.40_{a}	0.39_{a}	0.38_{a}	0.38_{a}	0.37_{a}	0.37_{a}	0.36_{a}
						Analysis of Variance Pr>F						
Land-use (0-5 cm)	0.01	0.02	0.08	0.322	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Land-use (30-35 cm)	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.03	0.02	0.03	0.03	0.04
Depth	0.01	0.10	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Depth x Land-use	0.04	0.02	0.02	0.04	0.05	0.06	0.07	0.10	0.10	0.10	0.10	0.10

†C_e, eroded long-term cornfield; W_e, eroded long-term wood field; C_f, flat surface long-term cornfield; W_f, flat surface long-term wood field; G_f, flat surface long-term grassland.

††Means within the same column, followed by different superscript letters are significantly different at $\alpha = 0.05$.

Table S.3. Soil nitrogen content (g kg $^{-1}$) of bulk soils and 1-2 mm aggregates for 0-30 cm, 30-60 cm, and 60-90 cm depths as influenced by different land-uses in Arlington, Wisconsin.

Land-use	Bulk	1 - 2 mm
	---- 0 - 30 cm ----	
C_e†	2.3^{b}	2.4^{cd}
W_e	1.7^{d}	2.1^{d}
C_f	1.8^{cd}	2.5^{bc}
W_f	3.5^{a}	3.0^{a}
G_f	2.1^{bc}	2.7^{ab}
	---- 30 - 60 cm ----	
C_e	-	-
W_e	-	-
C_f	1.9^{a}	2.3^{ns}
W_f	1.5^{b}	1.6
G_f	1.0^{c}	1.3
	---- 60 - 90 cm ----	
C_e	-	-
W_e	-	-
C_f	0.28^{b}	0.3^{b}
W_f	0.65^{a}	0.6^{a}
G_f	0.7^{a}	0.6^{a}
	Analysis of Variance Pr>F	
Land-use (0 -30 cm)	≤ 0.01	≤ 0.01
Land-use (30 -60 cm)	≤ 0.01	0.07
Land-use (60 -90 cm)	0.01	0.01
Erosion (0 - 30 cm)	0.10	0.70
Depth	≤ 0.01	≤ 0.01
Depth x Land-use	≤ 0.01	≤ 0.01

†C_e, eroded long-term cornfield; W_e, eroded long-term wood field; C_f, flat surface long-term cornfield; W_f, flat surface long-term wood field; G_f, flat surface long-term grassland.

††Means within the same column, followed by different superscript letters are significantly different at $\alpha = 0.05$.

Table S.4. Cold water-extractable nitrogen in different aggregate fractions ($mg\ kg^{-1}$) for 0-30 cm, 30-60 cm, and 60-90 cm depths as influenced by different land-uses in Arlington, Wisconsin.

Land-use	---------------------- Aggregate Fractions ----------------------				
	2-4 mm	1 - 2 mm	0.5-1 mm	0.25-0.5 mm	0.053-0.25 mm
			-- 0 - 30 cm --		
C_e†	14.4^{b}††	13.6^{b}	13.1^{b}	14.4^{abc}	16.8^{a}
W_e	13.5^{b}	10.7^{b}	12.4^{b}	9.1^{c}	10.1^{b}
C_f	22.0^{a}	21.3^{a}	19.5^{a}	20.3^{a}	20.4^{a}
W_f	21.1^{a}	20.2^{a}	22.0^{a}	17.4^{ab}	17.7^{a}
G_f	12.6^{b}	9.6^{b}	11.8^{b}	11.9^{bc}	11.0^{b}
			-- 30 - 60 cm --		
C_e	-	-	-	-	-
W_e	-	-	-	-	-
C_f	11.5^{a}	10.6^{ns}	9.1^{a}	9.2^{a}	7.7^{a}
W_f	9.4^{a}	11.1	9.7^{a}	6.2^{ab}	7.5^{a}
G_f	5.6^{b}	10.2	5.8^{b}	7.5^{b}	5.3^{b}
			-- 60 - 90 cm --		
C_e	-	-	-	-	-
W_e	-	-	-	-	-
C_f	10.2^{a}	10.0^{a}	10.6^{ns}	8.4^{ns}	7.9^{a}
W_f	6.8^{b}	11.9^{a}	5.7	5.1	4.1^{b}
G_f	4.0^{c}	5.3^{b}	6.6	5.7	2.9^{b}
			Analysis of Variance Pr>F		
Land-use (0 -30 cm)	≤ 0.01	≤ 0.01	≤ 0.01	0.02	≤ 0.01
Land-use (30 -60 cm)	≤ 0.01	0.90	≤ 0.01	0.05	0.05
Land-use (60 -90 cm)	≤ 0.01	0.02	0.30	0.20	≤ 0.01
Erosion (0 - 30 cm)	≤ 0.01	≤ 0.01	≤ 0.01	≤ 0.01	0.03
Depth	≤ 0.01	≤ 0.01	≤ 0.01	≤ 0.01	≤ 0.01
Depth x Land-use	≤ 0.01	0.01	0.01	0.03	0.01

†C_e, eroded long-term cornfield; W_e, eroded long-term wood field; C_f, flat surface long-term cornfield; W_f, flat surface long-term wood field; G_f, flat surface long-term grassland.
††Means within the same column, followed by different superscript letters are significantly different at $\alpha= 0.05$.

Table S.5. Dissolved organic nitrogen in different aggregate fractions (mg kg $^{-1}$) for 0-30 cm, 30-60 cm, and 60-90 cm depths as influenced by different land-uses in Arlington, Wisconsin.

Land-use	---------------------- Aggregate Fractions ----------------------				
	2-4 mm	1 - 2 mm	0.5-1 mm	0.25-0.5 mm	0.053-0.25 mm
			-- 0 - 30 cm --		
C_e†	14.8^{b}††	13.8^{bc}	18.4^{ns}	20.4^{ns}	26.4^{a}
W_e	14.1^{b}	12.3^{c}	23.7	18.8	12.6^{d}
C_f	20.3^{a}	19.7^{a}	24.9	15.6	24.1^{ab}
W_f	19.9^{a}	17.1^{ba}	14.5	14.7	18.8^{bc}
G_f	14.6^{b}	13.9^{bc}	10.2	13.7	15.5^{cd}
			-- 30 - 60 cm --		
C_e	-	-	-	-	-
W_e	-	-	-	-	-
C_f	13.1^{a}	14.4^{a}	11.9^{ns}	22.9^{ns}	19.7^{a}
W_f	7.6^{b}	7.8^{b}	6.2	5.8	8.4^{b}
G_f	6.8^{b}	5.8^{b}	8.3	13.0	11.4^{b}
			-- 60 - 90 cm --		
C_e	-	-	-	-	-
W_e	-	-	-	-	-
C_f	12.0^{ns}	12.0^{a}	22.1^{a}	12.0^{b}	11.1^{ns}
W_f	5.4	5.5^{b}	6.5^{b}	14.5^{b}	12.1
G_f	6.8	3.3^{c}	8.2^{b}	24.3^{a}	14.6
			Analysis of Variance Pr>F		
Land-use (0 -30 cm)	≤ 0.01	≤ 0.01	0.30	0.70	≤ 0.01
Land-use (30 -60 cm)	0.02	≤ 0.01	0.10	0.10	≤ 0.01
Land-use (60 -90 cm)	0.09	≤ 0.01	≤ 0.01	≤ 0.01	0.30
Erosion (0 - 30 cm)	≤ 0.01	≤ 0.01	0.80	0.30	0.60
Depth	≤ 0.01	≤ 0.01	0.20	0.70	≤ 0.01
Depth x Land-use	≤ 0.01	0.04	0.08	0.07	0.01

†C_e, eroded long-term cornfield; W_e, eroded long-term wood field; C_f, flat surface long-term cornfield; W_f, flat surface long-term wood field; G_f, flat surface long-term grassland.
††Means within the same column, followed by different superscript letters are significantly different at α= 0.05.

APPENDIX C

CHAPTER 4 SUPPLEMENTARY INFORMATION

Table S.1. The relative mass of 2-4 mm aggregates of 0-15 and 15-30 cm soil depths under impacts of tillage and manure applications at soil sampling times of 2018 and 2019.

Treatment	---------- 2018 ----------				---------- 2019 ----------			
	ATBP	DGS	BH	AH	BT	AT	DGS	BH
	0 - 15 cm							
CTNM†	$27.7^{ns\dagger\dagger}$	34.9^{ns}	27.7^{b}	29.9^{b}	29.0^{b}	33.9^{b}	27.3^{c}	23.4^{b}
CTSM	25.2	34.3	27.2^{b}	30.5^{b}	32.1^{b}	33.2^{b}	32.2^{bc}	30.2^{ba}
NTNM	31.3	39.4	39.3^{a}	37.2^{a}	40.2^{a}	40.4^{a}	38.4^{ba}	36.2^{a}
NTSM	33.1	36.8	39.3^{a}	37.6^{a}	41.0^{a}	39.9^{a}	41.7^{a}	36.5^{a}
	15 - 30 cm							
CTNM	35.9^{ns}	40.1^{ns}	38.7^{ns}	38.9^{ns}	41.4^{ns}	41.0^{ns}	40.9^{ns}	37.6^{ns}
CTSM	34.0	42.4	35.3	38.8	38.1	39.3	40.2	38.4
NTNM	39.1	40.2	38.6	37.3	41.7	41.8	38.2	38.0
NTSM	34.4	43.2	39.0	38.4	42.2	40.7	44.9	40.4
	Analysis of Variance							
Treatment (0 -15 cm)	0.20	0.70	0.03	0.03	0.01	0.05	0.01	0.30
Treatment (15 -30 cm)	0.50	0.90	0.30	0.90	0.30	0.70	0.50	0.30
Depth	0.01	0.03	0.06	0.01	0.01	0.20	0.02	0.01

†CTNM, chisel tillage no manure application; CTSM, chisel tillage with manure application; NTNM, no-till with no manure application; NTSM, no-till with manure application; ATBP, after tillage before planting; BT, before tillage; AT, after tillage; DGS, during growing season; BH, before harvest; AH, after harvest. ††Means within the same column, followed by different superscript letters are significantly different at $\alpha = 0.05$.

Table S.2. The relative mass of 1-2 mm aggregates of 0-15 and 15-30 cm soil depths under impacts of tillage and manure applications at soil sampling times of 2018 and 2019.

Treatment	---------- 2018 ----------			---------- 2019 ----------				
	ATBP	DGS	BH	AH	BT	AT	DGS	BH
				0 - 15 cm				
CTNM[†]	24.6^{ns}[††]	22.6^{b}	22.6^{ns}	23.6^{ns}	23.2^{ns}	23.5^{ns}	23.0^{ns}	22.6^{ns}
CTSM	25.0	22.4^{b}	21.3	22.3	25.5	26.0	22.2	23.7
NTNM	26.2	24.1^{ba}	21.9	23.9	26.2	25.5	25.0	24.3
NTSM	25.9	25.7^{a}	22.8	24.5	26.2	25.5	25.0	25.6
				15 - 30 cm				
CTNM	24.8^{ns}	24.6^{ns}	25.2^{ns}	26.7^{ns}	25.9^{ns}	26.2^{ns}	25.0^{ns}	25.2^{ns}
CTSM	26.8	23.9	25.7	27.2	26.4	26.5	25.5	26.9
NTNM	26.6	25.5	26.2	27.6	26.0	26.8	24.9	25.9
NTSM	26.7	25.8	26.4	26.1	26.8	27.2	26.3	26.0
				Analysis of Variance				
Treatment (0 -15 cm)	0.70	0.01	0.70	0.20	0.06	0.10	0.10	0.30
Treatment (15 -30 cm)	0.08	0.10	0.70	0.09	0.20	0.40	0.70	0.20
Depth	0.20	0.05	0.01	0.01	0.05	0.01	0.02	0.01

[†]CTNM, chisel tillage no manure application; CTSM, chisel tillage with manure application; NTNM, no-till with no manure application; NTSM, no-till with manure application; ATBP, after tillage before planting; BT, before tillage; AT, after tillage; DGS, during growing season; BH, before harvest; AH, after harvest. [††]Means within the same column, followed by different superscript letters are significantly different at α= 0.05.

Table S.3. The relative mass of 0.5-1 mm aggregates of 0-15 and 15-30 cm soil depths under impacts of tillage and manure applications at soil sampling times of 2018 and 2019.

Treatment	---------- 2018 ----------				---------- 2019 ----------			
	ATBP	DGS	BH	AH	BT	AT	DGS	BH
				0 - 15 cm				
CTNM†	21.1^{ns††}	18.3^{ns}	19.8^{ns}	19.5^{ns}	19.7^{a}	18.0^{ba}	20.7^{a}	22.5^{a}
CTSM	22.5	18.3	19.2	18.6	18.8^{a}	19.4^{a}	17.3^{b}	19.6^{ba}
NTNM	20.0	17.0	15.1	16.6	15.1^{b}	16.5^{b}	15.8^{bc}	16.9^{b}
NTSM	18.5	18.4	15.5	15.7	15.5^{b}	16.0^{b}	14.6^{c}	16.6^{b}
				15 - 30 cm				
CTNM	17.6^{ns}	16.3^{ns}	17.3^{ns}	17.4^{ns}	15.5^{ns}	16.3^{ns}	16.0^{ns}	17.3^{ns}
CTSM	19.7	15.3	20.0	18.6	16.8	18.2	16.2	18.2
NTNM	17.6	17.3	18.3	19.0	15.3	16.7	16.4	16.8
NTSM	18.9	16.7	18.3	18.4	15.3	17.2	15.2	16.9
				Analysis of Variance				
Treatment (0 -15 cm)	0.30	0.90	0.20	0.10	0.01	0.04	0.01	0.01
Treatment (15 -30 cm)	0.50	0.70	0.20	0.80	0.30	0.70	0.70	0.40
Depth	0.04	0.09	0.30	0.30	0.05	0.60	0.20	0.09

†CTNM, chisel tillage no manure application; CTSM, chisel tillage with manure application; NTNM, no-till with no manure application; NTSM, no-till with manure application; ATBP, after tillage before planting; BT, before tillage; AT, after tillage; DGS, during growing season; BH, before harvest; AH, after harvest. ††Means within the same column, followed by different superscript letters are significantly different at $\alpha = 0.05$.

Table S.4. The relative mass of 0.25-0.5 mm aggregates of 0-15 and 15-30 cm soil depths under impacts of tillage and manure applications at soil sampling times of 2018 and 2019.

Treatment	---------- 2018 ----------				---------- 2019 ----------			
	ATBP	DGS	BH	AH	BT	AT	DGS	BH
				0 - 15 cm				
CTNM†	14.2[ns††]	12.6[ns]	13.5[a]	13.5[ns]	13.6[a]	13.6[a]	15.2[a]	16.3[a]
CTSM	14.5	11.7	13.9[a]	13.3	11.9[a]	12.4[a]	12.9[ba]	13.3[ba]
NTNM	12.4	11.0	9.8[b]	10.5	8.5[b]	9.9[b]	10.1[bc]	10.7[bc]
NTSM	11.5	11.5	9.2[b]	9.5	8.6[b]	9.7[b]	8.5[c]	9.8[c]
				15 - 30 cm				
CTNM	10.9[ns]	10.2[ns]	10.7[ns]	10.1[ns]	8.0[ns]	9.5[ns]	9.3[ns]	10.2[ns]
CTSM	11.7	9.1	12.2	11.1	9.3	9.4	9.1	9.3
NTNM	10.2	10.3	10.6	11.3	8.3	8.9	11.0	9.9
NTSM	11.4	9.3	10.9	11.4	8.0	9.0	7.6	8.7
				Analysis of Variance				
Treatment (0 -15 cm)	0.50	0.70	0.02	0.09	0.02	0.01	0.01	0.01
Treatment (15 -30 cm)	0.80	0.90	0.50	0.80	0.40	0.90	0.60	0.30
Depth	0.03	0.02	0.60	0.40	0.02	0.01	0.05	0.01

†CTNM, chisel tillage no manure application; CTSM, chisel tillage with manure application; NTNM, no-till with no manure application; NTSM, no-till with manure application; ATBP, after tillage before planting; BT, before tillage; AT, after tillage; DGS, during growing season; BH, before harvest; AH, after harvest. ††Means within the same column, followed by different superscript letters are significantly different at α= 0.05.

Table S.5. The relative mass of 0.053-0.25 mm aggregates of 0-15 and 15-30 cm soil depths under impacts of tillage and manure applications at soil sampling times of 2018 and 2019.

Treatment	---------- 2018 ----------				---------- 2019 ----------			
	ATBP	DGS	BH	AH	BT	AT	DGS	BH
				0 - 15 cm				
CTNM[†]	11.6^{ns}[††]	11.1^{ba}	13.8^{ba}	12.1^{ns}	11.3^{a}	10.2^{ns}	11.7^{ns}	12.5^{ns}
CTSM	12.7	11.8^{a}	14.9^{a}	12.5	9.8^{ba}	8.3	12.4	10.5
NTNM	9.9	8.3^{bc}	10.1^{bc}	10.1	7.5^{b}	7.3	9.0	9.2
NTSM	10.9	7.4^{c}	9.7^{c}	10.6	7.3^{b}	7.5	8.7	8.8
				15 - 30 cm				
CTNM	10.7^{a}	8.5^{ns}	7.9^{ns}	6.8^{ns}	6.8^{ns}	6.5^{ns}	7.2^{ns}	7.2^{ns}
CTSM	7.7^{b}	8.5	6.8	4.4	7.5	6.3	7.0	5.6
NTNM	6.5^{b}	6.6	6.3	4.9	6.7	5.3	8.3	7.3
NTSM	8.6^{ba}	5.0	5.4	5.6	6.3	5.3	5.3	5.4
				Analysis of Variance				
Treatment (0 -15 cm)	0.70	0.04	0.03	0.30	0.02	0.10	0.10	0.20
Treatment (15 -30 cm)	0.05	0.20	0.10	0.09	0.40	0.40	0.60	0.20
Depth	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01

[†]CTNM, chisel tillage no manure application; CTSM, chisel tillage with manure application; NTNM, no-till with no manure application; NTSM, no-till with manure application; ATBP, after tillage before planting; BT, before tillage; AT, after tillage; DGS, during growing season; BH, before harvest; AH, after harvest. [††]Means within the same column, followed by different superscript letters are significantly different at α= 0.05.

Table S.6. The relative mass of aggregates smaller than 0.053 mm of 0-15 and 15-30 cm soil depths under impacts of tillage and manure applications at soil sampling times of 2018 and 2019.

Treatment	---------- 2018 ----------				---------- 2019 ----------			
	ATBP	DGS	BH	AH	BT	AT	DGS	BH
				0 - 15 cm				
CTNM†	0.73[ns]††	0.52[ns]	2.61[ns]	1.40[ns]	3.21[ns]	0.71[ns]	2.03[ns]	2.65[ns]
CTSM	0.17	1.51	3.62	2.81	1.98	0.63	3.07	2.76
NTNM	0.14	0.23	3.87	1.70	2.49	0.36	1.73	2.76
NTSM	0.16	0.05	3.51	2.19	1.44	1.39	1.63	2.72
				15 - 30 cm				
CTNM	0.15[ns]	0.17[b]	0.13[ns]	0.08[ns]	1.71[ns]	0.48[ns]	1.61[ns]	2.50[ns]
CTSM	0.05	0.84[a]	0.04	0.01	1.92	0.31	1.91	1.62
NTNM	0.10	0.08[b]	0.08	0.02	2.05	0.50	1.21	2.15
NTSM	0.04	0.03[b]	0.02	0.10	1.42	0.61	0.65	2.64
				Analysis of Variance				
Treatment (0 -15 cm)	0.50	0.20	0.90	0.30	0.50	0.80	0.30	0.90
Treatment (15 -30 cm)	0.40	0.01	0.30	0.50	0.90	0.90	0.20	0.30
Depth	0.20	0.30	0.01	0.01	0.30	0.40	0.04	0.20

†CTNM, chisel tillage no manure application; CTSM, chisel tillage with manure application; NTNM, no-till with no manure application; NTSM, no-till with manure application; ATBP, after tillage before planting; BT, before tillage; AT, after tillage; DGS, during growing season; BH, before harvest; AH, after harvest. ††Means within the same column, followed by different superscript letters are significantly different at α= 0.05.

Table S.7. Soil carbon content, nitrogen content, and carbon and nitrogen ratio of 0-15 and 15-30 cm soil depths under impacts of tillage and manure applications in the summer of 2018.

Treatment	Carbon Content	Nitrogen Content	C:N
	--------------- *0 - 30 cm* ---------------		
CTNM†	15.6b††	1.61b	9.70ns
CTSM	19.3a	2.07a	9.32
NTNM	18.5a	1.98a	9.33
NTSM	20.5a	2.24a	9.13
	--------------- *30 - 60 cm* ---------------		
CTNM	15.9ns	1.61ns	9.86ns
CTSM	15.8	1.71	9.37
NTNM	16.1	1.72	9.31
NTSM	15.3	1.64	9.25
	Analysis of Variance Pr>F		
Treatment (0 -15 cm)	0.01	0.01	0.06
Treatment (15 -30 cm)	0.90	0.90	0.40
Depth	0.07	0.06	0.60

†CTNM, chisel tillage no manure application; CTSM, chisel tillage with manure application; NTNM, no-till with no manure application; NTSM, no-till with manure application; ATBP, after tillage before planting; BT, before tillage; AT, after tillage; DGS, during growing season; BH, before harvest; AH, after harvest. ††Means within the same column, followed by different superscript letters are significantly different at α= 0.05.

Table S.8. Soil pH of 0-15 and 15-30 cm soil depths under impacts of tillage and manure applications at soil sampling times of 2018 (spring, summer, before harvest, and after harvest), and 2019 (before tillage, after tillage, summer, and harvest).

Treatment	---------- 2018 ----------				---------- 2019 ----------			
	ATBP	DGS	BH	AH	BT	AT	DGS	BH
				0 - 15 cm				
CTNM†	7.28$_{ns}$††	7.25$_{a}$	7.15$_{a}$	7.27$_{a}$	7.37$_{a}$	7.41$_{a}$	7.27$_{b}$	7.55$_{a}$
CTSM	7.24	7.20$_{a}$	7.09$_{ba}$	7.18$_{b}$	7.39$_{a}$	7.35$_{b}$	7.34$_{a}$	7.49$_{a}$
NTNM	7.16	7.08$_{b}$	7.16$_{a}$	7.17$_{b}$	7.22$_{b}$	7.24$_{c}$	7.32$_{ba}$	7.41$_{b}$
NTSM	7.12	7.03$_{b}$	7.01$_{b}$	7.09$_{c}$	7.19$_{b}$	7.23$_{c}$	7.18$_{c}$	7.37$_{b}$
				15 - 30 cm				
CTNM	7.26$_{a}$	7.11$_{ns}$	7.09$_{ns}$	7.15$_{a}$	7.26$_{a}$	7.38$_{a}$	7.23$_{ns}$	7.58$_{a}$
CTSM	7.15$_{b}$	7.07	7.06	7.14$_{a}$	7.22$_{ba}$	7.24$_{b}$	7.24	7.49$_{ba}$
NTNM	7.02$_{c}$	7.07	7.12	7.14$_{a}$	7.13$_{c}$	7.12$_{c}$	7.23	7.40$_{bc}$
NTSM	7.00$_{c}$	7.01	7.00	7.02$_{b}$	7.17$_{bc}$	7.08$_{c}$	7.17	7.38$_{c}$
				Analysis of Variance				
Treatment (0 -15 cm)	0.07	0.01	0.03	0.01	0.01	0.01	0.01	0.01
Treatment (15 -30 cm)	0.01	0.50	0.09	0.01	0.01	0.01	0.10	0.01
Depth	0.01	0.01	0.10	0.01	0.01	0.01	0.01	0.50

†CTNM, chisel tillage no manure application; CTSM, chisel tillage with manure application; NTNM, no-till with no manure application; NTSM, no-till with manure application; ATBP, after tillage before planting; BT, before tillage; AT, after tillage; DGS, during growing season; BH, before harvest; AH, after harvest. ††Means within the same column, followed by different superscript letters are significantly different at α= 0.05.

Table S.9. Soil electrical conductivity (µS cm-1) of 0-15 and 15-30 cm soil depths under impacts of tillage and manure applications at soil sampling times of 2018 (spring, summer, before harvest, and after harvest), and 2019 (before tillage, after tillage, summer, and harvest).

Treatment	---------- 2018 ----------				---------- 2019 ----------			
	ATBP	DGS	BH	AH	BT	AT	DGS	BH
				0 - 15 cm				
CTNM†	203ns††	208ns	261b	219ns	162ns	211ns	219b	194b
CTSM	225	234	286a	222	162	196	232b	188b
NTNM	197	232	254ba	206	161	192	247ba	212a
NTSM	215	223	274b	230	158	204	274a	205a
				15 - 30 cm				
CTNM	170ns	194ns	203a	169a	133a	154a	137ns	141b
CTSM	167	201	194a	155a	118b	127b	129	153b
NTNM	158	167	163b	127b	122ba	142ba	128	187a
NTSM	164	178	153b	132b	109b	103c	125	129b
				Analysis of Variance				
Treatment (0 -15 cm)	0.40	0.20	0.03	0.80	0.90	0.10	0.05	0.01
Treatment (15 -30 cm)	0.90	0.30	0.01	0.01	0.03	0.01	0.60	0.01
Depth	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

†CTNM, chisel tillage no manure application; CTSM, chisel tillage with manure application; NTNM, no-till with no manure application; NTSM, no-till with manure application; ATBP, after tillage before planting; BT, before tillage; AT, after tillage; DGS, during growing season; BH, before harvest; AH, after harvest. ††Means within the same column, followed by different superscript letters are significantly different at α= 0.05.

Table S.10. Soil bulk density (gr cm-3) of 0-15 and 15-30 cm soil depths under impacts of tillage and manure applications at soil sampling times of 2018 (spring, summer, before harvest, and after harvest), and 2019 (before tillage, after tillage, summer, and harvest).

Treatment	---------- 2018 ----------				---------- 2019 ----------			
	ATBP	DGS	BH	AH	BT	AT	DGS	BH
				0 - 15 cm				
CTNM†	1.05^{b††}	1.20^{ns}	1.21^{b}	1.29^{ns}	1.04^{ns}	1.1^{ns}	1.19^{ab}	1.13^{ns}
CTSM	1.09^{b}	1.22	1.27^{ab}	1.29	1.11	1.18	1.06^{b}	1.15
NTNM	1.29^{a}	1.23	1.39^{a}	1.31	1.23	1.22	1.33^{a}	1.21
NTSM	1.29^{a}	1.29	1.31^{ab}	1.34	1.21	1.16	1.27^{a}	1.29
				15 - 30 cm				
CTNM	1.25^{ns}	1.19^{ns}	1.31^{ns}	1.41^{a}	1.26^{ns}	1.23^{ns}	1.27^{ns}	1.28^{ns}
CTSM	1.16	1.20	1.22	1.26^{b}	1.26	1.28	1.21	1.30
NTNM	1.33	1.29	1.32	1.31^{ab}	1.34	1.33	1.29	1.30
NTSM	1.32	1.24	1.32	1.31^{ab}	1.33	1.33	1.28	1.31
				Analysis of Variance				
Treatment (0 -15 cm)	0.01	0.60	0.02	0.80	0.07	0.20	0.01	0.20
Treatment (15 -30 cm)	0.08	0.80	0.40	0.01	0.60	0.10	0.20	0.90
Depth	0.20	0.90	0.20	0.20	0.70	0.70	0.06	0.40

†CTNM, chisel tillage no manure application; CTSM, chisel tillage with manure application; NTNM, no-till with no manure application; NTSM, no-till with manure application; ATBP, after tillage before planting; BT, before tillage; AT, after tillage; DGS, during growing season; BH, before harvest; AH, after harvest. ††Means within the same column, followed by different superscript letters are significantly different at α= 0.05.

Table S.11. Soil hydraulic conductivity of 0-15 and 15-30 cm soil depths under impacts of tillage and manure applications at soil sampling times of 2018 (spring, summer, before harvest, and after harvest), and 2019 (before tillage, after tillage, summer, and harvest).

Treatment	---------- 2018 ----------				---------- 2019 ----------			
	ATBP	DGS	BH	AH	BT	AT	DGS	BH
	-------------------------------- *0 - 15 cm* --------------------------------							
CTNM†	239^{ns††}	127^{ns}	23^{ns}	160^{ns}	332^{ns}	21^{ns}	81^{ns}	348^{ns}
CTSM	181	40	30	52	340	27	64	99
NTNM	309	490	248	20	310	30	219	46
NTSM	302	200	30	192	114	108	68	32
	-------------------------------- *15 - 30 cm* --------------------------------							
CTNM	271^{ab}	74^{ns}	24^{ns}	18^{ns}	558^{ns}	535^{ns}	61^{ns}	219^{ns}
CTSM	560^{a}	38	275	128	229	122	24	146
NTNM	44^{bc}	78	277	63	118	215	41	296
NTSM	156^{b}	54	308	31	185	52	58	186
	Analysis of Variance							
Treatment (0 -15 cm)	0.90	0.60	0.50	0.30	0.80	0.20	0.20	0.10
Treatment (15 -30 cm)	0.01	0.80	0.70	0.20	0.30	0.20	0.70	0.90
Depth	0.30	0.70	0.70	0.10	0.70	0.10	0.20	0.50

†CTNM, chisel tillage no manure application; CTSM, chisel tillage with manure application; NTNM, no-till with no manure application; NTSM, no-till with manure application; ATBP, after tillage before planting; BT, before tillage; AT, after tillage; DGS, during growing season; BH, before harvest; AH, after harvest. ††Means within the same column, followed by different superscript letters are significantly different at $\alpha = 0.05$.

Table S.12. Soil water retention of 0-5 and 15-20 cm soil depths under impacts of tillage and manure applications after tillage and before planting of 2018.

-Kpa	0	2.5	5	10	15	20	30	50	100	200	300	500
						0 - 15 cm						
CTNM†	$0.54_{a\dagger\dagger}$	0.38_{b}	0.35_{b}	0.33_{b}	0.32_{b}	0.32_{b}	0.31_{b}	0.30_{ns}	0.30_{ns}	0.29_{b}	0.29_{b}	0.28_{b}
CTSM	0.53_{a}	0.37_{b}	0.35_{b}	0.34_{b}	0.33_{b}	0.33_{ab}	0.32_{ab}	0.31	0.31	0.30_{ab}	0.29_{ab}	0.29_{ab}
NTNM	0.46_{b}	0.40_{ab}	0.38_{ab}	0.37_{ab}	0.36_{ab}	0.35_{ab}	0.34_{ab}	0.33	0.32	0.32_{ab}	0.31_{ab}	0.31_{ab}
NTSM	0.50_{ab}	0.44_{a}	0.42_{a}	0.40_{a}	0.39_{a}	0.38_{a}	0.36_{a}	0.36	0.35	0.35_{a}	0.34_{a}	0.34_{a}
						15 - 30 cm						
CTNM	0.46_{ns}	0.33_{b}	0.32_{ab}	0.31_{ns}	0.31_{ns}	0.30_{ns}	0.30_{ns}	0.29_{ns}	0.29_{ns}	0.28_{ns}	0.28_{ns}	0.27_{ns}
CTSM	0.50	0.33_{b}	0.31_{b}	0.30	0.30	0.29	0.29	0.29	0.28	0.28	0.28	0.28
NTNM	0.46	0.36_{a}	0.34_{a}	0.34	0.33	0.33	0.32	0.31	0.31	0.30	0.30	0.30
NTSM	0.46	0.36_{a}	0.34_{a}	0.34	0.33	0.33	0.32	0.32	0.31	0.31	0.31	0.31
						Analysis of Variance						
Treatment (0 -15 cm)	0.01	0.01	0.01	0.01	0.02	0.03	0.04	0.06	0.06	0.04	0.04	0.03
Treatment (15 -30 cm)	0.30	0.01	0.01	0.03	0.04	0.04	0.09	0.09	0.09	0.08	0.06	0.05
Depth	0.09	0.10	0.10	0.20	0.30	0.30	0.50	0.60	0.60	0.60	0.60	0.70

†CTNM, chisel tillage no manure application; CTSM, chisel tillage with manure application; NTNM, no-till with no manure application; NTSM, no-till with manure application; ATBP, after tillage before planting; BT, before tillage; AT, after tillage; DGS, during growing season; BH, before harvest; AH, after harvest. ††Means within the same column, followed by different superscript letters are significantly different at α= 0.05.

Table S.13. Soil water retention of 0 - 5 and 15 - 20 cm soil depths under impacts of tillage and manure applications in the summer of 2018.

-Kpa	0.01	2.5	5	10	15	20	30	50	100	200	300	500
						------------------------------ 0 - 15 cm ------------------------------						
CTNM[†]	0.52^{ns}[††]	0.41^{ns}	0.39^{ns}	0.36^{ns}	0.33^{ns}	0.32^{ns}	0.30^{ns}	0.29^{ns}	0.29^{ns}	0.28^{ns}	0.27^{ns}	0.26^{ns}
CTSM	0.54	0.41	0.39	0.36	0.34	0.32	0.29	0.29	0.28	0.27	0.26	0.26
NTNM	0.52	0.42	0.41	0.36	0.34	0.33	0.31	0.30	0.29	0.29	0.28	0.27
NTSM	0.51	0.43	0.41	0.38	0.36	0.34	0.33	0.32	0.31	0.30	0.29	0.29
						------------------------------ 15 - 30 cm ------------------------------						
CTNM	0.56^{ns}	0.39^{ns}	0.36^{ns}	0.33^{ns}	0.32^{ns}	0.31^{ns}	0.29^{ns}	0.28^{ns}	0.27^{ns}	0.26^{ns}	0.25^{ns}	0.25^{ns}
CTSM	0.54	0.38	0.37	0.34	0.32	0.31	0.29	0.28	0.28	0.27	0.26	0.26
NTNM	0.52	0.38	0.36	0.33	0.32	0.31	0.29	0.28	0.28	0.26	0.26	0.25
NTSM	0.55	0.41	0.39	0.36	0.34	0.33	0.31	0.30	0.30	0.28	0.27	0.27
						Analysis of Variance						
Treatment (0 -15 cm)	0.60	0.60	0.70	0.70	0.50	0.50	0.40	0.50	0.50	0.60	0.60	0.50
Treatment (15 -30 cm)	0.60	0.80	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
Depth	0.60	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90

[†]CTNM, chisel tillage no manure application; CTSM, chisel tillage with manure application; NTNM, no-till with no manure application; NTSM, no-till with manure application; ATBP, after tillage before planting; BT, before tillage; AT, after tillage; DGS, during growing season; BH, before harvest; AH, after harvest. [††]Means within the same column, followed by different superscript letters are significantly different at α= 0.05.

Table S.14. Soil water retention of 0 - 5 and 15 - 20 cm soil depths under impacts of tillage and manure applications before harvest of 2018.

-Kpa	0.01	2.5	5	10	15	20	30	50	100	200	300	500
						0 - 15 cm						
CTNM[†]	$0.53^{a\dagger\dagger}$	0.39^{ns}	0.37^{ns}	0.35^{ns}	0.33^{ns}	0.32^{ns}	0.29^{ns}	0.29^{ns}	0.27^{ns}	0.28^{ns}	0.26^{ns}	0.27^{ns}
CTSM	0.51^{ab}	0.39	0.37	0.35	0.34	0.32	0.30	0.29	0.28	0.27	0.27	0.26
NTNM	0.48^{b}	0.41	0.39	0.37	0.35	0.34	0.32	0.31	0.30	0.29	0.29	0.29
NTSM	0.51^{ab}	0.42	0.40	0.38	0.36	0.35	0.33	0.32	0.31	0.30	0.30	0.29
						15 - 30 cm						
CTNM	0.52^{ns}	0.37^{ns}	0.35^{ns}	0.33^{ns}	0.32^{ns}	0.31^{ns}	0.30^{ns}	0.29^{ns}	0.28^{ab}	0.27^{ns}	0.27^{ns}	0.27^{ns}
CTSM	0.52	0.34	0.33	0.31	0.30	0.29	0.28	0.27	0.26^{b}	0.25	0.25	0.25
NTNM	0.50	0.35	0.34	0.32	0.31	0.31	0.30	0.29	0.28^{ab}	0.27	0.27	0.27
NTSM	0.50	0.36	0.35	0.33	0.32	0.32	0.31	0.30	0.29^{a}	0.28	0.28	0.27
						Analysis of Variance						
Treatment (0 -15 cm)	0.02	0.20	0.20	0.20	0.10	0.10	0.10	0.20	0.20	0.20	0.10	0.10
Treatment (15 -30 cm)	0.80	0.10	0.06	0.06	0.08	0.08	0.10	0.08	0.03	0.07	0.09	0.09
Depth	0.80	0.20	0.20	0.30	0.30	0.30	0.40	0.50	0.60	0.60	0.50	0.50

[†]CTNM, chisel tillage no manure application; CTSM, chisel tillage with manure application; NTNM, no-till with no manure application; NTSM, no-till with manure application; ATBP, after tillage before planting; BT, before tillage; AT, after tillage; DGS, during growing season; BH, before harvest; AH, after harvest. [††]Means within the same column, followed by different superscript letters are significantly different at $\alpha = 0.05$.

Table S.15. Soil water retention of 0 - 5 and 15 - 20 cm soil depths under the impacts of tillage and manure applications after harvest of 2018.

-Kpa	0.01	2.5	5	10	15	20	30	50	100	200	300	500
	------------ *0 - 15 cm* ------------											
CTNM[†]	$0.47^{ns\dagger\dagger}$	0.39^{ns}	0.37^{ns}	0.36^{ns}	0.34^{ns}	0.32^{ns}	0.31^{ns}	0.31^{ns}	0.29^{ns}	0.29^{ns}	0.27^{ns}	0.28^{ns}
CTSM	0.47	0.37	0.35	0.34	0.32	0.31	0.30	0.29	0.28	0.27	0.27	0.26
NTNM	0.48	0.38	0.36	0.35	0.33	0.32	0.31	0.30	0.30	0.29	0.29	0.28
NTSM	0.47	0.38	0.35	0.33	0.32	0.31	0.30	0.29	0.28	0.27	0.27	0.26
	------------ *15 - 30 cm* ------------											
CTNM	0.46^{ns}	0.38^{ns}	0.35^{ns}	0.34^{ns}	0.33^{ns}	0.32^{ns}	0.31^{ns}	0.31^{ns}	0.30^{ns}	0.29^{ns}	0.29^{ns}	0.28^{ns}
CTSM	0.51	0.35	0.34	0.32	0.31	0.31	0.29	0.29	0.29	0.28	0.27	0.26
NTNM	0.47	0.36	0.34	0.33	0.32	0.31	0.30	0.29	0.28	0.28	0.27	0.27
NTSM	0.48	0.37	0.34	0.33	0.32	0.31	0.30	0.30	0.29	0.29	0.29	0.28
	Analysis of Variance											
Treatment (0 -15 cm)	0.90	0.90	0.80	0.80	0.80	0.90	0.90	0.90	0.90	0.90	0.80	0.80
Treatment (15 -30 cm)	0.10	0.08	0.50	0.40	0.40	0.40	0.30	0.30	0.40	0.40	0.30	0.30
Depth	0.50	0.90	0.90	0.90	0.90	0.90	0.90	0.80	0.70	0.60	0.70	0.70

[†]CTNM, chisel tillage no manure application; CTSM, chisel tillage with manure application; NTNM, no-till with no manure application; NTSM, no-till with manure application; ATBP, after tillage before planting; BT, before tillage; AT, after tillage; DGS, during growing season; BH, before harvest; AH, after harvest.[††]Means within the same column, followed by different superscript letters are significantly different at $\alpha = 0.05$.

Table S.16. Soil water retention of 0 - 5 and 15 - 20 cm soil depths under impacts of tillage and manure applications before tillage of 2019.

-Kpa	0.01	2.5	5	10	15	20	30	50	100	200	300	500
						0 - 15 cm						
CTNM[†]	0.55[a][††]	0.33[ns]	0.32[ns]	0.31[ns]	0.30[ns]	0.29[ns]	0.27[ns]	0.27[ns]	0.26[b]	0.26[b]	0.24[b]	0.23[b]
CTSM	0.53[a]	0.34	0.33	0.32	0.31	0.30	0.28	0.28	0.27[ab]	0.26[ab]	0.25[ab]	0.25[ab]
NTNM	0.50[b]	0.38	0.37	0.35	0.34	0.33	0.32	0.31	0.30[ab]	0.30[a]	0.29[a]	0.29[a]
NTSM	0.52[ab]	0.38	0.37	0.36	0.34	0.34	0.32	0.31	0.31[a]	0.30[a]	0.30[a]	0.29[a]
						15 - 30 cm						
CTNM	0.49[ns]	0.32[ns]	0.31[ns]	0.31[ns]	0.30[ns]	0.3[ns]	0.29[ns]	0.28[ns]	0.28[ns]	0.27[ns]	0.27[ns]	0.27[ns]
CTSM	0.49	0.34	0.33	0.33	0.32	0.32	0.30	0.30	0.29	0.29	0.29	0.28
NTNM	0.45	0.35	0.34	0.33	0.33	0.32	0.32	0.31	0.31	0.30	0.30	0.30
NTSM	0.46	0.34	0.33	0.33	0.34	0.32	0.31	0.30	0.29	0.29	0.29	0.28
						Analysis of Variance						
Treatment (0 -15 cm)	0.01	0.10	0.20	0.10	0.20	0.20	0.04	0.05	0.03	0.01	0.02	0.01
Treatment (15 -30 cm)	0.30	0.40	0.40	0.40	0.30	0.40	0.30	0.40	0.40	0.40	0.40	0.50
Depth	0.80	0.40	0.50	0.50	0.80	0.60	0.40	0.40	0.30	0.20	0.20	0.20

[†]CTNM, chisel tillage no manure application; CTSM, chisel tillage with manure application; NTNM, no-till with no manure application; NTSM, no-till with manure application; ATBP, after tillage before planting; BT, before tillage; AT, after tillage; DGS, during growing season; BH, before harvest; AH, after harvest.[††]Means within the same column, followed by different superscript letters are significantly different at α= 0.05.

Table S.17. Soil water retention of 0 - 5 and 15 - 20 cm soil depths under impacts of tillage and manure applications at after tillage of 2019.

-Kpa	0.01	2.5	5	10	15	20	30	50	100	200	300	500
						0 - 15 cm						
CTNM†	$0.56^{ns\dagger\dagger}$	0.41^{ns}	0.37^{ns}	0.34^{ns}	0.32^{ns}	0.31^{ns}	0.29^{ns}	0.29^{ns}	0.28^{ns}	0.27^{ns}	0.25^{ns}	0.25^{ns}
CTSM	0.54	0.41	0.40	0.37	0.35	0.34	0.33	0.32	0.31	0.30	0.29	0.29
NTNM	0.53	0.39	0.38	0.36	0.34	0.33	0.32	0.31	0.30	0.29	0.29	0.28
NTSM	0.56	0.41	0.38	0.36	0.34	0.34	0.32	0.31	0.31	0.30	0.29	0.29
						15 - 30 cm						
CTNM	0.52^{ns}	0.35^{ns}	0.34^{ns}	0.32^{ns}	0.31^{ns}	0.31^{ns}	0.29^{ns}	0.29^{ns}	0.29^{ns}	0.28^{ns}	0.27^{ns}	0.27^{ns}
CTSM	0.50	0.36	0.35	0.33	0.32	0.32	0.31	0.30	0.29	0.29	0.28	0.28
NTNM	0.48	0.37	0.36	0.34	0.33	0.33	0.32	0.32	0.31	0.30	0.30	0.29
NTSM	0.48	0.37	0.35	0.34	0.33	0.33	0.32	0.31	0.31	0.3	0.29	0.29
						Analysis of Variance						
Treatment (0 -15 cm)	0.40	0.60	0.80	0.70	0.60	0.60	0.50	0.60	0.50	0.30	0.30	0.30
Treatment (15 -30 cm)	0.06	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.30	0.30
Depth	0.30	0.20	0.80	0.80	0.70	0.70	0.70	0.70	0.70	0.60	0.60	0.60

†CTNM, chisel tillage no manure application; CTSM, chisel tillage with manure application; NTNM, no-till with no manure application; NTSM, no-till with manure application; ATBP, after tillage before planting; BT, before tillage; AT, after tillage; DGS, during growing season; BH, before harvest; AH, after harvest.††Means within the same column, followed by different superscript letters are significantly different at $\alpha = 0.05$.

Table S.18. Soil water retention of 0 - 5 and 15 - 20 cm soil depths under impacts of tillage and manure applications in the summer of 2019.

-Kpa	0.01	2.5	5	10	15	20	30	50	100	200	300	500
						0 - 15 cm						
CTNM[†]	0.50$_{ab}$[††]	0.41$_{ab}$	0.39$_{ab}$	0.36$_{ab}$	0.35$_{a}$	0.33$_{b}$	0.31$_{bc}$	0.30$_{bc}$	0.29$_{bc}$	0.28$_{ac}$	0.28$_{bc}$	0.27$_{bc}$
CTSM	0.51$_{a}$	0.37$_{a}$	0.35$_{b}$	0.33$_{b}$	0.31$_{b}$	0.30$_{c}$	0.28$_{c}$	0.27$_{c}$	0.26$_{c}$	0.25$_{c}$	0.24$_{c}$	0.24$_{c}$
NTNM	0.47$_{b}$	0.41$_{ab}$	0.40$_{a}$	0.38$_{a}$	0.36$_{a}$	0.35$_{ab}$	0.34$_{ab}$	0.33$_{ab}$	0.32$_{b}$	0.31$_{b}$	0.31$_{ab}$	0.30$_{ab}$
NTSM	0.49$_{ab}$	0.41$_{ab}$	0.40$_{a}$	0.39$_{a}$	0.38$_{a}$	0.37$_{a}$	0.36$_{a}$	0.36$_{a}$	0.35$_{a}$	0.34$_{a}$	0.33$_{a}$	0.33$_{a}$
						15 - 30 cm						
CTNM	0.48$_{ns}$	0.36$_{ns}$	0.35$_{ns}$	0.33$_{ns}$	0.33$_{ns}$	0.31$_{ns}$	0.30$_{ns}$	0.29$_{ns}$	0.28$_{ns}$	0.27$_{ns}$	0.27$_{ns}$	0.27$_{ns}$
CTSM	0.49	0.36	0.34	0.33	0.32	0.31	0.29	0.29	0.28	0.27	0.26	0.27
NTNM	0.47	0.36	0.35	0.34	0.33	0.32	0.30	0.30	0.29	0.29	0.29	0.28
NTSM	0.47	0.36	0.35	0.34	0.33	0.32	0.31	0.30	0.29	0.29	0.29	0.28
						Analysis of Variance						
Treatment (0 -15 cm)	0.02	0.04	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Treatment (15 -30 cm)	0.50	0.90	0.90	0.70	0.60	0.60	0.60	0.50	0.40	0.30	0.20	0.30
Depth	0.40	0.08	0.05	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

[†]CTNM, chisel tillage no manure application; CTSM, chisel tillage with manure application; NTNM, no-till with no manure application; NTSM, no-till with manure application; ATBP, after tillage before planting; BT, before tillage; AT, after tillage; DGS, during growing season; BH, before harvest; AH, after harvest. [††]Means within the same column, followed by different superscript letters are significantly different at $\alpha = 0.05$.

Table S.19. Soil water retention of 0 - 5 and 15 - 20 cm soil depths under impacts of tillage and manure applications at harvest of 2019.

-Kpa	0.01	2.5	5	10	15	20	30	50	100	200	300	500
						0 - 15 cm						
CTNM[†]	0.52^{ns}[††]	0.38^{ns}	0.37^{ns}	0.35^{ns}	0.33^{b}	0.32^{b}	0.31^{ns}	0.30^{ns}	0.29^{ns}	0.30^{ns}	0.27^{ns}	0.29^{ns}
CTSM	0.51	0.40	0.38	0.36	0.34^{ab}	0.33^{ab}	0.31	0.30	0.29	0.28	0.27	0.27
NTNM	0.49	0.39	0.38	0.36	0.34^{ab}	0.33^{ab}	0.33	0.32	0.31	0.30	0.30	0.30
NTSM	0.49	0.43	0.42	0.40	0.39^{a}	0.38^{a}	0.37	0.37	0.36	0.35	0.35	0.35
						15 - 30 cm						
CTNM	0.50^{ns}	0.36^{ns}	0.35^{ns}	0.34^{ns}	0.32^{ns}	0.32^{ns}	0.31^{ns}	0.31^{ns}	0.30^{ns}	0.29^{ns}	0.29^{ns}	0.28^{ns}
CTSM	0.49	0.36	0.35	0.34	0.33	0.32	0.31	0.31	0.30	0.29	0.29	0.28
NTNM	0.48	0.36	0.36	0.34	0.33	0.32	0.32	0.31	0.30	0.30	0.29	0.29
NTSM	0.47	0.37	0.36	0.35	0.34	0.33	0.32	0.32	0.31	0.31	0.30	0.30
						Analysis of Variance						
Treatment (0 -15 cm)	0.30	0.06	0.09	0.05	0.05	0.05	0.06	0.07	0.06	0.06	0.06	0.06
Treatment (15 -30 cm)	0.30	0.90	0.90	0.80	0.80	0.70	0.80	0.70	0.60	0.50	0.60	0.60
Depth	0.90	0.40	0.30	0.20	0.20	0.20	0.20	0.20	0.10	0.10	0.10	0.10

[†]CTNM, chisel tillage no manure application; CTSM, chisel tillage with manure application; NTNM, no-till with no manure application; NTSM, no-till with manure application; ATBP, after tillage before planting; BT, before tillage; AT, after tillage; DGS, during growing season; BH, before harvest; AH, after harvest. [††]Means within the same column, followed by different superscript letters are significantly different at $\alpha = 0.05$.

Table S.20. Effects of time on soil properties of 0-15 cm depth under the impacts of tillage and manure applications.

Properties	Prb	---------- 2018 ----------				---------- 2019 ----------			
		ATBP	DGS	BH	AH	BT	AT	DGS	BH
pH	≤ 0.01	c††	de	e	dc	b	b	b	a
EC	≤ 0.01	dc	c	a	c	e	d	b	d
pb	≤ 0.01	dce	bc	ba	a	e	de	dc	dce
K_{sat}	0.20	ns							
ASD0.053	≤ 0.01	c	c	a	b	b	c	b	ba
ASD0053025	≤ 0.01	ba	ecd	a	ba	ed	e	bc	bcd
ASD0.2505	≤ 0.01	a	bc	ba	c	b	bc	ba	bc
ASD051	≤ 0.01	a	b	bc	c	bc	b	bc	b
ASD12	≤ 0.01	bc	ba	d	c	e	bac	d	a
ASD24	≤ 0.01	d	bc	bc	a	c	ba	c	ba
0 kPa	≤ 0.01	b	c	ba	a	b	b	c	c
- 2.5 kPa	≤ 0.01	bc	e	a	bc	ba	e	dc	de
- 5 kPa	≤ 0.01	bc	e	a	bc	ba	e	dc	de
- 10 kPa	≤ 0.01	a	e	a	dc	ba	de	bc	dce
- 15 kPa	≤ 0.01	a	c	ba	bc	a	c	bc	c
- 20 kPa	≤ 0.01	a	dc	bac	dc	ba	d	bdc	dc
- 30 kPa	≤ 0.01	a	bc	bc	c	ba	c	bc	bc
- 50 kPa	≤ 0.01	a	b	b	b	b	b	b	b
- 100 kPa	≤ 0.01	a	b	bc	bc	bc	c	bc	bc
- 200 kPa	≤ 0.01	a	b	bc	c	bc	c	bc	bc
- 300 kPa	≤ 0.01	a	b	bcd	d	bc	cd	cd	bc
- 500 kPa	≤ 0.01	a	ba	bcd	d	bc	cd	cd	bc
Macro	≤ 0.01	cd	bc	cd	ab	cd	a	d	cd
CMeso	0.20	ns							
FMeso	≤ 0.01	e	f	a	b	c	e	d	e
Micro	≤ 0.01	a	bc	bc	c	ba	c	bc	bc

††Different superscript letters are significantly different at $\alpha = 0.05$. ATBP, after tillage before planting; BT, before tillage; AT, after tillage; DGS, during growing season; BH, before harvest; AH, after harvest; EC, electrical conductivity; pH, soil pH; *pb*, bulk density; K_{sat}, hydraulic conductivity; ASD0.053, proportion of aggregates smaller than 0.053 mm; ASD0053025, proportion of 0.053-0.25 mm aggregates, ; ASD0.250.5, proportion of 0.25-0.5 mm aggregates; ASD0.51, proportion of 0.5-1 mm aggregates; ASD12, proportion of 1-2 mm aggregates; ASD24, proportion of 2-4 mm aggregates; 0 kPa, moisture content at 0 kPa; - 2.5 kPa, moisture content at -2.5 kPa; - 50 kPa, moisture content at -5 kPa; - 100 kPa, moisture content at -10 kPa; - 150 kPa, moisture content at -15 kPa; - 200 kPa, moisture content at -20 kPa; - 300 kPa, moisture content at -30 kPa; - 500 kPa, moisture content at -50 kPa; - 1000 kPa, moisture content at -100 kPa; - 2000 kPa, moisture content at -200 kPa; - 3000 kPa, moisture content at -300 kPa; - 5000 kPa, moisture content at -5000 kPa; Macro, proportion of macropores; Cmeso, proportion of coarse meso pores; Fmeso, proportion of fine meso pores; Micro, proportion of micro pores.

Table S.21. Effects of time on soil properties of 15-30 cm depth under the impacts of tillage and manure applications.

Properties	Prb	---------- 2018 ----------				---------- 2019 ----------			
		ATBP	DGS	BH	AH	BT	AT	DGS	BH
pH	≤ 0.01	c††	c	c	c	b	b	b	a
EC	≤ 0.01	bc	a	ba	de	f	fe	f	dc
pb	0.10	ns							
K_{sat}	0.03	a	bc	bac	bc	a	ba	c	bac
ASD0.053	≤ 0.01	ed	ed	e	e	b	d	c	a
ASD0053025	≤ 0.01	a	ba	bc	c	b	bc	b	bc
ASD0.2505	≤ 0.01	bc	d	ba	d	ba	dc	a	dc
ASD051	≤ 0.01	bc	d	ba	bcd	bcd	cd	a	bc
ASD12	≤ 0.01	c	ba	c	a	d	bc	d	bac
ASD24	≤ 0.01	bc	a	bc	a	dc	a	d	ba
0 kPa	≤ 0.01	b	e	a	dc	dc	de	c	de
- 2.5 kPa	≤ 0.01	b	c	a	b	a	b	a	b
- 5 kPa	≤ 0.01	b	c	a	b	a	b	a	b
- 10 kPa	≤ 0.01	c	c	ba	c	a	c	a	bc
- 15 kPa	≤ 0.01	b	b	ba	b	a	b	a	b
- 20 kPa	0.02	c	c	bac	bc	ba	c	a	bac
- 30 kPa	≤ 0.01	d	bdc	bac	bdc	ba	dc	a	bac
- 50 kPa	0.02	d	bdc	bdac	bdac	ba	dc	a	bac
- 100 kPa	0.02	c	bc	bac	bac	ba	c	a	bac
- 200 kPa	0.09	ns							
- 300 kPa	0.08	ns							
- 500 kPa	0.10	ns							
Macro	≤ 0.01	a	b	ba	b	c	bc	c	bc
CMeso	≤ 0.01	b	b	a	b	ba	b	ba	b
FMeso	≤ 0.01	cd	f	a	e	ba	de	bc	e
Micro	≤ 0.01	d	bdc	bac	bdc	ba	dc	a	bac

††Different superscript letters are significantly different at α = 0.05. ATBP, after tillage before planting; BT, before tillage; AT, after tillage; DGS, during growing season; BH, before harvest; AH, after harvest; EC, electrical conductivity; pH, soil pH; *pb*, bulk density; K_{sat}, hydraulic conductivity; ASD0.053, proportion of aggregates smaller than 0.053 mm; ASD0053025, proportion of 0.053-0.25 mm aggregates, ; ASD0.250.5, proportion of 0.25-0.5 mm aggregates; ASD0.51, proportion of 0.5-1 mm aggregates; ASD12, proportion of 1-2 mm aggregates; ASD24, proportion of 2-4 mm aggregates; 0 kPa, moisture content at 0 kPa; - 2.5 kPa, moisture content at -2.5 kPa; - 50 kPa, moisture content at -5 kPa; - 100 kPa, moisture content at -10 kPa; - 150 kPa, moisture content at -15 kPa; - 200 kPa, moisture content at -20 kPa; - 300 kPa, moisture content at -30 kPa; - 500 kPa, moisture content at -50 kPa; - 1000 kPa, moisture content at -100 kPa; - 2000 kPa, moisture content at -200 kPa; - 3000 kPa, moisture content at -300 kPa; - 5000 kPa, moisture content at -5000 kPa; Macro, proportion of macropores; Cmeso, proportion of coarse meso pores; Fmeso, proportion of fine meso pores; Micro, proportion of micro pores.

APPENDIX D
FIELD AND SAMPLING IMAGES

Figure S.1. An example of eroded woodland-used in chapter 2 and chapter 3.

Figure S.2. An example of flat grassland woodland-used in chapter 2 and chapter 3.

Figure S.3. An example of flat woodland and taking intact core samples from 0 – 90 cm depth, chapter 2, and chapter 3.

Figure S.4. An example of intact core samples divided into three depths 0 – 30 cm, 30 – 60 cm, and 60 – 90 cm depths, used in chapter 2 and chapter 3.

Figure S.5. An example of woodland, grassland, and cornfield surface examples, used in chapter 2 and chapter 3.

Figure S.6. An example of metal intact core sampling from surface 0 – 5 cm depth in a cornfield, used in chapter 2 and chapter 3.

Figure S.7. An example of metal intact core sampling and profile view from surface 0 – 5 cm and 30 – 35 cm depths in a woodland (left down), grassland (top), and cornfield (right down), used in chapter 2 and chapter 3.

Figure S.8. An example of saturation of metal intact core samples of woodland, grassland, and cornfield, used in chapter 2 and chapter 3.

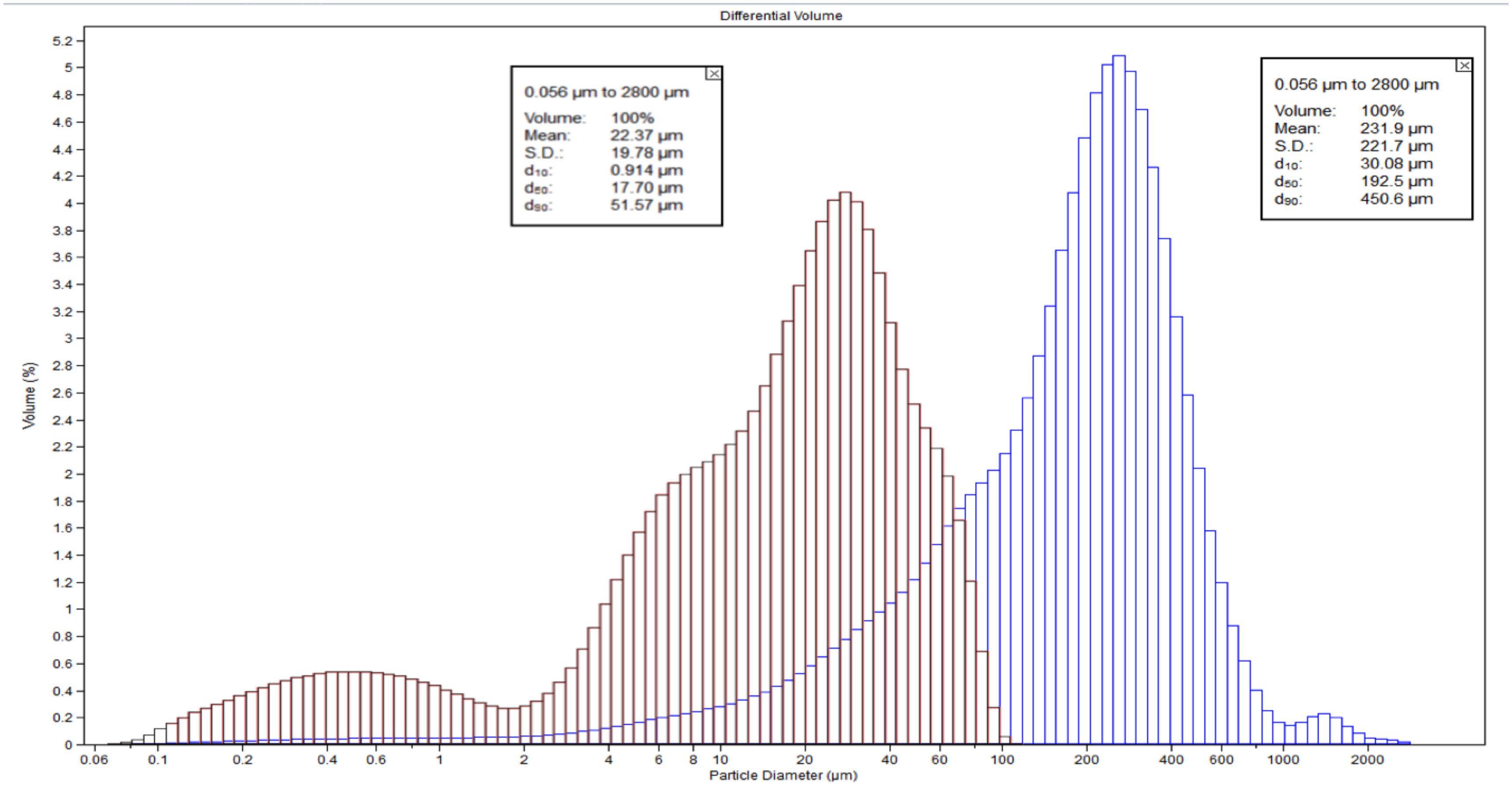

Figure S.9. An example of aggregate size distribution, particle size distribution, and disaggregation reduction by laser granulometry analyzer.

Figure S.10. An example of the study experiment in Arlington, Wisconsin, used in chapter 4. This image shows that this experiment was set on a slopping surface where two plots next to each other are established in a way can make erosion data collection easier.

Figure S.11. An example of manure application in Arlington, Wisconsin, used in chapter 4.

Figure S.12. An example of metal intact core sampling from surface 0 – 5 cm depth in Arlington, Wisconsin, used in chapter 4.

Figure S.12. An example of soil sampling in Arlington, Wisconsin, used in chapter 4.