WINTER WHEAT MANAGEMENT FOR IMPROVING SOIL QUALITY AND REDUCING GREENHOUSE GAS EMISSIONS

A Dissertation
Submitted to the Graduate Faculty
of the
North Dakota State University
of Agriculture and Applied Science

By

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In partial Fulfillment of the Requirements
for the Degree of
DOCTOR OF PHILOSOPHY

Major Program:
Natural Resources Management

August 2013

Fargo, North Dakota

North Dakota State University
Graduate School

Title

Winter Wheat Management for Improving Soil Quality and Reducing Greenhouse Gas Emissions

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DOCTOR OF PHILOSOPHY

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ABSTRACT

Carbon dioxide (CO_2) and nitrous oxide (N_2O) concentrations in the atmosphere have greatly increased in recent times. Intensive agricultural practices, combustion of fossil fuels, deforestation, and wetland drainage have been linked to increased greenhouse gases (GHG) levels. Although scientists are not unanimous in their belief that the increases in GHG is a cause behind recent global temperature rise, there is evidence that increases in GHG might directly increase global temperatures and unpredictable weather occurrences. Since human activity may be partially behind the rise in GHG emissions, it follows that changes in agricultural management might reduce the rate of GHG increases or even mitigate existing increases. Agricultural management practices proposed to mitigate GHG emissions in agricultural soils include conservation tillage, diversified cropping systems, and crop residue management. The objective of this study was to determine the impacts of high-residue no-till systems in a diverse rotation using seven cropping systems in which winter wheat (*Triticum aestivum* L.) was included or not included. The study was imposed on existing rotations present at the Conservation Cropping Systems Project (CCSP) farm near Forman, ND. The CCSP site was established in 2001 under no-till production and managed by the Wild Rice Soil Conservation District**.** Analysis of 2006 and 2010 soil organic carbon (SOC) data showed no significant difference between winter wheat rotation treatments and rotation treatments without winter wheat. Analysis of 2012 SOC data resulted in greater SOC in the corn (*Zea mays* L.)-soybean (*Glycine max* L.) rotation and lower SOC in the spring wheat (*Triticum aestivum* L.)-winter wheat (*Triticum aestivum* L.)-cover crop-soybean rotation. Some rotations had greater SOC than others, but the differences were not related to whether or not winter wheat was included in the rotations. Analysis of residue showed a greater C:N ratio and greater potential N requirement for the subsequent crop in fresh residue compared to aged residue. The COMET-VR model used to estimate SOC levels overestimated SOC in greater diversified rotations and underestimated SOC in lower diversified rotations. No-till production and crop residue retention can increase SOC levels, improve soil quality, and increase SOC sequestration in cropping systems.

ACKNOWLEDGEMENTS

I am deeply grateful to the Departments of Natural Resources Management, Range Science, and Soil Science in the College of Agriculture, Food Systems, and Natural Resources at North Dakota State University, Fargo, ND, USA, for granting me the opportunity to pursue a doctoral training. I would not have got this educational opportunity to pursue a graduate degree if I was in South Sudan. So thank you for uplifting me intellectually and professionally.

My special thanks go to my major advisor, Dr. Larry J. Cihacek, for his guidance, tutelage, mentoring, and friendship during this educational training. It was due to his understanding, patience, and expertise that I was able to finish my coursework, conduct research, pass comprehensive exams, and finally write this dissertation. I would also like to thank my graduate committee members, Dr. Dave Franzen, Dr. Jack Norland, and Dr. Tom DeSutter, whose professionalism and expertise tremendously contributed to this important academic achievement. Their discussions, suggestions, clarifications, and advice had made this educational endeavor a reality.

I am also thankful to Keith Jacobson and Joel Bell for helping me with laboratory analysis of soil samples and plant residues. I would like to thank Curt Doetkott and Dr. Jack Norland, who helped me with the statistical analysis. My thanks also go to department chairs (Dr. Frank Casey and Dr. Carolyn Grygiel) and supportive staff (Ms. Pam Loose, Ms. Valerie Larson, and Ms. Barbara Magnusson) for their leadership. I am grateful to Ted Alme (NRCS-ND State Agronomist) for training me in RUSLE2 erosion model. I would like to acknowledge the financial assistance that Ducks Unlimited provided me to conduct this research at the Conservation Cropping Systems Project (CCSP) site. I am also thankful to Kelly Cooper for the management of the CCSP site.

I am extremely grateful to my wife (Abuk Gop Chol) and my children (Aher, Abang, and Adhel) for their moral support throughout this graduate training. Their love, understanding, patience has got me this far.

I acknowledge that this research would not have been a success without the incredible support of School of Natural Resources Sciences Graduate Research Assistantship. Finally, I would like to thank my officemates (Brandon Montgomery, Hanggong Bu, and Lakesh Sharma) who helped me from day to day basis during my graduate studies.

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GENERAL INTRODUCTION

Many climatologists have predicted significant global warming over the next decades because of increased atmospheric CO_2 and other trace gases (Fischer et al, 1994). Anthropogenic enrichment of atmospheric GHGs may be affecting the balance between incoming solar radiation and outgoing infrared radiation within the Earth's atmosphere and is perceived to have increased global surface temperatures (Wang et al., 2010). Carbon dioxide concentrations within earth's atmosphere have increased from 280 to 378 parts per million by volume (ppmv) between the years 1750 and 2007 and have been projected to increase at the rate of 1.5 parts per million by volume (ppmv) per year (Wang et al., 2010). Nitrous oxide (N_2O) and methane (CH_4) atmospheric concentrations have increased, respectively, from 270 to 314 parts per billion by volume (ppbv) and 700 to 1745 parts per billion by volume (ppbv) during the same time. Most of these GHG increases are attributed to fossil fuel combustion and modified land use practices (IPCC, 1996).

As temperature continues to rise and precipitation becomes more variable and unpredictable, climate change is projected to impact our general environment (Kotir, 2011). A rise of 2ºC in the atmosphere has been predicted to cause increased frequency and intensity of floods and storms, water resource shortages, food shortages, and greater depth of seasonal permafrost thaw (Beddington et al., 2012).

The climate of Sub-Saharan Africa has already shown significant variability in average temperatures, amount of rainfall, and frequency and intensity of extreme weathers such as floods and droughts (Kotir, 2011). Climate change may lead to reduced crop yield due to shortening of crop growing seasons, decrease in plant available water due to higher evapo-transpiration rates, and poor vernalization of cereal crops in temperate regions (Parry et al., 1999; Parry et al., 2005).

Vernalization is important because it reduces the risks of winter crops entering the very cold sensitive reproductive development stage, thereby reducing the danger of low temperature damage (Fowler et al., 1996). Lack of vernalization can result in low flower bud initiation that can subsequently lead to yield reductions in winter wheat in temperate regions (Parry et al., 1999). A rise in temperature may also increase the range of many agricultural pests and their ability to overwinter and attack spring crops (Schmidhuber and Tubiello, 2007).

Climate change may affect agriculture in developed and developing countries in different ways (Parry and Rosenzwig, 1994). Global climate model (GCM) simulations have predicted positive changes in crop yields in middle and high latitudes where many developed countries are located and negative changes in crop yields in low latitudes where many developing countries are located (Parry and Rosenzweig, 1994; Tubiello et al., 2000; Parry et al., 2005; Kotir, 2011). Climate change may also increase dependency of developing countries on imports from developed countries and will decrease food security in Sub-Saharan Africa and perhaps South Asia (Schmidhuber and Tubiello, 2007).

It is estimated that agricultural practices may be responsible for about 20% of all GHG emissions (Follett et al., 2005; Wang et al., 2010). About 60% of pre-settlement soil organic carbon (SOC) in temperate regions and 75% of SOC in tropical regions have been decomposed or eroded away by plow-based tillage, thereby emitting about 23% of present GHGs into the atmosphere (IPCC, 1996; Lal, 2004a). Depending upon management practices, agriculture can either emit CO_2 or sequester CO_2. Lal and Kimble (1997) noted that changing prairies, grasslands, forests, and woodlands into agricultural lands has increased C effluxes from soil to the atmosphere. Tillage increases soil organic matter (SOM) oxidation by exposing a greater soil surface area to oxygen and increasing SOM-soil microbe contact (Lal and Kimble, 1997; Warren

Wilson College, 2012). Tillage disturbs soil biology through disruption of soil structure, rate and capacity of supplying water and nutrients to crops, and long-term soil productivity and economic profitability (Lal, 1991). Agricultural practices have led to the depletion of SOC through deforestation and biomass burning, wetland drainage, removal of crop residues, and the use of summer fallow (Krull et al., 2012). According to Sherrod et al. (2003), summer fallow interrupts the balance between mineralization and immobilization processes and subsequently increases soil moisture and temperature conditions that enhance SOC oxidation.

Higher soil temperatures may increase the rate of mineralization of SOM, which may decrease the integrity of soil structure, subsequently decreasing plant available water, and inhibiting nutrient cycling (Bhati and Tarnocai, 2009). Soil OM generally decreases as temperature increases due to increased microbial activity (Parr et al., 1990). Depletion of SOM reduces long-term soil fertility and crop productivity, increases soil crusting and compaction, increases soil susceptibility to wind and water erosion, decreases soil aggregation and aggregate stability, reduces plant nutrients, and reduces soil microbial activity (Allison, 1973; Lal and Kimble, 1997). Therefore, GHG concentrations have become a major concern to global citizens, government policy makers, and many scientists because of their possible link to rapid climate change and subsequent impacts on food production and agricultural sustainability.

Agronomic Management of Winter Wheat to Improve Yields and Soil Quality

Winter wheat (*Triticum aestivum* L.) is a native of southwest Asia and is part of the Poaceae family of grasses (Kumar et al., 2012). Winter wheat is seeded in mid-September through early December and harvested from mid-June and early July. It is a fast growing crop that has the ability to suppress annual weeds through its rapid spring soil coverage and possible allelopathic effects (Kumar et al., 2012). Hard red (HR) winter wheat is more winter-hardy than soft red (SR) winter wheat **(**Singer et al., 2005), making it a better option for growers in North Dakota. Field experiments in North Dakota have also noted that HR winter wheat usually produces higher yields compared to HR spring wheat (*Triticum aestivum* L.) (Entz and Fowler, 1991).

Winter wheat is grown throughout the US Great Plains due to its ability to capture moisture during the late fall, winter and early spring seasons. In much of the Great Plains, moisture is less during mid and late summer. However, winter wheat can increase its water use efficiency (WUE) by reducing the time for evaporative soil water loss and maximally utilizing the water during snowmelt in the early spring. More extensive and deeper root development as well as higher transpirational leaf area in the early season also improves greater early season water use efficiency. Earlier spring growth of winter crops is an important contributing factor to the higher productivity of winter wheat compared to other crops grown in the spring and summer (Entz and Fowler, 1991).

Winter wheat provides benefits to growers that include higher and more consistent yields, reduced cost of production, increased profitability, greater soil moisture recharge, reduced soil erosion, improved water quality, improved soil structure, diversity to crop rotation, and wildlife habitat (Ducks Unlimited, 2012). “Including winter wheat in crop rotations with summer crops improves control of problem summer annual and perennial weeds, reduces the incidence of residue-borne fungal diseases, and is an excellent source of residue cover for reduced tillage systems” (Staggenborge et al., 2003). To achieve these benefits, management of pests and diseases and timely application of fungicides, herbicides, and fertilizers is essential for increasing winter wheat productivity.

In no-till production, winter wheat should be seeded directly into standing stubble (Ducks Unlimited, 2012; Nleya, 2012). Consideration should be given to whether the previous crop residue height is sufficient to catch snow to protect winter wheat from extreme cold temperatures. Standing stubble should have the ability to trap about 51 mm (2 in**)** of snow to ensure winter wheat survival during the winter season (Ducks Unlimited, 2005). Singer et al. (2005) found that snow-covered fields tended to increase winter wheat survival in Iowa.

Another important management strategy of winter wheat is application of N and P fertilizers as well as selection of appropriate varieties. Nitrogen application to winter wheat is important not only for yield but to achieve adequate protein content. Research in North Dakota and Montana has indicated that 30 kg N/ha (0.04 lb. N/bu) is needed to achieve 12% protein in winter wheat (Ducks Unlimited, 2012). In southern Alberta, researchers found fall application of control released urea (CRU) and side-banded urea in mid-September more effective in increasing grain yields, protein content, and N uptake than seed-placed urea in a no-till winter wheat production (McKenzie et al., 2008).

Winter wheat gradually releases its immobilized N to the subsequent crop after residue decomposition (Kumar et al., 2012). Their study reported that winter wheat makes residual N available for the succeeding crop during the growing season although more N fertilizer is usually applied to subsequent crop after the wheat. In no-till production, observing and predicting the impacts of crop residue on nutrient availability over both short-and long-terms is a nutrient management challenge (Schoenau and Campbell, 1996). Nitrogen returned to the cropping systems through crop residues from previous years of cropping systems should be accounted for because it replenishes SOM reservoirs (Grant et al., 2002). Therefore, N management can be complicated by the influence of the previous crop residue and residual soil-NO_3-N on N availability to the following wheat crop.

Winter wheat that immediately follows summer crops such as soybean (*Glycine max* L.) and grain sorghum (*Sorghum bicolor* L.) needed different management strategies for each previous crop to maximize yields (Staggenborg et al., 2003). Wheat following grain sorghum required about 21 kg N/ha more N fertilizer to increase yields than wheat following soybean in Kansas (Staggenborg et al., 2003). Greater N requirement for wheat that succeeded grain sorghum was attributed to the greater residue produced by grain sorghum with low N content (Staggenborg et al., 2003). Their study recommended that an additional 24 kg N/ha should be applied when winter wheat follows grain sorghum compared with N rates when winter wheat follows soybean. Phosphorus helps winter wheat survive winter by promoting early root growth and fall tillering (Ransom et al., 2012). Selection of winter wheat varieties that have performed well over many years at different experimental locations nearby crop fields can also increase winter wheat survival and yields (Ransom and McMullen, 2008; Ransom et al., 2012). Characteristics to consider when selecting a winter wheat variety include winter hardiness, yield potential, protein content, maturity, test weight, disease and insect resistance, coleoptile length, lodging resistance, baking quality, and yield stability (Nleya, 2012).

Application of fungicides to control winter wheat diseases is important to maximize yields. Research trials conducted from 2001 to 2004 at NDSU found most consistently high winter wheat yields with split application of fungicides (Ducks Unlimited, 2005; Ransom and McMullen, 2008). Application of foliar fungicides was also an important management practice for wheat seed growers in regions where foliar diseases affected overall grain yields (Kelley, 2001). Fungicides were most beneficial where wheat had a relatively high productive potential.

Management of Cover Crop Residue to Improve Soil Quality

Management of cover crop residue prior to planting the subsequent crop can be an important component of the crop production management system (Kuo and Jellum, 2002). Wheat stubble is more effective in protecting the soil surface when standing than when laying on the soil surface (Allison, 1973). It is a good residue source that provides soil and environmental quality benefits when left on the soil surface in no-till cropland (Kumar et al., 2012). Winter wheat usually produces about 4.4 to 11 Mg/ha of residue of dry biomass (Kumar et al., 2012). Its residue contains about 44% C and 0.45% N and, therefore, has a C:N ratio of approximately 98:1 (C:N = 44/.045 = 98:1) (Kumar et al., 2012). They reported that winter wheat returns about 363 to 998 kg (800 to 2,200 lb.) of C and about 11 to 26 kg N/ha (9 to 23 lb. N/ac).

Winter wheat provides a more favorable soil surface cover and has the ability to anchor previous corn and soybean residues, increase water infiltration, and reduce both rill and inter-rill erosion (Singer et al., 2005). Therefore, residue stability is important for soil erosion management and long-term nutrient supply. Winter cover crops, including winter wheat, reduce the potential for NO_3-N leaching through absorbing and storing N in the plant tissue during late winter and early spring, thereby absorbing spring soil water and reducing water percolation (Weinert et al., 2002). The incorporation of the residual NO_3-N into the plant tissues helps reduce N leaching and denitrification. Cover crops contribute to sustainable crop production by increasing SOC, improving soil structure and aggregate stability, conserving soil water, and reducing runoff and soil erosion (Frye and Blevins, 1989).

Additional cover crops commonly grown in North Dakota are forage radish (*Raphanus sativus* L.) and field pea (*Pisum sativum* L.). Forage radish roots contain about 80% water and, therefore, degrade more easily than many cover crops (Hoffbeck et al., 2008). Forage radish is partly grown in parts of the US to reduce soil compaction and increase residue decomposition although its role in alleviating compaction in North Dakota is minimal due to the shrink-swell characteristics of native smectitic clay dominated soils in the state. Forage radish helps alleviate soil compaction through penetrating dense soil layers and producing channels that increase water infiltration rate, improve soil aeration, and allow deeper root penetration when the soil is dry. The process of root penetration into the compacted soil layers to create channels is sometimes called “biological drilling” (Hoffbeck et al., 2008). Their study also found that radishes increased microbial activity and degradation of excess wheat residue which makes seedbeds warmer and drier in the spring for corn planting.

REVIEW OF LITERATURE

Effects of Agricultural Production on Greenhouse Gas (GHG) Emissions and Soil Quality

Climate change is defined as long-term changes in temperature, precipitation, wind, and other elements of the Earth's climate system (Follett, 2001). In recent times, interest in climate change has increased across the globe. A major concern is the increasing level of atmospheric GHGs (IPCC, 2001) that many scientists believe are contributing to climate change. About 80 ppmv CO_2 concentration in the earth's atmosphere was released from agricultural activities prior to industrialization (Desjardins et al., 2002). Intensive agricultural practices and unsustainable land uses have increased atmospheric CO_2 concentration and rapid degradation of soil and water resources since then. Mechanical preparation of the seedbed is a predominant agricultural operation that exacerbates soil degradative processes and intensifies the rates of SOC mineralization and decomposition (Kimble and Lal, 1997).

Agriculture has been implicated in greenhouse gas emissions and global climate change because numerous studies have indicated that it is a principal contributing source of emissions and accumulation of GHGs in the earth's atmosphere (Paustian et al., 1997a). Their studies have indicated that past anthropogenic CO_2 emissions have contributed about 50 Pg SOC in the atmosphere through SOC mineralization in tilled soils. Agriculture accounts for 20% of the annual increase in all human-induced greenhouse emissions (Follett et al., 2005).

Increased use of fossil fuel for energy production and land use changes for agriculture production have also increased the concentrations of greenhouse gases in the earth's atmosphere (Watson et al., 1996). Intensive agricultural practices have resulted in the loss of 50% of the original SOC in the first 25 years of cultivation (Matson et al., 1997). Most soils already converted to agricultural lands have lost 30-50% (11-18 tons SOC per acre) of the original SOC level (Cihacek and Ulmer, 1995). As cultivation intensifies, initial SOC levels drop until some improved conservation management practices are adopted and implemented (Fig. 1).

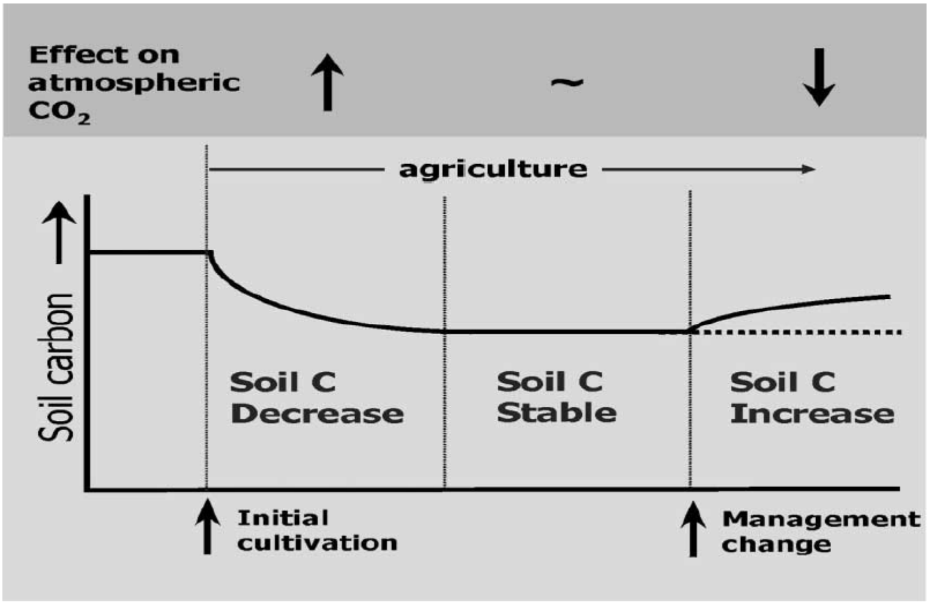

Figure 1. Changes in the long-term storage and release of soil carbon as CO_2 as a result of agricultural practices (Janzen et al; 1998; obtained from Follett, 2001).

Agriculture activities have also increased the C mineralization by bringing SOC into direct contact with microbes and exposing SOC to oxygen (Lal and Kimble, 1997). Soil OC mineralization rates are about 2% per year in temperate climates and 5% over per year in tropical climates (Woomer et al., 1994). In general, SOM levels decrease as temperature increases due to increased microbial mineralization rates and length of mineralization rates during a year (Parr el al., 1990).

Effects of Conservation Cropping Systems on SOC

Cropping systems are defined as crop rotations and associated agricultural management operations that make the crop rotations possible (Wang et al., 2010). An ideal cropping system should produce and return enough organic C to the soil to at least maintain SOC levels. Intensive cropping systems and reduced tillage is required to reduce SOC losses in the Northern Great

Plains soils (Cihacek and Ulmer, 1995; Halvorson et al., 2002). Cropping systems that reduce tillage and increase soil surface residue tend to increase SOC in agricultural soils. Soil OC sequestration can also be augmented in agricultural lands by adding sufficient plant residue biomass (Follett, 2001).

No-till systems are variants of conservation tillage practices that minimize soil disturbance, increase soil surface residue, reduce erosion, and increase SOC (Franzluebbers, 2011). Agricultural soils under conservation tillage, especially no-till production, can also increase SOC necessary to increase food production and agricultural sustainability (Wang et al., 2010). Adoption of no-till and continuous cropping systems has the potential to reduce CO_2 loss from croplands through capturing and storing SOM (Bell et al., 2003). Reduced tillage increases SOC because it decreases the mixing and aeration of crop residues and promotes the stabilization of aggregates in the soil surface. No-till management, use of cover crops, diverse crop rotations, and appropriate fertilizer and manure applications can help capture CO_2 and store SOC (Desjardins et al., 2002). Soil OC levels can be expected to increase beginning from 5 to 10 years of start date and reach a higher SOC steady state in 15 to 20 years using no-till production (Liu et al., 2006).

Nitrogen rate experiments conducted in North Dakota from 1971 through 2009 suggested that spring wheat in no-till systems required less N fertilizer compared to conventional tillage (Franzen et al., 2011). Spring wheat under conventional tillage required a 146 kg N/ha (130 lb. N/ac) to attain a 2.7 Mg/ha yield, while no-till system required less than a 90 kg N/ha (80 lb. N/ac) to achieve the same yield. The study also reported that no-till systems in eastern and western North Dakota required about 56 kg N/ha (50 lb. N/ac) less to produce similar yield and protein content compared to conventional tillage systems.

Effects of Crop Rotation on Soil Quality and SOC Sequestration

Crop rotation can be defined as a cropping system in which one or more crops are alternated in the cropping system over a period of time on the same piece of land (West and Post, 2002). They reported that crop rotation complexity can be increased through: (i) a change from monoculture to continuous rotation cropping system, (ii) a change from a crop fallow system to a continuous cropping rotation system, and (iii) increase in the number of crops used in the rotation cropping systems.

Crop rotation can influence soil health by improving soil aggregate, maximizing crop efficient use of soil water and nutrients, providing a better weed control, and reducing insects and diseases lifecycles (Carter et al., 2003). Inclusion of legumes into corn cropping systems resulted in higher corn yields, N cost savings, SOC sequestration, and GHG emission reductions (Meyer-Aurich et al., 2006). Crop rotation systems efficiently reduced long-term yield variation better than monoculture systems and increased total soil C and N concentrations (Varvel, 2000; Kelley et al., 2003).

Crop rotations which maximize soil C inputs and maintain a large quantity of labile C are essential for creating sustainable cropping systems (Overstreet and Dejong-hughes, 2009). Intensification of cropping systems and reduction of fallow frequency can improve total crop production over years, increase C inputs, and increase SOC (Campbell et al., 2001). Campbell et al. (1999) found higher SOC levels in a wheat-lentil rotation than in wheat monoculture. The difference in SOC levels was attributed to more efficient conversion of plant residue C to SOC in the wheat-lentil rotation system compared with the wheat monoculture system**.** Sawyer et al. (2006) reported that lower rates of N fertilizer were required for a corn crop when corn followed soybean than when corn followed corn (Sawyer et al., 2006). The US Corn Belt states (Iowa, Minnesota, Nebraska, and Illinois) have reduced their N recommendation rates when the preceding crop is soybean. Including legumes in a crop rotation not only reduced chemical fertilizer N inputs but also reduced the use of fossil fuel required to make N provided by legumes (Campbell et al., 2001).

Greater residue biomass and SOC sequestration level were found in crop rotations in which legumes and non-legumes were alternated (Meyer-Aurich et al., 2006; Wang et al., 2010). Total dry weight and N content of crop biomass produced per a unit area was greater when legumes and non-legumes were planted in a mixture than when each crop was planted alone (Allison, 1973; Carter et al., 2003). A 15 year study that alternated corn and soybean observed larger total biomass in the corn-soybean rotation than corn or soybean in monoculture (Drinkwater et al., 1998).

Use of Soil Quality Indicators for Soil Management

Indicators are metrics which show desirable or undesirable changes in land, water, and vegetation management that may have happened or may happen in the future (Dalal et al., 2003). Effects of agriculture on soil quality and soil productivity can be observed through changes in soil quality indicators. Soil quality indicators can be monitored through field observation, field sampling, remote sensing, survey, and gathering of existing information to determine changes in the various ecosystems (Walker and Reuter, 1996). Soil quality indicators are important soil evaluation tools for: 1) maintaining and enhancing the soil conditions; 2) evaluating soil management practices and techniques; 3) relating soil quality to the quality of other resources (e.g., surface-and groundwater quality); 4) collecting the necessary information to determine trend of changes; 5) determining trends in soil health; and 6) guiding land manager’s decisions (USDA-NRCS, 1996).

General Review of Crop Residues

One management practice that has been proposed to increase SOC storage is the use of crop residues (Lal, 2011**)**. Crop residue was defined as a biomass that has been left in the farmland after grains and other economical components have been removed (Lal, 2011). Biomass has been defined as a "wide range of plant and animal-based products including grass, short rotation trees or woody/herbaceous perennials, animal waste, by-products of food processing and timber industry, agricultural processing and crop residue" (Lal, 2005).

The areal extent of major crops produced in the United States are in order of corn > wheat > soybean (Blanco-Canqui and Lal, 2009). The quantity of corn, rice, sorghum, wheat, millet, barley, and rye in the USA and in the world in 2001 was about 0.5×10^9 Mg/yr (Mg = 1000 kg) and about 4×10^9 Mg/yr (Mg = 1000 kg), respectively, (Lal, 2005). The average of this crop residue contains about 0.8% N (8 g N/kg), 0.1% P (1 g P/kg), and 1.3% K (13 g K/kg) (Lal, 2011). Crop residue is about 40% to 45% of the total aboveground crop biomass on a dry weight basis (Lal, 1997; Lal, 2011).

Small-grain cereals provide the most important crop residues for soil and water conservation and soil surface management (Lal, 1997). Small-grain residues always have a high straw: grain ratio, low oxidation potential, and high C:N ratio. The high-residue property of cereal grains makes them an ideal resource for soil cover and SOC sequestration over a long period of time. Crop residue nutrient concentration is determined by the season, management, time of crop harvest, and location (Wortman et al., 2008).

Quantity of residue biomass is influenced by soil quality, eco-regional properties, cropping systems, soil and crop management practices, and climatic conditions (Lal et al., 1998). Transformation of residue into SOM is influenced by type, quantity, quality, and management of residue (Franzluebbers, 2009). Temperature and precipitation have an important effect on residue-derived SOC because different amounts of residues are required for warm and cool regions to achieve a significant level of SOC sequestration (Blanco-Canqui and Lal, 2009). Thus, warmer climates require more residue cover than cooler climates.

Age of crop residue also influences soil moisture and temperature. Fresh residue which is denser than aged residue provides more soil surface insulation and, thereby, reduces evaporation and temperature (Sauer et al., 1996). They noted that fresh residue provided a greater soil cover and soil surface reflectance due to more leaves than the aged residue.

Effects of Crop Residue on Soil and Water Conservation

Crop residue mulch is an important component of soil surface management because residue improves soil and water conservation, maintains SOM, and augments soil microbial activities (Lal, 1991). Residue-covered no-till systems help increase aggregate stability and maintain the continuity of soil pores which, therefore, increases infiltration rates and mitigates soil erosion (USDA, 1996). Reduced tillage systems in conjunction with surface residue retention can increase soil water by increasing infiltration rate and reducing the runoff (Van Donk, 2010; Wall and Thierfelder, 2012). Leaving more standing crop residue captures more snow and anchors it where it falls during the winter, thereby storing more soil water when the snow melts.

An increase in SOC due to residue retention has been associated with increased water infiltration rate, reduced evaporation rate, improved soil internal drainage, developed extensive and deeper root systems, and increased yields (Allison, 1973). Residue degradation in winter enhances the partially weathered residue capacity to store more water than fresh residues (Wilhelm et al., 2004). Crop residue left on the soil surface in Kansas was important for soil and water conservation during the non-growing season and the next growing season (Klocke et al., 2009).

Effects of Crop Residue on Crop Yields

Crop residue conserves water and soil moisture for crop growth and yield increase. Power et al. (1986) observed an increase in corn and soybean yields in fields where residues were retained on the soil surface compared to the corn and soybean fields where residues were removed. A strong relationship was found between crop yields and increased SOC from an increased root biomass and quantity of residues produced and returned to the soil (Reilly and Fuglie, 1998).

Research conducted in the West African Sahel reported the greatest millet grain and straw yields, increased water and fertilizer use efficiency, and increased SOC under residue retained conditions (Yamoah et al., 2002). Wilhelm et al. (1986) found an increase in grain and residue yields from residue additions under a corn-soybean rotation. The increase in grain and residue yields in both corn and soybean was attributed to water conservation from residue retention on the soil surface.

Effects of Crop Residue on Soil Physical Properties

Plant residue retention and tillage management practices affect soil physical properties that are important for capturing water, conserving soil, and increasing infiltration (Shaver, 2010). Bulk density is a parameter that is always affected by tillage (Aparicio and Costa, 2007). No-till production increases surface residue which, in turn, influences bulk density (Shaver, 2010). A 10-year study reported bulk densities of 1.51 Mg/m^3, 1.47 Mg/m^3, 1.44 Mg/m^3, 1.48 Mg/m^3 for 0, 50, 100, and 150% quantities of residues applied to the soil surface, respectively, (Power et al., 1998). Analysis of effects of residue management on soil porosity reported porosities of 43.5 %, 44.2%, and 45.7% for harvested residue, normal residue cover, and for double residue cover treatments, respectively, (Karlen et al., 1994). The increase in soil porosity was attributed to plant residue production and its retention on the soil surface.

A 10-year study under residue no-till system showed higher macro-aggregate stability in a double residue retained treatment compared to normal-and removed-residue treatments (Karlen el al., 1994). Increase in soil aggregation is important due to its positive effects on bulk density, porosity, and water infiltration and use efficiency (Carter, 2002; Shaver, 2010). Well-aggregated soils are very productive because they allow seed placement, seedling growth, nutrient uptake, and water absorption (Blanco-Canqui and Lal, 2009). Soil aggregation conserves and protects SOM and allows the preserved SOM to act as a pool for plant nutrients and energy (Carter, 2002). Aggregate SOM serves as an indicator of soil permeability and erodibility because it regulates air and water infiltration rates as well as soil stability (Feller and Beare, 1997).

Effects of Crop Residue Removal

Removal of crop residues reduces C input and nutrient cycling, increases surface sealing and crusting, reduces soil aggregation, decreases food and habitat for soil microorganisms, and reduces soil quality (Blanco-Canqui and Lal, 2009). Residue removal can increase soil erosion and runoff and increase soil crusting and compaction. Removal, burning, and soil-incorporation of crop residues can increase erosion, deplete soil fertility, pollute surface water sources and contaminate groundwater resources (Lal, 1997). A study reported that removal of crop residues removes potential soil cations such as Ca, Mg, and K which subsequently reduces soil pH (Wortmann et al., 2008; Blanco-Canqui and Lal, 2009). Removing 907 kg (1 ton) of corn residue is equivalent to removing cations containing about 16 kg (35 lb.) of agricultural limestone equivalent. Residue removal may increase N, P, and K deficiencies as well as remove other essential nutrients important to crop production (Blanco-Canqui and Lal, 2009).

Description of COMET-VR

CarbOn Management Evaluation Tool-Voluntary Reporting (COMET-VR) has been proposed for use by farmers and ranchers to quantify and report SOC sequestration and GHG emissions on their farmlands. The model was developed by the Natural Resources Conservation Service (NRCS) of USDA in collaboration with researchers at the Natural Resources Ecology Laboratory (NREL) at Colorado State University (NRCS, 2003-2004). The COMET-VR is a decision-making tool that can be used by agricultural producers, agro-foresters, land managers, soil scientists, and other agricultural interests. It provides a web interface to a database that contains land use data and determines in real time the annual SOC changes using a dynamic CENTURY model. It is available at http://www.cometvr.colostate.edu. The model also helps producers and ranchers to voluntarily report their land management changes under section 1605(b) of the 1992 Energy Policy Act. The 1605(b) section of the Energy Policy Act created a voluntary reporting program for GHG emissions and reductions. Under the 1605(b) section, there is a registry that allows the users or producers to voluntarily report SOC sequestration and GHGs emissions reductions annually. Under the program, users or producers are allowed to enter their location information, SOC storage, fertilizer application, emissions information, and fuel usage. This information is available at climate change website: http://soils.usda.gov/survey/global_climate_change.html.

The model provides farmers with an opportunity to experiment using different management options to determine what management changes may reduce GHG emissions. Farmers who adopt management operations that capture and store C in the soils are able to sell the stored SOC to intermediary buyers who seek to offset GHG emissions (American Society of Agronomy, 2007). Farmers are also required to document and provide verification that their management practices have increased SOC stocks on their farms. The COMET-VR model has the following features that are available at (ftp://ftp-fc.sc.egov.usda.gov/AIR/AAQTF/200809201009/200909_DesMoines_IA/AAQTF_200909_Paustian.pdf) (Paustian, 2009).

- Web-based, easy to use
- Incorporates effects of different soils types, climatic conditions, and land use history
- Allows for wide range of management choices
- Uses state-of-the-art science
- Quantifies uncertainty
- Fast response time 1-2 seconds

Each run in the model is based on users' inputs for a unique parcel that is located in their entity (field) or sub-entity (sub-field). A parcel was defined as an "area of land that has uniform soils and common historical and present day drainage, crop rotations, and grazing or tillage management" (COMET-VR, 2012). Users input data for the COMET-VR execution process are: parcel location and size; soil characteristics; past and present crop rotations and tillage or rangeland practices. Users choose menu options and select inputs based on the regional characteristics.

Users are required to keep records of their individual parcel estimates and add these estimates to make entity or sub-entity level estimates. To log into the COMET-VR system, users can access the model at http://www.cometvr.colostate.edu, and then execute seven general steps. These steps include state selection, county selection, parcel (farm) selection, soil selection, rotation selection, tillage selection, and fuel and fertilizer selection as explained by Yellajosula (2010).

CSRA Data Gathering Process

The Carbon Sequestration Rural Appraisal (CSRA) contains a series of data sheets that detail historical land-uses and dominant management practices such as drainage, irrigation, crop rotations, tillage and fertilization, and grazing over time. The input data in CSRA was used for land management and cropping system histories in 20 regions in the United States. Examples of such areas where a team of NRCS experts worked to input the required information into the CSRA were Indiana, Iowa, and Nebraska (Yellajosula, 2010). The data sheets were put together by experts in each Land Resource Region (LRR). Consequently, the model focuses on the US Corn Belt cropping systems.

To gather the data, individual Land Resource Region (LRR) maps that described the specific land cover such as irrigated and non-irrigated agricultural lands and the area in each category were developed. More data information was collected at the county levels to address management decisions that were important for crop production. This information included irrigated or non-irrigated crop rotations, fallowing periods, fertilizer rates and timing, tillage events and timing, crop yields, grassland type, fire frequency, fertilizer rates and timing, and grazing intensity and duration. Where necessary, CSRA data was compared with other published data for their validity**.** Experts collected data from 1890 to the present time. Additional data was obtained from tillage practices that included moldboard plow to the current conservation management practices. Any information related to manure use and inorganic fertilizer applications were obtained from local farmers. The collected information was entered into a GIS system.

Finally, based on the specific information that was obtained from each area, maps were created for those locations. The results were organized and reported in a way that would make the voluntary reporting convenient for potential users to report their individual GHG emissions and SOC sequestration rates in their fields to the U.S. DOE. The compiled data collection is available at http://www.cometvr.colostate.edu/about/. To accomplish the data entry, a data for each parcel of the land was entered into the CSRA, which had land use and main management practices such as drainage, irrigation, crop rotation, tillage and fertilizer application, and grazing information.

Interaction of COMET-VR Web Interface and CENTURY Run Controller

The web interface has the ability to collect the user's information and build the needed history details from the SQL database (Fig. 2). The collected information is then sent by the IIS WEB server through an APACHE WEB server to the CENTURY Run Controller.

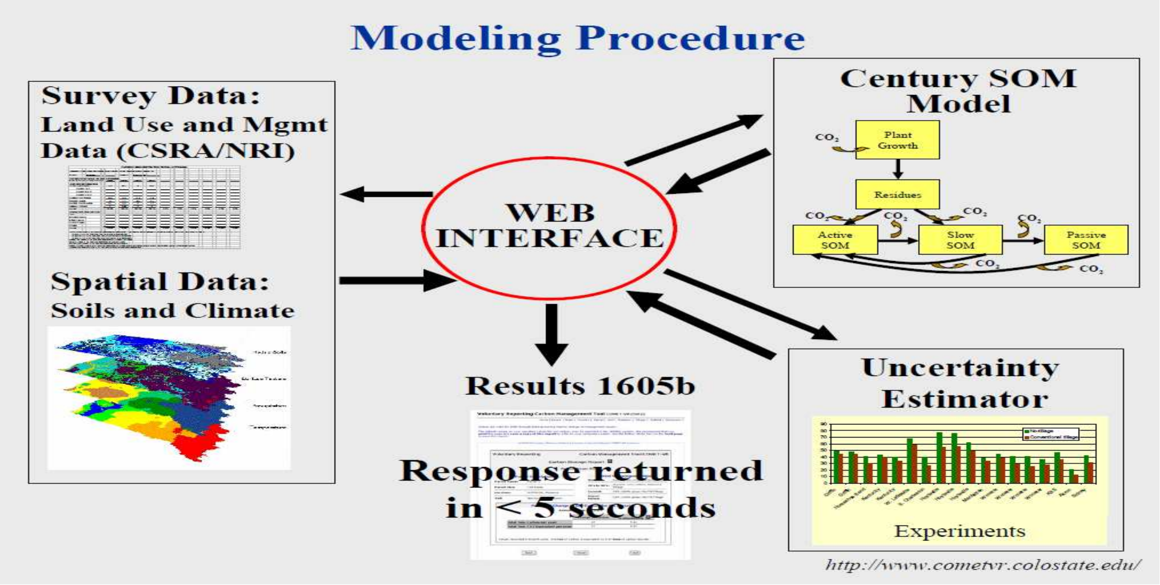

Figure 2. Diagrammatic view of interaction of COMET-VR model and CENTURY model for estimating SOC fluxes.

The controller develops each user's unique history and calls the CENTURY executable to calculate the C fluxes and estimates the associated uncertainty. Based on the management information a user provides, C numbers and uncertainty estimates are returned to the COMET database where the web interface extracts the appropriate fuel C and returns the user's results in the form of two tables (USDA-NRCS, 2012) (Fig. 2). This process usually takes about 2 to 4 seconds to create a fully personalized report of SOC changes and associated uncertainty values.

Reporting SOC Storage and N_2O Fluxes

Users run the COMET-VR to generate and estimate the parcel level information of soil C and N fluxes and keep their own records. When the input data in the COMET-VR is submitted, the web interface will run the CENTURY model to produce SOC estimates and provide results to the user through a web browser. The result summarizes input data and provides an estimate of SOC fluxes for the parcel and associated percent uncertainty. The uncertainty represents a range around the estimate that is defined by ± the percentage of the value within which the true value is 95% likely to fall. Soil OC flux rates are determined on long-term soil dynamics.

Parcel SOC estimates can remain valid for a period of ten years. This means that users may use the same SOC and N_2O information for a parcel for up to ten years if the cropping rotation or tillage system has not changed over the past report period. But when changes happen in rotation systems or tillage management practices on the same parcel, a new query of the COMET-VR must be initiated. Under new tillage or rotation changes, all input data will remain the same but entries for the Report Period rotation and tillage practices will change.

If no-till practices are stopped and intensive or reduced tillage system is adopted, the bulk of C that was previously stored in soils under appropriate management systems will be assumed to have been re-emitted to the atmosphere. Under this condition, changing from no-till management to intensive or reduced tillage will lead to SOC losses that are similar to the sum of all reported SOC sequestration for that period. When this condition occurs, users will not be required again to use the COMET-VR to estimate SOC losses. However, they will be required to refer to their own previous records to estimate SOC losses.

Description of CENTURY MODEL

The CENTURY model is used in the background in the COMET-VR to estimate SOC fluxes under different soil management practices, crops, and climatic conditions. CENTURY is a multi-purpose ecosystem tool that was developed through the collaborative efforts of Colorado State University and the USDA-ARS to determine the SOC changes in the Great Plains grasslands (Parton et al., 1987). The CENTURY model had been used to estimate and establish the long-term dynamics of C, N, S, and P on the monthly basis. It has also been effective in providing reliable measurements of SOC changes in the depth of 0-20 cm in the topsoil (Smith et al., 1997). It was also developed to simulate long term C, N, P, and S changes in grassland ecosystems (Parton et al., 1987).

The model is comprised of three SOM pools such as active, slow, and passive with different potential decomposition rates. An active organic fraction represents organic matter that is still undergoing a decomposition process while both slow and passive organic fractions represent extensively decomposed and recalcitrant organic fractions, respectively. The active fraction (SOM1C(2)) represents soil microorganisms and microbial products and has a turnover time of months to a few years, depending on the climatic conditions and soil texture. Slow pool (SOM2C) represents a resistant plant material that has been derived from the structural pool and soil-stabilized microbial products that have been derived from the active and surface microbe pools (Cole et al., 1993). The turnover time of the slow SOM pool is 20 to 50 years.

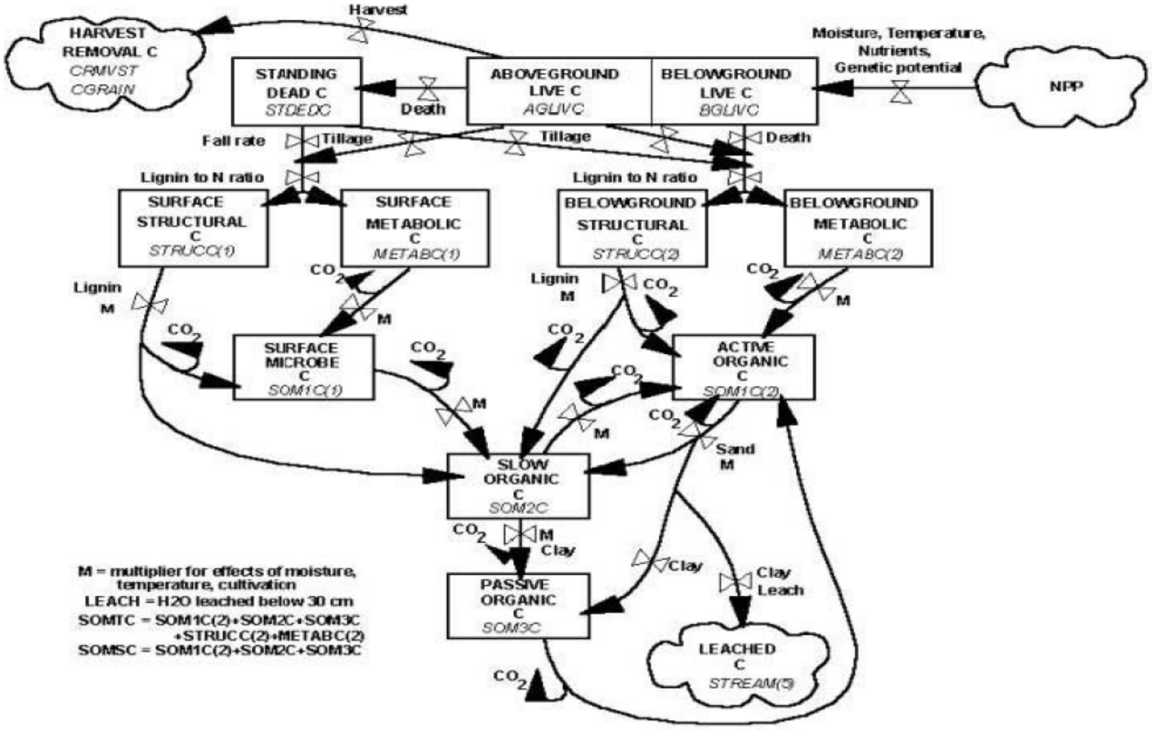

Figure 3. Diagram of major organic C state variable and C flows in CENTURY (COMET-VR, 2011) (adapted from CENTURY, version 4.0, manual).

The passive SOM pool is comprised of physically and chemically stabilized SOM and is very resistant to decomposition. The passive SOM pool has a turnover time of 400 to 2000 years. Cole et al. (1993) reported that proportions of the decomposition products that that enter the passive pool from the slow and active pools increase with increasing clay content. Although the CENTURY model cannot be substituted for a direct estimation of SOC under different management systems, it allows incorporation of various factors which control decomposition processes on SOM changes.

Description of Revised Universal Soil Loss Equation-Version 2 (RUSLE2) Model

Removal of the topsoil has been shown to have many deleterious consequences on soil productivity and environmental quality (Obalum et al., 2012). Soil erosion is a process by which soil particles are displaced by forces of wind and water. It occurs when soil particles are separated from the entire soil mass and transported somewhere else as sediments or dust. Erosion can be a fast or gradual process that reduces soil productivity in such a way that reduction may not be noticed until agricultural land is no longer economically suitable for crop production (National Soil Erosion-Soil Productivity Research Planning Committee, 1981; Nyakatawa et al., 2001; Obalum et al., 2012). However, catastrophic erosions from torrential rainfall or dust storms are easily noticed.

Quantifying and predicting soil loss under different cropping systems and crop management systems require statistical tool (Huggins, 2013). Producers and land managers can use soil erosion prediction models to address their long-term land management planning under natural and agricultural conditions (Angima et al., 2003). A model that has been widely accepted and used within USA to predict erosion rates and sediment yields is the revised universal soil loss equation (RUSLE2). The RUSEL2 model was collaboratively developed by Agricultural Research Service (ARS), Natural Resources Conservation Service (NRCS), and the Biosystems Engineering and Environmental Science Department of the University of Tennessee (RUSLE2, 2013).

RUSLE2 is a new mathematical model that uses equations in a computer program to estimate erosion rates. It uses a modern and powerful user interface rather than the text-based interface that RUSLE1 uses. RUSLE2 has improved computational procedures and, therefore, provides useful output that can be used for conservation planning. RUSLE2 estimates soil loss, sediment yield, and sediment characteristics from rill and inter-rill erosion caused by rainfall and runoff. It evaluates potential erosion rates at specific sites, guides management decisions and conservation planning, inventories erosion rates over large geographical areas, and estimates sediment production on upland areas that might become sediment yields in watersheds. RUSLE2 is also a land use independent model. It estimates erosion on cropland, pastureland, rangeland, disturbed forestland, construction sites, mined land, reclaimed land, landfills, military lands, and in other mineral soils exposed to raindrop impact and surface runoff (RUSLE2, 2013). RUSLE2 works best in croplands. However, it is not a precise estimator of soil loss or residue cover.

Major Factors Used in RUSLE2

Parameters used in RUSLE2 to compute erosion include climate (erosivity, rainfall, and temperature), soil erodibility, topography, cover-management, and support management practices. RUSLE2 factors are represented by equation: A = RKLSCP. Where: A = predicted long-term average of annual sheet and rill soil loss from a defined slope (Nyakatawa et al., 2001); R = rainfall and runoff erosivity factor; K = soil erodibility factor; L = slope length factor; S = slope steepness factor; C = cover-management factor; and P = supporting practices factor.

Climate affects erosion through the amount of rainfall and rainfall intensity and temperature. RUSLE2 “predicts a linear increase in sheet and rill erosion with increasing rainfall erosivity, which reflects the influences of both rainfall depth and rainfall intensity” (Dabney et al, 2012). Soil loss is high in Mississippi due to intense rainfall and low in Nevada due to its desert-like climate (RUSLE2, 2013). About 60% of the annual erosivity (R) happens in North Dakota during June and July, when intensively-cultivated row crops are vulnerable to water and wind erosion due to low soil surface cover (RUSLE2, 2013). Increasing temperature and rainfall can increase residue oxidation and surface roughness degradation, thereby making soil vulnerable to soil attacking forces and runoff (Dabney et al, 2012). In RUSLE2, climate input values are used to describe weather at each location, county, and crop management zone.

Soil type has a major influence on the soil erosion. Some soil types are more erodible than other soils. Soil texture and structure determine the erodibility (K) of each soil. A soil that has a high content of clay and sand is less erodible than a soil that has high silt. High clay soils tend to be more resistant to detachment and, therefore, have low K values. High sand soils tend to have low K values due to their high infiltration rates. High silt soils tend to have greater K values due to their higher detachment rate. The K parameter represents the combined effect of soil detachment, potential soil surface runoff, and the transportation of the eroded soil from the soil mass (RUSLE2, 2013). Soil characteristics are assigned by soil components and map unit. RUSLE2 uses values for clay, sand, and silt fractions to determine the distribution of the sediment particle classes at the point of the detachment. Applicable soils in RUSLE2 include medium texture (best), fine texture (moderate), coarse texture (acceptable), and organic texture (not acceptable) (RUSLE2, 2013).

Topography affects soil erosion through slope steepness and slope length. Generally, topography describes overland flow slope length and slope length for eroding parts of hillslope, steepness, and hillslope shape. Applicable topographical slope lengths include 15 to 91 m (50 to 300 ft.) (best), 15 and 91 to 183 m (50 and 300 to 600 ft.) (moderate), 183 to 305 m (600 to 1000 ft.) (acceptable), and greater than 305 m (1000 ft.) (not acceptable) (RUSLE2, 2013). Applicable slope steepness includes 3 to 20% (best), 0 to 3% and 20 to 35% (moderate), 35 to 100% (acceptable), and greater than 100% (not acceptable).

Land use is the most important factor that influences soil erosion. Management practices that minimize soil erosion include vegetative cover, crop rotations, conservation tillage, residue retention, applied mulch, contouring, strip cropping, terraces and diversions, impoundments, and tile drainage. No-till and mulch-till practice affect the cover-management factor by reducing soil degradation, reducing runoff, and increasing infiltration and SOM, which subsequently reduces soil loss (Nyakatawa et al., 2001). Vegetation is also an important resisting force because it intercepts rainfall, restrains soil movement, increases infiltration, reduces runoff, and improves soil structure and aggregation (Huggins, 2013).

Calculating Soil Loss Using RUSLE2

RUSLE2 uses climate, soil, topography, land uses, supporting practices, and site-specific conditions to calculate soil losses (RUSLE2, 2013). RUSLE2 incorporates rainfall erosivity (R), soil erodibility (K), and topography, and land use management that are associated with soil loss by water (Nyakatawa et al., 2001). A user can select a name of a location under a menu list in the RUSLE2 for each of the land specific factors to determine soil loss. When RUSLE2 is executed, a user chooses a name from the menu list for each of input parameters, and then RUSLE2 extracts the data that is associated with these names from its database (RUSLE2, 20013).

A user may change values of particular parameters from those stored in the RUSLE2 database to represent land use-specific conditions related to topography, yield, rock cover, and type and quantity of manure and mulch applied (RUSLE2, 2013). RUSLE2 works like a spreadsheet because it quickly updates its calculations in a cell as a user changes values for particular variables. When using the RUSLE2, a user may change values for specific variables if the values in the RUSLE2 database are not pertinent for the field conditions where RUSLE2 will be applied. RUSLE2 opening screen provides a user with two options whenever its program is operated (RUSLE2, 2013). The first option is to choose either a profile or worksheet to perform soil loss calculations. The second option is to choose a template. Templates are used to control the appearance of the RUSLE2 interface to determine the complexity of the field conditions to be analyzed (USDA-NRCS, 2013). The RUSLE2 profile view is used to determine a single calculation of soil loss for one hillslope in one field. Climate, soil, cover-management, supporting practices, and topography of a specific overland flow path describe a particular hillslope profile. This is a template that a user can use to build a rotation management system (RUSLE2, 2013). A user that uses the profile view is able to save rotations created in the local (c) crop management zone (CMZ) file folder and use it in the future to save entry time.

The RUSLE2 worksheet view is used to guide conservation planning by calculating soil loss for alternative conservation practices for a uniform hillslope profile for a specific site, soil, climate, and topography. The worksheet component provides a convenient way to compare alternative management practices. It is an important tool to compute several soil loss alternatives for one hillslope or one field (RUSLE2, 2013). The RUSLE2 plan view is a template that is used to compute soil erosion on multiple fields for conservation planning.

Soil Conditioning Index (SCI) and Soil Tillage Intensity Rating (STIR)

Within the RUSLE2 model, the SCI and STIR are used to predict SOC conditions and to determine soil disturbance rating, respectively, under cropland management systems. The SCI is used to predict the effects of cropping systems on SOC conditions (Warren Wilson College, 2012; NRCS, 2013). The SCI can also be used to plan and design conservation crop rotations and residue management when low SOC, poor soil tilth, surface crusting, and soil erosion are observed (USDA-NRCS, 2002; NRCS, 2013). Input parameters for the SCI include SOM, field operations, and erosion (Franzluebbers et al., 2011). The SCI uses equation (SCI = [organic matter (OM) × (0.4)] + [field operation (FO) × (0.4)] + [erosion (ER) × (0.2)] to predict qualitative changes in SOC in the soil depth of 10 cm based on the combined effects of SOM, field operations, and soil erosion (Zobeck et al., 2007).

The SCI assumes that intensive tillage operations decrease SOC by enhancing oxidation and maintaining plant residues increase SOC levels (Zobeck et al., 2007). The SCI is also used to determine the eligibility of cropland for the Conservation Security Program (CSP) (USDA-

NRCS, 2013). Any cropland must have a greater value than 0.00 in order to qualify for the CSP program because positive SCI values are indicators of high-residue conditions and appropriate conservation management practices. SCI and STIR are also used to calculate enhancement payment component of Conservation Security Program (CSP) (USDA-NRCS, 2013). The SCI reports a qualitative value between -1 and +1 that represents the change that is expected to occur over time in SOC level due to management practices (Warren Wilson College, 2012). Field-level SCI can be improved by growing high-residue crops and cover crops, limiting number of tillage operations, minimizing wind and water erosion on the field, and applying manure and mulch to the field (USDA-NRCS, 2013).

Soil tillage intensity rating (STIR) uses operational speed of tillage equipment, tillage type, depth of tillage operation, and percent of the soil surface disturbed area to calculate a tillage intensity rating (USDA-NRCS, 2008a; USDA-NRCS, 2011b). STIR is a numerical value and is calculated using RUSLE2 (USDA-NRCS, 2011b). This study reported that no-till operations require a STIR value of 15 or less. Reduction in intensive tillage practice and adoption of no-till systems can greatly improve STIR ratings (USDA-NRCS, 2011b). Use of soil conserving crops such as alfalfa and grass in the cropping systems can reduce STIR values (USDA-NRCS, 2008a; USDA-NRCS, 2011b). Low STIR values help reduce sheet and rill erosion, increase SOM, reduce SOM decomposition, reduce SOC emission to the atmosphere, improve soil consolidation conditions, and improve infiltration rates (USDA-NRCS, 2008a; USDA-NRCS, 2011b).

Description of Conservation Cropping Systems Project (CCSP) Study Site

The Conservation Cropping Systems Project site is a demonstration farm established in 2001 and managed by the Wild Rice Soil Conservation District with a board of directors that serves from Soil Conservation Districts in Ransom, Richland, and Dickey Counties in North

Dakota and Marshall and Day Counties in South Dakota. This site is located in a 130-acre (53 ha) parcel of farmland about two miles (3.2 km) South of Forman, ND, on the west side of Highway 32 (longitude, 97° 38' 38̋⍰ and latitude, 46° 05' 05). The area has average annual air temperature of 42 °F (5.56 °C) average annual precipitation of 19 inches (483 mm). The CCSP research site receives its funding from governmental, corporate, and private stakeholders. The Wild Rice Soil Conservation District (2013) is the main cooperating agency that provides office space and facilitates and administers the project. Other cooperating agencies included Natural Resources Conservation Services (NRCS), North Dakota State University (NDSU), and South Dakota State University (SDSU).

The soils at the CCSP site are described as Aastad (fine-loamy, mixed, superactive, frigid Pachic Argiudolls) and Forman (fine-loamy, mixed, superactive, frigid Calcic Argiudolls) soil series. The Forman soil series consists of very deep, well-drained, moderate and slow permeable soil that was formed from calcareous till. The description of the Forman series is available at https://soilseries.sc.egov.usda.gov/OSD_Docs//F/FORMAN.html. Forman is found on moraines and till plains with slopes that range from 0 to 30 percent. Horizontal flow of surface water is low to very high depending on a slope. A typical pedon of a Forman clay loam found in cultivated fields in Sargent County, North Dakota, has mollic (AP and A), argillic (Bt), and calcic (Bk) horizons.

The Aastad soil series is comprised of very deep, moderately well drained soils that were formed from calcareous till on moraines and till plains. The description of the Aastad series is available at https://soilseries.sc.egov.usda.gov/OSD_Docs/A/AASTAD.html. Horizontal flow of surface water on the soil surface is low to medium depending on a slope. Slopes range from 0 to 6 percent. The parent material of the Aastad soil is calcareous till. A typical pedon at the site is an Aastad clay loam. It has a mollic epipedon (Ap and A horizons), argillic horizon (Bt), and calcic horizon (Bk).

Treatments within the CCSP farm consist of crop rotations in a three-replicated randomized complete block design under a high-residue no-till management system. The study site was designed so that the first replication is located on the east side of the area, the second replication in the center of the area, and the third replication is found on the west side of the area. At the CCSP site, different crops are planted in 16 rotations with two to six years of duration under a no-till management system but with allowance for strip tillage, shank tillage, or disk drill tillage systems. Each crop rotation has every crop represented each year on individual plots that make up the rotation. Each plot size is 67 m by 18 m (220 ft. by 60 ft.). The crops are then planted in the rotation sequence on each of the plots in succeeding years of the rotation. Figure 4 shows a diagrammatic view of different crops during the growing season at the site. Thus, the impacts of the crops within each rotation are cumulative over the time since the inception of the study site. This makes the CCSP site unique in that it is one of relative few such long-term (>5years) sites available for research in North Dakota and Northern Great Plains region.

Figure 4. Diagrammatic view of no-till crop rotation at the CCSP site for 2009 (Cooper, 2009).

All rotations are designed to evaluate their impacts on environmental quality, soil structure and aggregation, water retention, SOC content, and increase in crop yields. The cropping treatments used in this study are shown in Table 1. Treatments were divided into rotations containing winter wheat and rotations containing no winter wheat. All crops grown in each crop rotation produce and return cumulative residue biomass and residue C and N to that crop rotation over the time.

Table 1. Rotation treatments and crop rotation sequences.

Rotation Treatments	Crop Rotation Sequences[†]
A	SW-WW-C-S
D	SW-C-S
E	SW-S
F	C-S
I	SW-WW-F-C-C-S
KH	WW-CC-C-S
N	SW-WW-A-A-C-S

[†] SW-WW-C-S = spring wheat-winter wheat-corn-soybean; SW-C-S = spring wheat-corn-soybean; SW-S = spring wheat-soybean; C-S = corn-soybean; SW-WW-F-C-C-S = spring wheat-winter wheat-flax-corn-corn-soybean; WW-CC-C-S = winter wheat-cover crop-corn-soybean; SW-WW-A-A-C-S = spring wheat-winter wheat-alfalfa-alfalfa-corn-soybean.

Crops grown in low-diversity systems such as C-S and SW-S rotations are more frequently planted than crops grown in high-diversity systems such as SW-WW-F-C-C-S and SW-WW-A-A-C-S rotations. Each crop is annually planted in each plot and replicated three times in each rotation. Crops grown include hard red winter wheat (*Triticum aestivum* L.), hard red spring wheat (*Triticum aestivum* L.), corn (*Zea mays* L.), soybean (*Glycine max* L.), alfalfa (*Medicago Sativa* L.), flax (*Linum usitatissimum* L.), pea (*Pisum sativum* L.), and radish (*Raphanus sativus* L.). These crops are annually alternated as parts of treatments in different plots in the seven rotations (Table 1). In 2008, traditional and non-traditional cover crops were introduced into the

CCSP crop rotation system. Cover crops were principally introduced to help cycle and stabilize nutrients, manage soil salinity, and improve soil health.

Objectives

The objectives of this study were to: 1) determine the effects of diversified crop rotations and crop residue retention on SOC levels; 2) determine the amount of residue biomass, residue C and N, and supplemental N fertilizer requirements in aboveground aged and fresh residues; and 3) estimate SOC and GHG (CO_2 and N_2O) emissions and soil losses using the COMET-VR model and RUSLE2 model, respectively.

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PAPER 1. EVALUATION OF CROP ROTATIONS AND RESIDUE RETENTION IN A NO-TILL SYSTEM ON SOC CHANGE

ABSTRACT

The current trajectory of an increase in greenhouse gas (GHG) emissions may be decreased through SOC sequestration. Soil OC is widely used as a measure of soil quality due to its impact on soil biological, chemical, and physical properties. This study was conducted to evaluate differences in the amount of SOC stored in no-till production between crop rotations that included winter wheat (*Triticum aestivum* L.) and those without winter wheat (*Triticum aestivum* L.) at the Conservation Cropping Systems Project (CCSP) site, Sargent County, North Dakota. Winter wheat was included in the SW-WW-C-S, SW-WW-F-C-C-C, WW-CC-C-C, and SW-WW-A-A-C-S rotations and not included in the SW-C-S, SW-S, and C-S rotations. Soil OC and bulk densities at the depths of 0-15 cm and 15-30 cm were determined within rotation treatments. Soil cores were sampled during three years (2006, 2010, and 2012). In 2006, soil samples were taken from the C-S and SW-WW-F-C-C-S rotations. In 2010, soil cores were collected from the SW-WW-C-S, SW-C-S, SW-S, WW-CC-C-S, and SW-WW-A-A-C-S rotations. In 2012, soil samples were again collected from all rotations sampled in 2006 and 2010. The 2012 SOC data was compared to the baseline SOC data of 2006 and the 2010 sampling. From the 2006 and 2010 samplings, analysis of SOC showed no significant difference between rotation treatments. Analysis of 2012 SOC showed that the C-S rotation had greater SOC level than the WW-CC-C-S rotation probably due to greater frequency of corn production in the rotation. Analysis of 2012 SOC also showed that the WW-CC-C-S rotation had lower SOC level than the C-S rotation. The WW-CC-C-S rotation produced lower SOC level perhaps due to low-residue crops such as forage radish (*Raphanus sativus* L.), field pea (*Pisum sativum* L.), and

soybean (*Glycine max* L.) in the rotation. Rotations in which winter wheat was included appeared to have a neutral effect on SOC. No-till management and crop residue retention has the potential to increase SOC levels and improve soil quality over the long-term in cropping systems.

INTRODUCTION

Conservation Management Practices Increase SOC and Improve Soil Quality

Crop residue management, improved rotations, N fertilization, and conservation tillage can increase SOC levels and improve soil quality in agricultural soils. Soil OC is important to agricultural production because it influences soil physical, biological, and chemical properties (Chan, 2008). No-till systems have been shown to increase SOC in the topsoil (A horizon) by about 40% (Grandy and Snapp, 2011). Wood et al. (1990) reported greater SOC concentration near soil surface in no-till due to large amount of plant residue produced and maintained on the soil surface. Conservation management practices also promote SOC sequestration by increasing C inputs and minimizing C outputs (Sherrod et al., 2003; Franzluebbers, 2011). The soil C and N stored in a corn-corn-soybean-wheat rotation was greater than that stored in a continuous corn system in Michigan, resulting in an associated improvement in soil quality (Sanchez et al., 2004).

Halvorson et al. (1999) reported that SOC sequestration can be increased by no-till production with adequate N fertilization. Soil OC sequestration can be improved through returning crop residue as a surface mulch, practicing no-till and mulch farming systems, growing seasonal cover crops during the non-growing season, and rotating different crops (Lal, 2004; Wang et al., 2010). The amount of SOC that can be restored and maintained depends on the cropping systems, soil types and climatic conditions, and initial SOC levels of the site (Chan, 2008).

Restoration and maintenance of SOC can be attained through frequent addition of crop residues and application of deficient mineral nutrients (Millar et al., 1958). Soil OC consists of diverse organic materials, including living organisms, slightly changed plant and animal organic residues, partially decomposed plant and animal tissues, and substantially altered plant and animal remains that are more or less resistant to further decomposition (Magdoff, 1992). Soil OC has been called the most crucial soil attribute in improving and maintaining soil quality resources (USDA, 1996).

Soil OC is a common metric in evaluating long-term agricultural studies and is a good indicator of soil quality and sustainable agronomic production due to its influence on soil biological, chemical, and physical attributes **(**Reeves, 1997). Soil OC measurement is also used to assess the retention or loss of SOC in soil. Soil quality has been defined as “the capacity or capability of a soil to produce safe and nutritious crops in a sustained management over the long-term and to enhance human and animal health without impairing the natural resource base or adversely affecting the environment” (Parr et al., 2012).

Soil quality is therefore an important component to agricultural productivity and environmental quality (Reeves, 1997). Soil quality is partially dependent on SOC content due to its effects on soil aggregation, soil biological activity, nutrient cycling, permeability and water retention. Implementing methods for increasing and maintaining SOC is linked to improving soil quality and attaining sustainable agriculture (Lal and Kimble, 1997).

Soil C and N are indicators of soil quality (Kuo and Jellum, 2002). Soil quality indicators are used to evaluate sustainability of land uses and soil management practices (Shukla et al., 2006). Indicators should be easy to measure, able to determine change in soil function within experimental unity, accessible to and useable by farmers, and should represent soil physical, biological, and/or chemical properties (Kinyangi, 2007).

Objectives

The objectives of this study were to: 1) determine effects of different crop rotation systems on SOC levels in no-till production; 2) compare the rate of SOC change under rotations with winter wheat and those without winter wheat; and 3) evaluate the effects of winter wheat rotations on soil quality.

MATERIALS AND METHODS

This study was imposed within ongoing treatments within a study initiated in 2006 at the CCSP site (Augustin, 2009). The study was a randomized complete block design with three replications. Each rotation and each crop within each rotation were replicated three times. The same crops in each rotation were rotated over three sampling years (2006, 2010, and 2012) at the CCSP site (Table 2). Each crop in each rotation was planted each year. Crops in low-diversity systems such as C-S and SW-S rotations were more frequently planted than crops in high-diversity systems such as SW-WW-C-S and WW-CC-C-S rotations (Table 2).

Crops grown in each rotation contributed to total SOC by producing and returning residue biomass to that rotation for each of the three sampling years (2006, 2010, and 2012) under no-till production. But high residue yielding crops such as corn (*Zea mays* L.) and wheat (*Triticum aesticum* L.) had probably produced and returned greater residue biomass to cropping systems compared to low residue yielding crops such as soybean (*Glycine max* L.), field pea (*Pisum sativum* L.), forage radish (*Raphanus sativus* L.), alfalfa hay (*Medicago sativa* L.), and flax (*Linum usitatissimum* L.).

Soil samplings were conducted on the SW-WW-C-S, SW-C-S, SW-S, C-S, SW-WW-F-C-C-S, WW-CC-C-S, and SW-WW-A-A-C-S rotations during three individual years (2006, 2010, and 2012) (Table 2). All sampling locations were geo-referenced with a handheld Garmin 76 Global Positioning Satellite (GPS) receiver unit at the initial sampling years (2006 and 2010). Sampling locations in each plot where soil cores were to be taken were first identified by latitude and longitude so that this information could be consistently related to past and future samplings.

In 2006, the first sampling was conducted to establish baseline SOC levels and bulk densities in the C-S rotation without winter wheat and the SW-WW-F-C-C-S rotation with winter wheat (Table 2). Crops grown in each of these two rotations contributed to SOC by producing and returning cumulative residue biomass to that rotation for the period of five years (2001-2006). The 2006 sampling was conducted using steel tube 30 cm long with an acetate liner. Before soil cores were sampled, loose surface plant residue was removed from each sampling area where each individual core was to be taken.

Table 2. Crop rotation treatments, first (baseline) sampling year and second sampling year.

Crop Rotation Treatments[†]	First (baseline) Sampling Year	Second Sampling Year
SW-WW-C-S	2010	2012
SW-C-S	2010	2012
SW-S	2010	2012
C-S	2006	2012
SW-WW-F-C-C-S	2006	2012
WW-CC-C-S	2010	2012
SW-WW-A-A-C-S	2010	2012

[†] SW-WW-C-S = spring wheat-winter wheat-corn-soybean; SW-C-S = spring wheat-corn-soybean; SW-S = spring wheat-soybean; C-S = corn-soybean; SW-WW-F-C-C-S = spring wheat-winter wheat-flax-corn-corn-soybean; WW-CC-C-S = winter wheat-cover crop-corn-soybean; SW-WW-A-A-C-S = spring wheat-winter wheat-alfalfa-alfalfa-corn-soybean.

The sampled cores were taken within a five-meter radius of the geo-referenced point to characterize each sampling location (Cihacek et al., 2010). Seven soil cores were sampled from each of twenty six (26) plots. Each plot was measured 67 m by 18 m (220 ft. by 60 ft.). Soil samples were collected at the depth intervals of 0-15 cm and 15-30 cm. All of the cores were sampled to a depth of 30 cm because SOM is mostly concentrated in the top 30 cm of the soil which is the most dynamic area relative to plant root and biological activity (Cihacek et al., 2010).

Before the sampled cores were processed, they were removed from the liners and divided into depth intervals of 0-15 cm and 15-30 cm depth intervals. Each tube that contained a sample was capped and kept in a cold storage before the samples were processed and analyzed for SOC content and bulk densities (Augustin, 2009). Bulk densities were determined for all cores in each plot to calculate SOC values for the seven crop rotations. All SOC values were averaged across all crops within a rotation to determine average SOC in each rotation treatment to indicate long-term rotation effects on SOC.

In 2010, another baseline sampling was conducted on the SW-WW-C-S, SW-C-S, SW-S, WW-CC-C-S, and SW-WW-A-A-C-S rotations for the same purpose (Table 2). Crops grown in each rotation contributed to SOC by producing and returning cumulative residue biomass to that rotation for the period of nine years (2001-2010). Seven soil cores were again obtained from each plot within the same area near the geo-referenced point similar to 2006 sampling.

However, at this sampling and subsequent sampling, seven soil cores were collected using hand probe (diameter = 1.9 cm**)** with a slotted steel sampling tube without a liner and separated into 0-15 and 15-30 cm intervals as described by Cihacek et al. (2010). All the cores were kept in coolers during the sampling time until delivered to the laboratory. The cores collected within each plot were combined in separate plastic bags by depth. The combined soil cores were weighed prior to determining bulk densities. In 2012, all rotation treatments sampled in 2006 and 2010 were sampled to determine SOC levels and bulk densities at the previously geo-referenced locations**.** Crops grown in each rotation contributed to SOC by producing and returning cumulative residue biomass to that rotation for the period of eleven years (2001-2012). Seven soil cores were again sampled in each plot using the same procedure as for the sampling 2010. The 2012 SOC was to be compared with the baseline SOC data sampled in 2006 and 2010.

For the determination of bulk densities, soil cores from 0-15 cm and 15-30 cm depth interval were separately hand-crushed. Soil bulk density was determined by a version of the core method of Blake and Hartge (1986) as proposed by Cihacek et al. (2010). The weights of can, lid, and moist soil samples were measured and recorded for soil moisture determination and bulk densities. About 30-50 grams of hand-crushed, properly mixed, field-moist soil subsamples were collected in pre-weighed steel or aluminum moisture cans with a sealing lid to determine soil water moisture (Cihacek et al., 2010). After the initial weighing, the subsamples were placed in a drying oven for a period of two days (48 hours) at 105˚C (221˚F). The subsamples and cans were then removed from the drying oven and placed into a desiccator that contained a drying agent to prevent moisture accumulation while cooling. After the dried subsamples were cooled, the lids were placed on the cans and can weights were again measured and recorded. The remaining subsamples were air-dried and crushed to pass a 2-mm sieve. A 10-12 g subsample of soil was milled to pass 100-mesh screen for soil C analysis (Cihacek and Jacobson, 2007).

A Skalar Primacs^{SC} TOC Analyzer was used to determine the total organic carbon (TOC) content for soil analysis for each of the three sampling years. The Skalar instrument was also used to determine inorganic carbon (IC) by measuring the CO_2 evolved by addition of a 20% H_3PO_4 solution to the soil. To determine soil organic (OC), IC was subtracted from TOC (OC = TOC – IC). Prior to adjusting for bulk densities of the soil, the C data was reported in percent.

The C percentages were first converted to decimal point by dividing the C masses by 100. The SOC for each depth within each plot was computed by bulk density × 15.2 cm × C mass. This allows the use of the data to convert C masses to Mg/ha/depth by using a multiplier of 10. All the calculated values were at least carried to three places after the decimal point as recommended (Cihacek et al., 2010). The 2006 and 2010 C mass levels were used as a baseline to determine SOC changes when compared to the 2012 C mass levels. However, it is important to note that pre-project (baseline) SOC was not available from the pre-CCSP conventional system although that data would have been extremely useful in evaluation of the long-term system changes (Olson, 2013).

Statistical Analysis

The rotations within the CCSP site were arranged in a three-replicate randomized complete block design with the seven rotation treatments. The SAS GLM procedure and least significant differences (LSD) (SAS Institute, 2002-2010) at $P \leq 0.05$ were used to analyze SOC data for 2006, 2010, and 2012. For each sampling year, SOC data was analyzed separately to evaluate differences between the seven crop rotations (Tables 3 and 4). Changes in SOC and annual SOC values were also analyzed for the baseline and final sampling years (Table 5). The SOC value in each rotation represented the total SOC resulting from the accumulated residue C produced and returned to each rotation by all crops in that rotation for each of the three sampling years (2006, 2010, 2012) under no-till production at the CCSP site. Treatment means reported (Tables 3, 4, and 5).

RESULTS AND DISCUSSIONS

There were no significant differences in baseline SOC data between the seven rotations in 2006 and 2010 (Table 3). Lack of significant difference was in part attributed to relatively similar soil texture, drainage, and climatic conditions between treatments. Another possible explanation for low variation in SOC between treatments was that the rate of SOC accumulation was low due to low variability in climatic conditions. Lack of significant difference between the rotation treatments could also be attributed to decrease in the rate of SOC accumulation.

Previous studies suggest that SOC starts to increase from 5 to 10 years after no-till initiation and stabilizes from 15 to 20 years under no-till production systems (Liu et al., 2006). Therefore, the rate of SOC accretion might have already been reduced because seven crop rotations had been under no-till production for eleven years (2001-2012) at the CCSP site. Soil OC can also increase and stabilize at different times under no-till management systems in different locations.

Table 3. Crop rotation treatments, initial sampling year and baseline SOC.

Crop Rotation Treatments[†]	Initial Sampling Year	Baseline SOC
		---kg/m^2---
SW-WW-C-S	2010	7.63a[‡]
SW-C-S	2010	8.07a
SW-S	2010	7.86a
C-S	2006	8.09a
SW-WW-F-C-C-S	2006	7.27a
WW-CC-C-S	2010	7.90a
SW-WW-A-A-C-S	2010	8.03a

[†] SW-WW-C-S = spring wheat-winter wheat-corn-soybean; SW-C-S = spring wheat-corn-soybean; SW-S = spring wheat-soybean; C-S = corn-soybean; SW-WW-F-C-C-S = spring wheat-winter wheat-flax-corn-corn-soybean; WW-CC-C-S = winter wheat-cover crop-corn-soybean; SW-WW-A-A-C-S = spring wheat-winter wheat-alfalfa-alfalfa-corn-soybean.

[‡] Means with the same letter are not significantly different at $p \leq 0.05$.

Additional factors (soil texture and mineralogy, climate, management efficacy, and residue amount) can determine the time required for SOC to increase and stabilize under a no-till regime at a given location. Therefore, time of SOC increase and stabilization can vary from each no-till management to another depending on each location site-specific conditions.

Analysis of SOC data for the final sampling year 2012 is shown in Table 4. The C-S rotation (9.47 kg/m^2) was significantly greater than the WW-CC-C-S rotation (8.41 kg/m^2). The C-S rotation and all of the other rotations contained similar SOC and were not significantly different. The C-S rotation had greater SOC compared to the WW-CC-C-S rotation likely due to more frequent production of corn and its associated greater residue biomass compared to the more diversified WW-CC-C-S rotation. Tables 6 and 7 (Paper 2) show greater amount of residue biomass and residue C in the C-S rotation compared to residue biomass and residue C in other rotations which showed that greater frequent production of corn has a greater potential to increase SOC in cropping systems.

Table 4. Crop rotation treatments, final sampling year and final SOC.

Crop Rotation Treatments[†]	Final Sampling Year	Final SOC
		---kg/m^2---
SW-WW-C-S	2012	8.64ab[‡]
SW-C-S	2012	9.35ab
SW-S	2012	8.64ab
C-S	2012	9.47a
SW-WW-F-C-C-S	2012	8.70ab
WW-CC-C-S	2012	8.41b
SW-WW-A-A-C-S	2012	8.98ab

[†] SW-WW-C-S = spring wheat-winter wheat-corn-soybean; SW-C-S = spring wheat-corn-soybean; SW-S = spring wheat-soybean; C-S = corn-soybean; SW-WW F-C-C-S = spring wheat-winter wheat-flax-corn-corn-soybean; WW-CC-C-S = winter wheat-cover crop-corn-soybean; SW-WW-A-A-C-S = spring wheat-winter wheat-alfalfa-alfalfa-corn-soybean.

[‡] Means with the same letter are not significantly different at $p \leq 0.05$.

The COMET-VR model (Paper 3, Table 12) also predicted greater SOC levels in the corn-soybean simulations than other simulations for the other six cropping systems. A corn crop has been shown to produce and return greater than 40% of above-ground residue C to the soil surface compared to a soybean crop (Huggins et al., 1998).

High-residue producing crops such as corn and wheat have also been shown to produce greater SOM levels and have a greater potential for C and N sequestration than low-residue yielding crops such as alfalfa hay and soybean (Wright and Hons, 2005). Drinkwater et al. (1998) also reported the greatest amount of total residue produced and returned to the soil surface under a 15-year rotation study using corn-soybean rotation system over other rotations. Therefore, greater SOC level in the C-S rotation was likely due to corn residue biomass being produced and returned in greater quantity and frequency to the system. Corn residue dry matter also had lower lignin content (56 g/kg) compared to soybean residue dry matter (119 g/kg) and wheat residue dry matter (141g/kg) (Sylvia et al., 2005). Because of its resistance to decomposition, lower lignin content in corn residue may have also contributed to greater SOC level in the C-S rotation.

Lower SOC in the WW-CC-C-S rotation was related to cover crops such as field pea (*Pisum sativum* L.) and forage radish (*Raphanus sativus* L.) that probably produced and returned low residue C to the system over the years under no-till management. Planting cover crops often has the same negative effects on SOC levels as planting green manure crops due to additional soil disturbance and increased SOC mineralization due to cover crop seeding (Allison, 1973). Therefore, lower SOC level in the WW-CC-C-S rotation might be attributed to increased SOC oxidation due to more frequent seeding of cover crops (pea and radish) into wheat stubble in this system. Field pea, forage radish, and soybean residue C may also have mineralized more rapidly due to lower C:N ratio and greater N content as evidenced by crop residue C:N ratios and C and N contents in the Table 8 (Paper 2). These qualities likely contributed to lower SOC level in the WW-CC-C-S rotation compared to the C-S rotation. Corn and soybean residues also were each being produced 25% of the time in the WW-CC-C-S rotation which decreased cumulative residue C in the system. It has been reported that winter wheat produces greater residue biomass per a unit of grain yield compared to spring wheat (Black and Bauer, 1983), indicating that winter wheat is a high residue crop. In comparison, corn residue was being produced 50% of the time in the C-S rotation while winter wheat residue was being produced 25% of the time in the WW-CC-C-S rotation. Therefore, lower production of winter wheat residue biomass in the WW-CC-C-S rotation reduced residue C in the system compared to greater production of corn residue biomass in the C-S rotation which increased residue C in the system.

Lower SOC levels in the WW-CC-C-S rotation do not necessarily discredit the agronomic and environmental value of cover crops. Cover crops scavenge residual soil NO_3-N, a process that captures and retains nutrients in their tissues for subsequent crop use. Cover crops use excess moisture during their growing period. Use of residual soil NO_3-N and excess moisture by cover crops has a positive impact on environment because it reduces the potential losses of N (N_2O and NO_3-N) to the environment. Cover crops also reduce soil salinity by reducing evaporation rate from the soil surface and using excess water that otherwise would contribute to shallower water tables in these soils and similar soils. If legume crops are grown in long-term rotations, they can provide additional N to subsequent crops. Forage radish deep roots also can reduce soil compaction in non-smectitic soils through “biological drilling” and produce root channels that aid water infiltration.

The 2006 and 2010 SOC values were subtracted from 2012 SOC values and divided by the years between samplings to determine differences between two sampling periods (Table 5). The WW-CC-C-S rotation (0.51 kg/m^2) had lower total SOC than other rotations due to low-residue crops such as forage radish, field pea, and soybean and additional soil surface disturbance. Table 5 also shows the SOC change over time periods between initial (baseline) and final sampling. The WW-CC-C-S rotation had lower SOC level than other rotations although the increase in SOC per year was similar to the C-S and SW-WW-F-C-C-S rotations. The annual change in SOC was similar in the C-S, SW-WW-F-C-C-S, and WW-CC-C-S rotations because SOC in the C-S and SW-WW-F-C-C-S rotations was divided by six (6) years while SOC in the WW-CC-C-S rotation was divided by two (2) years.

Table 5. Crop rotation treatments, sampling year and annual change in SOC.

Crop Rotation Treatments[†]	Sampling Year	Change in Total SOC	Annual Change in SOC
		---kg/m^2---	---kg/m^2---
SW-WW-C-S	2012 - 2010	1.00a[‡]	0.50a
SW-C-S	2012 - 2010	1.28a	0.64a
SW-S	2012 - 2010	0.79a	0.40a
C-S	2012 - 2006	1.38a	0.23b
SW-WW-F-C-C-S	2012 - 2006	1.44a	0.24b
WW-CC-C-S	2012 - 2010	0.51b	0.26b
SW-WW-A-A-C-S	2012 - 2010	0.95a	0.48a

[†] SW-WW-C-S = spring wheat-winter wheat-corn-soybean; SW-C-S = Spring wheat-corn-soybean; SW-S = spring wheat-soybean; C-S = corn-soybean; SW-WW-F-C-C-S = spring wheat-winter wheat-flax-corn-corn-soybean; WW-CC-C-S = winter wheat-cover crop-corn-soybean; SW-WW-A-A-C-S = spring wheat-winter wheat-alfalfa-alfalfa-corn-soybean.

[‡] Means with the same letter are not significantly different at $p \leq 0.05$.

The lower annual changes for the C-S and SW-WW-F-C-C-S rotations may have been due to an integration of SOC changes over a longer period of time (6 years) than the other rotations. The lower annual change in SOC levels could also reflect the effect of varying annual weather variation over a greater time period due to the fact that some seasons are wetter or dryer than others.

SUMMARY AND CONCLUSIONS

Restoration and maintenance of SOC can be achieved by increasing intensification and diversification of cropping systems as well as increasing the frequency of producing high residue crops and retaining greater residue biomass on soil surface. Analysis of the 2006 and 2010 SOC data showed no significant differences between the seven rotations. Lack of significant differences was attributable to relatively similar abiotic conditions. The CCSP site had relatively uniform soils, common historical and present day drainage, and a long-term no-till management system although slopes and erosion potential in the WW-CC-C-S rotation was greater than other rotations. Soil OC changes under conservation tillage systems occur slowly over time. Since the CCSP site had been in a continuous no-till management for eleven years, the SOC increase might have been reduced due to a maturing SOC equilibrium.

The C-S rotation had greater SOC for 2012 SOC compared to the WW-CC-C-S rotation. Greater SOC level in the C-S rotation was related to greater production of corn residue C in the rotation since the plots were established. More frequent cropping of corn in the C-S rotation was a probable reason why there was a greater SOC level in the system. Therefore, the C-S rotation has a greater potential to increase SOC in the Northern Great Plains. Analyses showed that rotations containing winter wheat appeared to have a neutral impact on SOC levels. Separating out the impact of winter wheat on SOC in the rotations in which it was included was difficult because winter wheat was being alternated with other crops in high diversity crop rotations. This made it difficult to compare the impacts of corn and winter wheat on SOC in the rotations in which corn and winter wheat were included such as C-S, SW-WW-C-S, SW-WW-F-C-C-S, and SW-WW-A-A-C-S rotations. Winter wheat is a high residue crop and also produces greater residue biomass per a unit of grain yield than spring wheat. This study suggests that cropping systems such as winter wheat-soybean and corn-soybean rotations can make a valid comparison between corn and winter wheat. The winter wheat-soybean rotation can also be compared with the spring wheat-soybean rotation in this study.

The study showed that SOC levels are not only influenced by intensity and diversity of cropping systems but also by the amount of residue biomass produced and returned by each crop to each system. Therefore, greater frequent production of high-residue crops and greater residue retention in the cropping systems has a greater potential to increase SOC levels. Low-residue crops such as cover crops (forage radish and field pea) and soybean may not increase SOC sequestration due to low residue production and increased soil erosion associated with low soil surface cover. The annual change in SOC was lower SOC level in the C-S rotation compared to the SW-WW-C-S, SW-C-S, and SW-WW-A-A-C-S rotations. The SOC in the C-S rotation was lower because the SOC in this rotation was divided by six years while the SOC in other rotations was divided by two years.

Furthermore, although there was no pre-CCSP conventional tillage (baseline) SOC obtained prior to establishment of no-till management, SOC over the three sampling periods showed an increasing trend in SOC levels. The 2006/2010 SOC levels were slightly lower than the 2012 SOC levels at the CCSP site. The C-S rotation showed 8.09 kg/m^2 for 2006 SOC and 9.47 kg/m^2 for 2012 SOC data. No-till cropping systems in the Northern Great Plains of the U.S have the potential to increase SOC levels and improve soil quality under a broad mix of crops and crop rotations including those with winter wheat. Because winter wheat produces greater residue biomass than spring wheat, it remains an essential crop for increasing residue production and soil surface cover in the Northern Great Plains region.

Recommendation for Future Research Trials

- Conventional tillage (baseline) SOC data was not taken at the Conservation Cropping Systems Project (CCSP) site prior to the establishment of the no-till system in 2001. The impacts of the no-till production systems on SOC sequestration and GHG emissions reductions can only be determined by comparing conventional tillage SOC data to conservation tillage SOC data. It has been reported that pre-project (baseline) SOC data under conventional or other agricultural management systems should be determined and compared with post-treatment SOC level under conservation systems in order to accurately evaluate the rate of SOC trends (Olson, 2013).

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PAPER 2. EVALUATION OF THE CONTRIBUTION OF AGED AND FRESH RESIDUES IN A NO-TILL SYSTEM TO SOIL QUALITY AND NUTRIENT CYCLING

ABSTRACT

Conservation crop residue management can increase SOC storage and increase nutrient cycling and availability. Crop residue retention tends to improve soil quality, increase water availability, reduce soil erosion, provide habitat for soil microbes, improve soil physical properties, and may increase crop yields. However, it is challenging to accurately predict the amount of nutrients released from previous crop residues over short-and long-terms. This study was conducted to evaluate the amount of residue biomass, residue C:N ratio, residue C and N, and residue N fertilizer deficit (supplemental N fertilizer requirement) from crop residue decomposition in no-till production at the Conservation Cropping Systems Project (CCSP) site, North Dakota. Aboveground aged and fresh residues were collected in spring 2011 and fall 2012, respectively. Aged residue was the residue from grain harvested from the fall 2010 crops and sampled in the spring 2011. Fresh residue was collected immediately after the fall 2012 crop was harvested. Crop residues can result in N immobilization due to N assimilation by microorganisms decomposing high C residues. Because supplemental N is required by most non-legume crops, the objective of this study was to estimate the amount of N required by subsequent crops in a high residue environment. Statistical analysis of both aged and fresh residue showed slightly greater residue dry matter weight in aged residue than fresh residue. Analysis of aged and fresh residue C:N ratio showed wider C:N ratios in fresh residue than the aged residue. Both aged and fresh residue also showed wider C:N ratio in the corn (*Zea mays* L.)-soybean (*Glycine max* L.) rotation and narrower C:N ratio in the spring wheat (*Triticum aestivum* L.)-winter wheat

(*Triticum aestivum* L.)-alfalfa (*Medicago sativa* L.)-alfalfa-corn (*Zea mays* L.)-soybean (*Glycine max* L.). Fresh crop residues sampled in the 2012 fall showed narrower C:N ratios for legume and green manure crops than non-legume crops. Analysis of potential supplemental N fertilizer requirements showed greater potential N requirement for the fresh residue than the aged residue. Crop residue retention under no-till production has the potential to improve nutrient cycling and soil quality and protect soil surface from wind and water erosion.

INTRODUCTION

Crop Residue Retention Increases SOC and Improves Nutrient Cycling

Recent shifts in climate patterns have encouraged scientists and governments to seek management strategies to reduce GHG emissions and increase SOC sequestration as well as nutrient cycling and availability in agricultural lands. Conserving residue management under no-till production has been proposed as a strategy to increase SOC sequestration, improve soil fertility and nutrient cycling, and improve soil quality. The increase in atmospheric CO_2 might also be reduced by sequestering CO_2 with terrestrial vegetation, retaining SOC, and converting the atmospheric C to plant biomass and SOM (Wang et al., 2010).

Residue retention and improved rotations under reduced tillage can increase SOM and crop productivity (Havlin et al., 1990). Intensified and diversified cropping systems can increase the amount of residue biomass returned to the soil surface which can subsequently increase SOC and improve soil quality (Grant et al., 2002). Intensified cropping systems under no-till production have a potential to increase SOC and improve the environment (Halvorson et al., 1999; Halvorson et al., 2002). Their studies found greater SOC under no-till system than minimum and conventional tillage systems due to reduced tillage intensity.

Production of greater quantities of plant residues by intensifying cropping systems under no-till regimes can increase SOC and soil organic nitrogen (SON) levels in the soil surface (Ortega et al., 2002). Wright and Hons (2004) reported the greatest SOC and SON storage under intensified no-till system. Residue retention under reduced tillage regimes can also conserve soil moisture and subsequently increase crop production (Schlegel et al., 2005). Cover crops can also increase sustainable crop production by increasing SOM, improving the long-term soil N status, improving soil structure, conserving soil water, and reducing soil surface runoff and erosion (Frye and Blevins, 1989). Sustainable agriculture is important because its achievement maintains environmental quality while increasing per capita crop production, increases crop production on agriculturally suitable soils while restoring the productivity of degraded croplands and reduces agrochemical inputs while augmenting grower profit margin (Lal, 1991).

Greater residue retention and slower decomposition rates observed in the reduced tillage systems tend to promote soil fertility by promoting the slow release of readily mineralizable organic forms of nutrients and generally increasing the nutrient reserve of soils (Schoenau and Campbell, 1996). However, high residue conditions may increase N requirements in intensified cropping systems by reducing N-mineralization contributed during shorter non-growing periods and increasing N immobilization and urea volatilization due to surface residue and surface-applied urea-containing fertilizer (Schlegel et al., 2005). Nitrogen immobilization may be more important factor in N management than loss of N under residue-retained conditions (Allison, 1973). It has also been reported that net N-mineralization will release inorganic N from crop residue if the amount of residue N is greater than the amount of N required by decomposing microbes (Cabrera et al., 2005). These conditions require a better understanding and prediction of N-mineralization rate under residue-covered tillage regimes.

Most crop residues have a high C:N ratio which leads to residue-N immobilization. Decomposition rate of residue is often linked to C:N ratio in crop residues (Allison, 1973; Havlin et al., 2005). A C:N ratio lower than 25:1 tends to result in a rapid oxidation of C and mineralization release of N, whereas a C:N ratio greater than 25:1 may require supplemental N to compensate for the residue N immobilization during residue decomposition. Crop residues that have similar C:N ratios may mineralize different quantities of mineral N due to differences in more or less recalcitrant organic compounds in other residues that are not reflected in the C:N ratios (Cabrera et al., 2005).

Objectives

The objectives of this study were to: 1) determine residue dry matter weights in both aged and fresh residues; 2) determine C and N returns in both aged and fresh residue within each of the seven cropping systems; 3) estimate the availability of N for subsequent crops within each cropping system; and 4) estimate the potential effects of the residue C and N contents on subsequent crop nutrient requirements.

MATERIALS AND METHODS

This study was structured as a randomized complete block design with three replications. Aboveground residue biomass was collected within each of the seven crop rotation treatments: spring wheat-winter wheat-corn-soybean, spring wheat-corn-soybean, spring wheat-soybean, corn-soybean, spring wheat-winter wheat-flax-corn-corn-soybean, winter wheat-cover crop-corn-soybean, and spring wheat-winter wheat-alfalfa-alfalfa-corn-soybean. These were the same rotation treatments where soil samples for the determination of SOC were taken. The seven rotation treatments had different sequences of high-N requiring crops such as corn (*Zea mays* L.) and wheat (*Triticum aestivum* L.) and low-N requiring crops such as alfalfa (*Medicago sativa*

L.), field pea (*Pisum sativum* L.), and soybean (*Glycine max* L.) in their respective rotations. Crops in low-diversity systems such as C-S and SW-S rotations were more frequently planted than crops in high-diversity systems such as SW-WW-C-S and WW-CC-C-S rotations.

Crops within each rotation treatment produced and returned residue biomass to that rotation although high residue yielding crops such as corn and wheat appeared to have produced and returned greater residue to that rotation than low residue yielding crops such as soybean, field pea, and flax (*Linum usitatissimum* L.). The quantity of residue in each rotation was a cumulative residue produced and returned to each rotation by all crops grown in that rotation since 2001 under no-till management. Fresh crop residues collected from winter wheat, spring wheat, corn, soybean, alfalfa, flax, field pea, and forage radish (*Raphanus sativus* L.) were sampled to determine residue C:N ratio and C and N contents for each crop prior to the crop contribution to the total residue in the plot. These residues were used for comparison with values obtained from the cumulative residues in each rotation treatment.

Aboveground aged and fresh residues were collected in the spring 2011 and fall 2012. The 2011 spring residue sample was designated ‘aged residue’ because it was residue from crops harvested in 2010 and overwintered into 2011. The samples designated ‘fresh residue’ were collected in the fall of 2011 and 2012 and were immediately collected after the crops were harvested. The fresh residue sample in fall 2011 was affected by a hail and wind storm in July that may have impacted the quantity and quality of the residue, especially corn residue. Due to much lower fresh residue dry matter weight from fall 2011 sampling than the aged residue dry matter weight in the fall 2011sampling, fresh residue was resampled in fall 2012 and fall 2011 fresh residue data was not used in this study.

A total of 78 plots were sampled during each sampling season. The main plot size for each plot was 67 m by 18 m (220 ft. by 60 ft.) (Area = 0.12 ha). Before sampling the residue, weights of three large buckets were first determined and recorded using a scale calibrated in kilograms. Three randomly-selected areas were defined using a 0.9 m by 0.9 m (3 ft. by 3ft.) steel quadrant frame in each plot within each plot where soil samples for the analysis of SOC were taken. Within each sampling area, all residues on the soil surface were collected in order to capture the crop residue variability. Any observed crop residue variability was likely caused by residue distribution during crop harvest. The surface residue was first raked, and then clipped at the soil surface. Loose and raked surface crop residues were collected and placed in the three buckets. When the buckets were filled with residue, the buckets were again weighed. Then, three handful residue subsamples were grabbed from each of the three buckets and placed in separate paper bags for laboratory analysis. All the residue sample bags were marked with a plot number and rotation treatment. The remaining residues in the three buckets were returned to the original plot areas from which they were harvested.

In the laboratory, moist residue subsamples were immediately weighed and then oven-dried at 60 °C. Next, residue samples were separated from soil particles that might have been included in the residues before they were analyzed for C and N contents. After the soil particles were removed from plant residues, the three residue subsamples in three separate bags from each plot were combined in one larger paper bag marked with a plot number and rotation treatment. The combined samples were again oven-dried at 60 °C to remove adsorbed moisture and then shredded using a garden shredder made by a Craftsman® Chipper Shredder to homogenize the residue from each plot. The shredded samples were again oven-dried at 60 °C before they were ground using a Wiley mill to pass a 2-mm screen. Three-50 mg ground subsamples from each plot were weighed, placed in foil sheets and rolled into pellets for the C and N analysis. An Elementar VarioMax® CNS analyzer (Elementar AnalySensyteme GmbH, 2010) was used to determine C and N on the pellets using high temperature combustion.

Determination of Residue Dry Matter Weight, C:N Ratio, and Fertilizer N Deficits

The results from the laboratory analysis were used to determine residue dry matter weights, residue N deficits (supplemental N requirements), C: N ratios, and C and N concentrations in both aged and fresh residue. Residue dry matter weights were determined for the seven crop rotation treatments previously described. Percent residue moisture was determined to calculate residue dry matter weight (DMW) and C and N contents. Percent residue moisture (% H_2O) was computed by subtracting oven-dry residue weight from wet residue weight and divided by the wet residue weight. The percent residue moisture was subtracted from 1 to obtain the residue dry matter weight. The mass of residue in an oven-dry basis was computed by multiplying residue dry matter weight by the residue sample dry matter weight. The mass of residue was computed by dividing the mass of residue on an oven dry basis by the area ($0.84 \text{ m}^2 = 9 \text{ ft}^2$) of quadrant frame. Residue dry matter weight was multiplied by 10 to convert into megagrams per hectare (Mg/ha) ($1\text{Mg} = 1000$ kg; $1 \text{ ha} = 10{,}000 \text{ m}^2$). Carbon and N concentrations were computed by multiplying residue dry matter weight by the C and N contents in each residue sample.

“The term immobilized nitrogen, if strictly defined, refers to the nitrogen that is assimilated by the microorganisms that decompose organic matters that are added to soil or formed in it” (Allison, 1973). Presence of substantial quantities of crop residues that have N content less than 1.5 to 1.7% N (C:N ratio of 30:1 to 25:1) will generally reduce yields of most non-leguminous crops if a supplemental N fertilizer is not added to the soil to meet the needs of the microbes and crops (Allison, 1973; Havlin et al., 2005). Therefore, the literature recommends that the quantity of supplemental N needed to compensate for N to be potentially immobilized should be determined by multiplying the residue dry matter weight by the difference between 1.7% N and the residue N content.

Havlin et al. (2005) noted that both residue N content and inorganic soil N are used by microorganisms during the residue breakdown when high C:N ratio residues are added to the soil. About 65% of residue C was liberated as CO_2 during the decomposition process while 35% was incorporated into microbial biomass (Havlin et al., 2005). Microbial decomposition of fresh plant material usually converts 60% or more of the C into CO_2 and only 5 to 25% of the C is incorporated into microbial biomass (Allison, 1973). Thus, the amount of N to be potentially assimilated in both aged and fresh residue was computed using the 1.7% N (Allison, 1973) and 35% C (Havlin et al., 2005) values. The amount of supplemental N was determined by multiplying the residue dry matter weight by the amount of residue C to obtain the mass of C per hectare. The mass of C per hectare was multiplied by 35% C (approximate amount of C incorporated into microbial cells) (Havlin et al., 2005) to obtain the amount of C consumed by microbes decomposing the residue. The amount of N required by the microorganisms was computed by dividing the amount of residue C used by microorganisms decomposing residue by a microbial C:N ratio (8:1) (Havlin et al., 2005).

The amount of N in plant residues was also used to estimate the amount of supplemental N fertilizer required in compensation for the residue N depleting effects due to microbial N immobilization. The amount of N in residue was computed by multiplying the residue dry matter weight per hectare by the difference of residue N content and 1.7% N (Allison, 1973). After the residue N was calculated, residue N fertilizer deficit (supplemental N fertilizer) was computed by subtracting the amount of N required by microbes from the amount of N in the residue. The value obtained from this calculation was the amount that would be, in theory, required by a subsequent crop in order to meet its fertilizer N requirements. These estimated supplemental N fertilizer rates were considered as N fertilizer amounts that farmers and producers would need to apply to subsequent crops in crop production systems.

Actual C:N ratios for fresh crop residues sampled in fall 2012 were also determined to evaluate the C:N ratios for eight individual crops including alfalfa, corn, flax, pea, radish, soybean, spring wheat, and winter wheat cropped at the CCSP site. These C:N ratios were to be compared with the accumulated residue for the aged and fresh residues collected from the seven rotations in the spring 2011 and fall 2012, respectively. These fresh residues were carefully selected to avoid collecting old residue from previous crops. The residue C and N content percent (%) values were multiplied by 10 to convert them into gram per kilogram (g/kg) and then the C:N ratios were computed by dividing the residue C values (g C/kg) by residue N values (g N/kg).

Statistical Analysis

The SAS GLM program and least significant differences (LSD) (SAS Institute, 2002-2010) at $P \leq 0.05$ were used to analyze residue dry matter weights (residue biomass), residue C:N ratios, residue N fertilizer deficits (supplemental N fertilizer requirements), and residue C and N contents for aged and fresh residues (Tables 6-7). The statistical analysis was done to determine if there were significant differences in the amount of residue dry matter weight, C:N ratios, residue N deficit (supplemental N requirement), and residue C and N for each of the seven crop rotations. The residue dry matter weight, C:N ratio, C and N contents, and N fertilizer deficit data reported in each of the seven rotations represented the grand total produced and returned to each rotation by all crops in that rotation over a time period. Individual plot data are found in Tables A3 and A4. Results reported as means in Tables 6 and 7. The C:N ratios and residue C and N contents for fresh crop residues are reported in Table 8.

RESULTS AND DISCUSSIONS

The analysis of aged residue dry matter weight (residue biomass) is shown in Table 6. Total residue dry matter weight was significantly greater in the C-S rotation compared to the SW-WW-F-C-C-S, WW-CC-C-S, and SW-WW-A-A-C-S rotations. There was greater total residue biomass in the C-S rotation because corn residue was being produced and returned in greater amount and frequency to the rotation. Winter wheat and spring wheat generally produce lower amount of residue than corn. This was the reason why the C-S rotation had greater residue biomass compared to the SW-WW-F-C-C-S, WW-CC-C-S, and SW-WW-A-A-C-S rotations that had winter wheat and spring wheat.

Table 6. Crop rotation treatments, residue weight, residue C and N, residue C:N ratio and residue N fertilizer deficit for the spring 2011 aged residue sampling.

Crop Rotation Treatments[†]	Residue Weight	Residue C	Residue N	Residue C:N Ratio[§]	Residue N Fertilizer Deficit
	--kg/ha--	--kg C/ha--	--kg N/ha--	--------	--kg N/ha--
SW-WW-C-S	10080ab[‡]	4230ab	85.3b	49.4b	99.7a
SW-C-S	9080ab	3799ab	77.7b	49.4b	88.5ab
SW-S	8895ab	3660ab	54.8bc	36.1c	105a
C-S	11768a	5018a	124a	66.6a	95.1a
SW-WW-F-C-C-S	8359b	3443b	80.6b	54.9b	70.1bc
WW-CC-C-S	7405bc	3145b	68.4b	55.7b	69.2bc
SW-WW-A-A-C-S	4232c	1782c	22.3c	35.7c	55.7c

[†] SW-WW-C-S = spring wheat-winter wheat-corn-soybean; SW-C-S = spring wheat-corn-soybean; SW-S = spring wheat-soybean; C-S = corn-soybean; SW-WW-F-C-C-S = spring wheat-winter wheat-flax-corn-corn-soybean; WW-CC-C-S = winter wheat-cover crop-corn-soybean; SW-WW-A-A-C-S = spring wheat-winter wheat-alfalfa-alfalfa-corn-soybean.

[‡] Means with the same letter are not significantly different at $p \leq 0.05$.

[§] C:N = carbon:nitrogen ratio.

The total amount of residue that corn and soybean produced and returned to the SW-WW-F-C-C-S, WW-CC-C-S, and SW-WW-A-A-C-S rotations was also lower than the total amount of residue that corn and soybean produced and returned to the C-S rotation. The difference in amount of residue being produced and returned to each of the four rotations was related to the frequency of planting corn, soybean, or wheat in each rotation. The main reason for lower total residue biomass in the SW-WW-F-C-C-S rotation was that flax residue was being produced and returned in lower amount and frequency to the rotation. Low frequent production of corn, soybean, and wheat residue in the SW-WW-F-C-C-S rotation also reduced the total amount of residue in the rotation.

The WW-CC-C-S rotation had lower total residue biomass due to the production of low-residue crops such as field pea, forage radish, and soybean which reduced the total amount of residue in the rotation. The amount of corn and wheat residue being produced in the WW-CC-C-S rotation was also low due to low frequent production of these crops in the system. The total residue biomass in the SW-WW-A-A-C-S rotation was lowest due to the production of low residue-crops such as two alfalfa crops and soybean in the rotation. Alfalfa residue was also being removed as hay which contributed to lower total residue biomass in the SW-WW-A-A-C-S rotation compared to the C-S rotation where no residue was removed.

Table 6 also shows analysis of residue C and N contents for the aged residue. Total residue C and N contents were significantly greater in the C-S rotation compared to the SW-WW-F-C-C-S, WW-CC-C-S, and SW-WW-A-A-C-S rotations. Total residue C and N contents in the SW-WW-A-A-C-S rotation were significantly lower than other rotations, except the SW-S rotation. Greater total residue C and N contents in the C-S rotation were attributed to greater cumulative residue biomass collected from the rotation due to greater frequency of corn production in the system. Higher residue C and N contents in the C-S rotation were also attributed to greater cumulative corn residue C and N being produced and returned 50% of the time to the soil surface in the rotation. Soybean residue with relatively greater C and N (Table 8) than other crops was also being produced and returned 50% of the time to the C-S rotation which contributed to the total residue C and N in the rotation. However, the SW-WW-C-S, SW-C-S, and SW-S rotations had lower total residue N in the systems compared to the total residue N the C-S rotation. Greater residue N content in the C-S rotation was attributed to slightly greater cumulative residue biomass collected in the system compared to the SW-WW-C-S, SW-C-S, and SW-S rotations although residue dry matter weight showed no significant difference in the four systems (Table 6).

There were lower total residue C and N contents in the SW-WW-F-C-C-S rotation because lower total residue biomass was being produced and returned to the rotation due to lower frequency of corn production in the rotation. Although high residue crops such as corn and wheat were each present in the rotation two-thirds (67%) of the time, wheat biomass production is generally lower than corn. Flax residue which is high in C and low in N was also being produced in lower amount and frequency in the SW-WW-F-C-C-S rotation which contributed to lower total residue C and N contents in the rotation. Although flax showed greater residue C than other crop residues (Table 8), lower frequent production of flax in the SW-WW-F-C-C-S rotation resulted in lower cumulative residue C in the system. Lower residue C and N contents in the WW-CC-C-S rotation were due to the production of low-residue crops such as forage radish, field pea, and soybean in the system. Corn and soybean residue was also being produced in lower amount and frequency in the WW-CC-C-S which reduced total residue C and N contents in the system compared to the C-S rotation where greater corn and soybean residue was being produced in greater quantity and frequency. Lower residue C and N contents in the SW-WW-A-A-C-S rotation were attributable to lower total residue biomass collected in the rotation due to low-residue yielding crops such as two alfalfa crops and soybean. The removal of cumulative crop residue during haying of the alfalfa also influenced the total residue C and N in the SW-WW-A-A-C-S rotation. Leaching of soluble residue C and N in alfalfa and soybean N-rich residue during the spring 2011 snowmelt and precipitation might have also contributed to lower total residue C and N in the SW-WW-A-A-C-S rotation. Greater total residue C content also corresponded with greater total residue N content in aged residue (Table 6). Rotations that showed greater total residue C also showed greater total residue N while rotations that showed lower total residue C also showed lower total residue N. As evidenced by residue biomass in Table 6, greater total residue C and N contents also were related to the total residue collected in each rotation (Table 6).

Aged residue C:N ratios are also shown in Table 6. Total residue C:N ratio was significantly wider in the C-S rotation compared to the SW-S and SW-WW-A-A-C-S rotations. The wider total C:N ratio in the C-S rotation was attributed to low-N corn residue being produced and returned 50% of the time to the rotation which increased the C:N ratio in the rotation. The wider C:N ratio in the C-S rotation was also due to greater residue biomass collected from the rotation compared to the SW-WW-F-C-C-S, WW-CC-C-S, and SW-WW-A-A-C-S rotations where lower residue biomass was collected. Lower C:N ratio in the SW-WW-A-A-C-S rotation was attributed to alfalfa and soybean high-N residue being produced in the rotation as well as lower total residue biomass in proportion to greater residue N collected in the rotation. Lower total C:N ratio in the SW-S rotation was due to soybean N-rich residue being produced and returned 50% of the time to the rotation and with spring wheat biomass being generally lower relative to corn residue in the C-S rotation. Therefore, the SW-S and SW-WW-A-A-C-S rotations had lower C:N ratios due to relatively higher legume N-rich residues in the rotations. The C:N ratio also tends to decrease as crop residue decomposes due to conservation of N and evolution of C as CO_2 (Brady, 1974). Leaching of soluble residue C has also been shown to decrease a C:N ratio of aged plant material compared to fresh plant material (M. Russelle, 2012, personal communication). This was probably the reason why the aged residue C:N ratios (Table 6) were slightly lower than the fresh residue C:N ratios (Table 7).

Furthermore, although actual winter wheat residue had greater C:N ratio (101:1) than actual corn residue C:N ratio (73:1) (Table 8), the SW-WW-C-S, SW-WW-F-C-C-S, WW-CC-C-S, and SW-WW-A-A-C-S rotations with winter wheat had lower total C:N ratios in the rotations compared to the C-S rotation without winter wheat (Table 6). Winter wheat aged residue was presumed to have been physically and biologically degraded over the spring season, thereby reducing soluble residue C before sampled in the spring 2011. But cornstalk residue may not have been physically weathered and biologically degraded by the same environmental conditions over the winter and spring seasons possibly due to the chemical composition of corn residue C. The fact that wheat was harvested in July and August while corn was harvested in October also allowed wheat residue to weather before corn residue although both corn and wheat were harvested in the fall 2010 and residues overwintered into the spring 2011.

Winter wheat contribution to the rotations with winter wheat might have also been masked because residue C:N ratios were computed from combined crop residue samples across all plots within rotation treatments. Winter wheat was also less frequently cropped in the rotations in which it was included than corn in the C-S rotation. These conditions made it difficult to accurately determine winter wheat contribution to the rotations in which it was included and further research is necessary to elucidate the differences in residue contribution by corn and winter wheat in cropping systems.

Also, the aged residue C:N ratios for the seven rotations (Table 6) were greater than the C:N ratios of 25:1 to 30:1 required for residue N mineralization reported by Allison (1973). Legume crop residue C:N ratios and non-legume crop residue C:N ratios (Table 8) were lower and slightly greater, respectively, than the aged residue C:N ratios (Table 6) which showed that combined residues across the plots within the rotation treatments influenced the aged residue C:N ratios (Table 6). Wide C:N ratios (Table 6) have a greater potential to increase N immobilization due to low residue N. Therefore, application of supplemental N fertilizer to subsequent crops would be required to reduce N immobilization by microorganisms decomposing high C residues.

The analysis of aged residue N fertilizer deficits (supplemental N fertilizer requirements) is shown in Table 6. Supplemental N fertilizer would be the amount of inorganic N fertilizer required by a subsequent crop as well as microorganisms decomposing high C residue. Supplemental N fertilizer need was significantly greater in the SW-WW-C-S, SW-S, and C-S rotations compared to the SW-WW-F-C-C-S, WW-CC-C-S, and SW-WW-A-A-C-S rotations. The SW-WW-C-S, SW-S, and C-S rotations required greater supplemental N fertilizer because corn and wheat residue with corresponding low N content was being produced and returned to the rotations. Corn and wheat residue with corresponding low N content may have been produced and returned 75% of the time to the SW-WW-C-S rotation which increased the need for supplemental N fertilizer in the rotation. Spring wheat residue with corresponding low N content was being produced and returned 50% of the time to the SW-S rotation which also increased the need for supplemental N fertilizer in the rotation. The C-S rotation required greater supplemental N fertilizer because greater corn residue with low N content was being produced and returned 50% of the time to the rotation. There was less supplemental N fertilizer needed in the SW-WW-F-C-C-S, WW-CC-C-S, and SW-WW-A-A-C-S rotations because lower residue biomass was produced in each of these rotations. The SW-WW-A-A-C-S rotation also required less total supplemental N fertilizer because alfalfa and soybean N-rich residue was being produced and returned to the rotation. As evidenced by residue biomass (Table 6), rotations with greater residue biomass required more supplemental N fertilizer for a subsequent crop compared to rotations with lower residue biomass. Therefore, there was lower supplemental N fertilizer required in the SW-WW-A-A-C-S rotation due to lower total residue biomass with greater total N collected in the rotation.

The analysis of fresh residue dry matter weight (residue biomass) is shown in Table 7. Total residue biomass was significantly greater in the SW-C-S and C-S rotations and lower in the SW-WW-A-A-C-S rotation. Greater total residue biomass in the SW-C-S rotation was due to corn and wheat residue being produced and returned in greater quantity and frequency to the rotation. Soybean residue also was being produced and returned 33% of the time to the SW-C-S rotation which contributed to the greater total residue biomass in the system. The C-S rotation had greater total residue biomass because corn residue was being produced and returned in greater amount and frequency to the rotation. Soybean residue also produced and returned 50% of the time to the C-S rotation which contributed to the total residue biomass in the system. Therefore, greater frequency of corn, soybean, and wheat production in the SW-C-S and C-S rotations increased total residue biomass in the systems. There was lower residue biomass in the SW-WW-A-A-C-S rotation because lower total residue biomass was collected in the rotation due to the removal of the accumulated crop residue and alfalfa biomass by haying compared to rotations where greater residue quantity was collected. Corn, soybean, and wheat residue also was being produced and returned in lower amount and frequency to the SW-WW-A-A-C-S rotation which resulted in the lower residue biomass in the system.

Analysis of fresh residue C and N contents is shown in Table 7. Total residue C and N contents were significantly greater in the SW-C-S and C-S rotations compared to the SW-S and SW-WW-A-A-C-S rotations. Greater residue C and N contents in the SW-C-S and C-S rotations were due to greater total residue biomass with corresponding greater total residue C produced in the two rotations. Corn and soybean residue were each produced and returned 50% of the time to the C-S rotation which influenced residue C and N in the rotation. Corn and soybean residue were also each produced and returned 33% of the time to the SW-C-S rotation which also likely influenced residue C and N in the rotation. Therefore, greater residue C and N contents in the SW-C-S and C-S rotations were due to greater frequency of corn, wheat, and soybean production in each of these rotations.

Table 7. Crop rotation treatments, residue weight, residue C and N, residue C:N ratio and residue N fertilizer deficit for the fall 2012 fresh residue sampling.

Crop Rotation Treatments[†]	Residue Weight	Residue C	Residue N	Residue C:N ratio[§]	Residue N Fertilizer Deficit
	--kg/ha--	--kg C/ha--	--kg N/ha--	--------	--kg N/ha--
SW-WW-C-S	9053ab[‡]	3937ab	86.6ab	61.2ab	85.6abc
SW-C-S	10354a	4488a	98.2a	58.4ab	98.1a
SW-S	7243ab	3184b	68.0bc	58.6ab	71.3bc
C-S	10278a	4503a	103a	64.4a	93.3ab
SW-WW-F-C-C-S	8949ab	3890ab	85.2ab	61.6a	85.0abc
WW-CC-C-S	8801ab	3861ab	92.5ab	67.0a	76.4abc
SW-WW-A-A-C-S	6850b	2837b	56.4c	45.6b	67.7c

[†] SW-WW-C-S = spring wheat-winter wheat-corn-soybean; SW-C-S = spring wheat-corn-soybean; SW-S = spring wheat-soybean; C-S = corn-soybean; SW-WW-F-C-C-S = spring wheat-winter wheat-flax-corn-corn-soybean; WW-CC-C-S = winter wheat-cover crop-corn-soybean; SW-WW-A-A-C-S = spring wheat-winter wheat-alfalfa-alfalfa-corn-soybean.

[‡] Means with the same letter are not significantly different at $p \leq 0.05$.

[§] C:N = carbon:nitrogen ratio.

The SW-WW-A-A-C-S rotation had lower total residue C and N contents than other rotations, except the SW-S rotation. This was likely due to low residue yielding crops such as the two alfalfa crops and soybean in the rotation. Alfalfa was also being removed as hay and thereby reduced residue C and N input into the rotation. The amount of residue C and N produced and returned to the SW-WW-A-A-C-S rotation by corn and wheat was also lower than the amount of residue C and N produced and returned to the SW-C-S and C-S rotations by corn and wheat over the same period of time. Difference in the amount of residue C and N produced and returned to each of these systems was related to the frequency of producing each crop in each system.

Also, greater total residue C content corresponded with greater total residue N content in fresh residue (Table 7). Rotations that had greater total residue C showed greater total residue N while rotations that had lower total residue C showed lower total residue N. As evidenced by total residue biomass in each rotation in Table 7, greater total residue C and N contents were also related to the quantity of total residue collected in each rotation (Table 7).

Fresh residue C:N ratios are shown in Table 7. Residue C:N ratios were significantly greater in the C-S, SW-WW-FX-C-C-S, and WW-CC-C-S rotations compared to the SW-WW-A-A-C-S rotation. Greater C:N ratios in the C-S, SW-WW-FX-C-C-S, and WW-CC-C-S rotations were due to greater total residue production with corresponding greater total residue C in each of the rotations. There was a wider C:N ratio in the C-S rotation due to the production of greater corn residue C in proportion to lower N in the rotation. Winter wheat residue C:N ratio (101:1) (Table 8) may have increased the total C:N ratios in the SW-WW-FX-C-C-S and WW-CC-C-S rotations. There was a narrower C:N ratio in the SW-WW-A-A-C-S rotation due to alfalfa and soybean N-rich residue in the rotation. Lower amount of residue biomass with greater residue N was also collected in the SW-WW-A-A-C-S rotation which reduced the C:N ratio in the system. Table 8 also shows narrower C:N ratios for legume crops and wider C:N ratios for non-legume crops, indicating that legume crops have a greater potential to influence crop residue C:N ratio compared to non-legume crops.

Also, the fresh residue C:N ratios for the seven rotations (Table 7) were much greater than the C: N ratios of 25:1 to 30:1 required for residue N mineralization reported by Allison (1973). Legume crop residue C:N ratios and non-legume crop residue C:N ratios (Table 8) were lower and slightly greater, respectively, than the fresh residue C:N ratios (Table 7) which showed that cumulative residue across the plots within the rotation treatments influenced the fresh residue C:N ratios (Table 7). These wide C:N ratios (Table 7) are likely to increase residue N immobilization due to low N. Supplemental N fertilizer would likely be required by subsequent crops to reduce a potential N tie-up due to microorganisms decomposing high C residue.

The analysis of fresh residue N fertilizer deficit (supplemental N fertilizer requirement) is shown in Table 7. The supplemental N fertilizer was significantly greater in the SW-C-S rotation compared to the SW-WW-A-A-C-S rotation. As evidenced by residue biomass in the SW-C-S rotation (Table 7), greater supplemental N fertilizer requirement for the SW-C-S rotation was due to greater total residue quantity produced in the rotation. The SW-WW-A-A-C-S rotation required lower supplemental N fertilizer because alfalfa and soybean N-rich residue was being produced and returned to the rotation. Also, as evidenced by residue biomass in each rotation (Table 7), rotations with greater residue biomass required greater supplemental N fertilizer compared to rotations with lower residue biomass. This was the reason why the SW-WW-A-A-C-S rotation which had lower residue biomass required lower supplemental N fertilizer than the rotations which had greater residue biomass.

The actual C:N ratios and residue C and N concentrations for fresh crop residues are shown in Table 8. These C:N ratios were wider for non-legume crops such as corn, flax, spring wheat, and winter wheat and narrower for legume crops such as alfalfa, pea, soybean, as well as forage radish, which was due to legume crops and radish having greater N contents than non-legume crops. Winter wheat residue showed the greatest C:N ratio (101:1) similar to a C:N ratio (98:1) reported by Kumar et al. (2012). Greatest winter wheat residue C:N ratio was due to lowest residue N in proportion to residue C. Among legume crop residues (Table 8), soybean residue showed the greatest C:N ratio (53:1) similar to a C:N ratio (54:1) reported by Smith and Sharpley (1990). The greatest soybean residue C:N ratio (53:1) was due to the fact that its residue was sampled when dry (Table 8) compared with fresh plant material for pea, radish, and partially green alfalfa residue at sampling.

Pea residue (18:1) and radish residue (8:1) had much lower C:N ratios compared to other fresh crop residues due to greater residue N in proportion to residue C. Pea and radish were in a vegetative green stage when sampled and as cover crops, pea and radish were not yet killed by frost at sampling.

Table 8. Crop residues, scientific names, residue N, residue C and residue C: N ratios for the fresh crop residues for the fall 2012 sampling.

Crop Residues	Scientific Names	Residue N	Residue C	Residue C:N Ratios[§]
		--g N/kg--	--g C/kg--	--------
Alfalfa	*Medicago sativa* L.	21.8	446	21.0
Corn	*Zea mays* L.	5.90	429	73.0
Flax	*Linum usitatissimum* L.	6.10	472	77.0
Pea	*Pisum sativum* L.	24.7	442	18.0
Radish	*Raphanus sativus* L.	44.2	364	8.00
Soybean	*Glycine max* L.	8.40	443	53.0
Spring wheat	*Triticum aestivum* L.	5.60	425	76.0
Winter wheat	*Triticum aestivum* L.	4.40	444	101

[§] C:N = carbon:nitrogen ratio.

This was why pea and radish residues had much lower C:N ratios because green organic materials most often contain greater N than dry plant materials. These C:N ratios also show the potential of each crop residue to mineralize or immobilize N. Legume crops had greater residue C and N contents than non-legume crops as evidenced by residue C and N (Table 8). These residue C and N contents show the amount of residue C and N each crop can produce and ultimately return to cropping systems. Nitrogen contents in each crop residue can determine whether residue N will result in N mineralization or N immobilization.

Residue N has been reported to mineralize in the order of alfalfa > peanut > soybean > oat ≥ sorghum > wheat > corn (Smith and Sharpley, 1990). Therefore, high-N legume residue has the potential to increase N mineralization and N availability for subsequent crops compared to low-N non-legume residue. Greater N contents in legume crop residues show the importance of alternating high N-use crops such as corn and wheat with low N-use crops such as alfalfa, pea, and soybean. Including legume crops in cropping systems can reduce supplemental N fertilizer required by non-legume crops. Growers can also gain greater economic benefits by reducing the amount of supplemental N fertilizer that can be applied to non-legume crops. Reduction of supplemental N fertilizer that can be applied to non-legume crops can also reduce environmental problems often associated with greater fertilizer N application in cropping systems that do not include legume crops.

SUMMARY AND CONCLUSIONS

Aboveground crop residue was evaluated to determine the quantity of residue biomass produced and returned to each rotation treatment and impact of residue retention on nutrient cycling in the northern Great Plains. Aged and fresh residue biomass was greater in the C-S rotation. The main reason for greater residue biomass in the C-S rotation was that greater cumulative corn residue was being produced in this rotation. Aged and fresh residue biomass was lower in the SW-WW-A-A-C-S rotation due to lower production of corn and wheat in the rotation. Low-residue producing crops such as alfalfa and soybean which were being produced in the SW-WW-A-A-C-S rotation also contributed to the lower total residue biomass in the system.

The C:N ratios are generally used to predict the rate of residue N mineralization-immobilization and decomposition. Residue C:N ratios are also important in ensuring that there is sufficient N available to meet fertilizer N requirements of subsequent crops. There was lower C:N ratio in the aged residue than fresh residue due to greater residue C in fresh residue compared to the aged residue. The aged and fresh residue C:N ratios were greater than a C:N ratio of 25:1 to 30:1 which showed that supplemental N fertilizer would likely be required by subsequent crops to reduce residue N immobilization. Legume crops and forage radish had lower C:N ratios than non-legume crops which showed that legumes can increase residue N mineralization and non-legumes can promote residue N immobilization. Legume crops can also increase N availability for subsequent crops due to increased N mineralization. Lower C:N ratios for legumes and forage radish were related to legumes having greater N content in proportion to greater residue C content. Winter wheat residue had the greatest C:N ratio (101:1) compared to other crop residues due to its greater C relative to lower N. Radish residue had the lowest C:N ratio (8:1) compared to other fresh crop residues due to its greater N content and also due to the fact it was still in a green vegetative stage when sampled compared to other crop residues sampled when dry.

The C-S rotation had greater total C and N contents for aged and fresh residue because corn residue was being produced and returned in greater quantity to the rotation. The main reason for greater total residue C and N in the C-S rotation was that greater total residue C and N was being produced and returned to the rotation by corn. Soybean residue also was being produced 50% of the time in the C-S rotation which contributed to greater total residue biomass in the system. The SW-WW-A-A-C-S rotation had lower total residue C and N contents for the aged and fresh residues because corn and wheat residue was being produced and returned in lower amount and frequency to the rotation. Lower total residue C and N in the SW-WW-A-A-C-S rotation was also due to lower total residue biomass collected in the rotation compared to other rotations where greater total residue biomass was collected. In comparison, corn residue was produced and returned in greater amount to the C-S rotations while corn residue was produced and returned in lower amount to the SW-WW-A-A-C-S rotation. Residue C and N contents in cropping systems are not only increased by intensification and diversification of crops but also by frequency of planting each crop in cropping systems. Planting high residue producing crops such as corn and wheat more frequently can increase residue C and N on the soil surface than planting corn and wheat less frequently. This was the reason why the C-S rotation which had greater frequency of corn production in the system contained greater residue C and N compared to the rotations which had lower frequency of corn and wheat production in the systems. The actual residue C and N contents for legume and non-legume crops showed the amount of C and N each crop can produce and return to cropping systems. Residue C and N contents show that legume crop residues can increase N mineralization and N availability for subsequent crops than non-legume crop residues, indicating that non-legume crop residues may require additional N fertilizer to reduce residue N tie-up by microorganisms decomposing high C residues.

The residue N fertilizer deficits were potential supplemental N fertilizer requirements required by subsequent crops to reduce residue N immobilization due to microorganisms decomposing high C residue. Supplemental N fertilizer requirements were slightly greater for fresh residue than aged residue. Aged residue required lower supplemental N fertilizer probably due to leaching of soluble residue C and N during the 2011 spring snowmelt and precipitation. Lower supplemental N fertilizer requirement for the aged residue was also due to lower total residue biomass collected from the aged residue in the spring 2011 which was due to partial decomposition of the residues between harvest and crop seeding the following spring compared to greater total residue biomass collected from the fresh residue in the fall 2012. The amount of residue biomass in each of the seven rotations also corresponded with the mount of supplemental N fertilizer required by subsequent crops to reduce residue N immobilization in each system. Rotations that had greater residue biomass required greater supplemental N fertilizer for the systems while rotations that had lower residue biomass required lower supplemental N fertilizer for the systems. This shows that high residue biomass can increase supplemental N fertilizer requirement for subsequent crops and microorganisms decomposing high C residue under no-till management systems.

Recommendations for Future Research Trials

Sustainable management of cropping systems is required to balance nutrient removal with nutrient replenishment and mitigate SOC emissions in the Northern Great Plains. The estimated supplemental N requirements are the estimated N fertilizer amounts intended to offset the residue N immobilization due to microbes decomposing high C residues. These estimated N fertilizer amounts should be applied to subsequent crops as recommended by Allison (1973).

The intent of the recommendations is to provide information that will be important for determining N fertilizer requirements and adjusting fertilizer application rates for different crops in cropping systems. Different locations have different climatic conditions and soil types.

Therefore, use of these sources and estimated supplemental fertilizer amounts should be based on site-specific climatic conditions, soil types, and SOM levels. The economic value of all these recommendations should be determined in future studies to help determine “return to N” fertilizer based on grain income as recommended by Franzen et al. (2011). Specific areas in using residue information in the future include:

- A study already conducted in North Dakota showed that spring wheat and durum wheat (*Triticum durum* Desf.) required 50 kg N/ha less fertilizer under long-term no-till systems than conventional systems (Franzen et al., 2011). That study indicated that residue information can potentially be used to modify fertilizer N recommendations to account for N mineralized from the previous crop residue. The intent of that study was to provide spring wheat and durum growers in North Dakota with fertilizer N recommendations they could use in their nutrient management, N adjustment, and timing of N application in long-term no-till (> 5 years) wheat production. A fertilizer N recommendation guide in Montana suggests that fertilizer N rate should be decreased by 45 kg N/ha (40 lb. N/ac) where the previous crop was alfalfa (Dinkins and Jones, 2007). A recent study conducted in Montana reported that urea-based and anhydrous ammonia fertilizers should be incorporated under high residue conditions to minimize a conversion of urea to NH_4^+ and subsequent NH_3 volatilization (Jones et al., 2013). Another study conducted in Wisconsin reported that 34 kg N/ha (30 lb. N/ac) should be added to corn where at least 50% of the soil surface was covered by previous corn residue (Bundy, 1998). This additional fertilizer N would be mainly required to compensate for low annual amount of mineralized N from SOM and N-immobilized in surface residues under high corn residue conditions. This amount would not be required if the previous crop was either soybean or forage legume**.** But 34 kg N/ha can probably be halved for corn that may be planted in 100% residue-covered surface similar to the CCSP site. Reduction of 34 kg N/ha under 100% residue treatments would be necessary because high residue amount increases residual soil NO_3-N for the next crops. “High levels of residual inorganic N in the root profile contribute a major portion of the total plant N and should be taken into account when formulating fertilizer N recommendations for improving N use efficiency” (Sowers et al., 1994). Therefore, residual soil NO_3-N tests are also recommended for future determination of fertilizer N. Using such studies in conjunction with site-specific conditions will be important when evaluating future use of these estimated N fertilizer amounts.

- The amount of fertilizer N required by corn is almost always greater than the amount of fertilizer N required by other crops. Therefore, additional experiments should be established to determine the amount of fertilizer N required by high-N consuming crops such as corn and wheat and low-N requiring crops such as alfalfa, pea, and soybean. Different plots will need to be established. Sizes of sub-plots can be designed to fit into the current sizes of plots at the CCSP site with different rates of the supplemental N fertilizer being applied to different sub-plots to determine the exact amount each crop will need to attain its yield potential goal and protein content. For example, 0 kg N/ha, 50 kg N/ha, 100 kg N/ha, and 150 kg N/ha, and 200 kg N/ha of N fertilizer amounts should be applied to different plots with the same crop to determine the yield potential and grain protein content and relative to the residue N content. These N fertilizer rates should be split-applied to crops to enhance seed germination, reduce in-season N deficiencies, and reduce crop growth variability, with greater in-season N to achieve both grain yield and protein content (Jones and Olson-Rutz, 2012). Spring N application to crops is also important because it increases N uptake efficiency and reduces N (N_2O and NO_3-N) losses to the environment compared to fall N application. This work will need to be conducted on long-term no-till trials in order to make valid assumptions and conclusions. A drawback to conducting this research is lack of long-term research sites that would allow research to continue for more than five years. A five-year study under no-till management can provide a valid evaluation of its impacts on SOC sequestration, soil health, and nutrient cycling, especially with regard to N.

- It has been reported that residue left on the soil surface may increase NH_3 volatilization (De Ruijter et al., 2010). Low-N residue such as corn and wheat residues may not result in NH_3 volatilization under high residue cropping systems. However, high-N residue such as alfalfa and soybean residues may increase NH_3 volatilization if not incorporated in the soil. Therefore, incorporating high-N residue can reduce NH_3 volatilization and increase NH_4^+ availability for subsequent crops (De Ruijter et al., 2010). Incorporating N-rich residue can also reduce supplemental N fertilizer required by subsequent crops due to increased N availability in the soil. One way to experimentally conduct this would be to compare two plots where N-rich residue would be surface-applied in one plot and N-rich residue would be soil-incorporated in another plot. This would likely defeat the purpose of no-till management but a comparison still should be made to advance science.
- Fertilizer N management and recommendations have traditionally relied on soil tests, protein content, and potential yield goals. It has been reported that soil test and previous year grain yield variation techniques cannot predict the nutrient availability of mobile nutrients such as N fertilizer during the reproductive growth of winter wheat and similar

crops (Stone et al., 1996). A study has also reported that fertilizer N application to wheat during reproductive growth will increase the potential for the crop to increase its grain yield and protein content (Jones and Olson-Rutz, 2012). “The highest recovery of added fertilizer N in the crop is obtained when a readily available form of nitrogen is applied directly to the growing crop, and in such amounts that it will be assimilated promptly” (Allison, 1973). A study has also shown that N uptake by crops is often low at the beginning of the growing season, high during vegetative stage, and rapidly reduce as crops reach their maturity (Millar et al., 2010). Therefore, new technologies should be used for detecting mid-season N deficiencies and recommending N fertilizer during crop growing seasons. Chlorophyll meter and normalized difference vegetation index (NDVI) have recently been used to asses a mid-season N stress (Stone et al., 1996; Schlegel et al., 2005). These technologies can be used to apply and manage the estimated supplemental N fertilizer rates for the future research trials. Although these new technologies require specialized equipment (Schlegel et al., 2005), they are important for evaluating in-season N stress and recommending N fertilizer for growing crops. These technologies can help growers and scientists to detect N stress in some parts of field, determine timing of N application, adjust N fertilizer rate, improve the N use efficiency (NUE), increase yield and residue biomass, and eliminate overestimation of N fertilizer. Implementing these techniques as well as synchronizing N application with plant N demand can increase N use efficiency and reduce N (N_2O and NO_3-N) losses to the environment.

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PAPER 3. EVALUATION OF SOIL C SEQUESTRATION, GREENHOUSE GAS EMISSIONS, AND SOIL LOSS IN A NO-TILL SYSTEM USING THE VOLUNTARY REPORTING TOOL COMET-VR AND RUSLE2.

ABSTRACT

Models have been used to estimate SOC levels, GHG emissions, and soil losses under agricultural management practices in the United States and the world. The CarbOn Management Evaluation Tool-Voluntary Reporting (COMET-VR) and Revised Universal Soil Loss Equation version 2 (RUSLE2) models were used to estimate SOC levels and soil losses under the seven crop rotations, respectively. The Soil Conditioning Index (SCI) and Soil Tillage Intensity Rating (STIR) programs in the RUSLE2 model were used to predict the impacts of the seven rotations on SOC conditions and soil disturbance ratings, respectively. The SW-WW-C-S, SW-WW-F-C-C-S, WW-CC-C-S, and SW-WW-A-A-C-S rotations with winter wheat and SW-C-S, SW-S, and C-S rotations without winter wheat were evaluated using these models. The COMET-VR model predicted slightly greater SOC levels and GHG emissions in high-intensity rotations with winter wheat compared to low-intensity rotations without winter wheat. The model estimated lower SOC levels in the rotations such as SW-S and C-S compared with the rotations such as SW-WW-F-C-C-S and SW-WW-A-A-C-S. A comparison of ten-year projected model-based and field-based SOC levels showed that the model estimated lower SOC levels in the seven rotations than the actual SOC levels. The RUSLE2 model estimated lower soil losses for 3% slope and greater soil losses for 6% slope as expected with a correlation of r = 1.00. The SW-WW-C-S, SW-WW-F-C-C-S, and SW-WW-A-A-C-S rotations had lower soil losses than the SW-C-S, SW-S, and C-S rotations for 3% and 6% slopes, respectively. The WW-CC-C-S rotation had greater soil losses compared to other six rotations due to lower residue cover in the system. The SCI and STIR

predicted positive SOC conditions and low soil disturbance ratings, respectively. Low soil losses, positive SCI values, and low STIR values reflected the positive impact of crop residue retention and crop rotation under no-till management at the CCSP site.

INTRODUCTION

Use of Models to Estimate GHG Emissions, SOC Storage, and Soil Losses

Increased global demand for food to meet the growing human population has increased soil surface disturbance, fossil fuel consumption, biomass burning, and GHG emissions (Follet et al., 2005). The GHGs associated with the climate change include carbon dioxide (CO_2) and nitrous oxide (N_2O) (Bracmort, 2010). As gases are released into the atmosphere, they trap heat within the atmosphere and increase the air temperature which may consequently lead to the greenhouse effects (USDA-NRCS, 2007). The N_2O may contribute to the global climate change (Yung et al., 1976) and destruction of the stratosphere layer (Crutzen, 1981).

No-till systems have been linked to increased N_2O emissions due to greater NH_4^+ and NO_3^- on the soil surface compared to conventional tillage systems (Mackenzie et al., 1998). Staley et al. (1990) reported high N_2O emissions under residue no-till system due to greater mineralizable SOC on the soil surface. The N_2O emissions are influenced by soil temperature, volumetric soil water content, precipitation, and air temperature (Omonode et al., 2010). Higher N denitrification and N_2O emissions have been reported under high residue conditions system due to greater soil moisture, SOC, and microbial populations on the soil surface (Doran, 1980; Aulakh et al., 1984).

Corn and soybean have been observed to be responsible for the greatest N_2O emissions in the USA (Del Grosso et al., 2005). Fall N application has been associated with greater N_2O emissions than spring N application due to increased wetness during the fall season snowmelt and precipitation (Novoa and Tejeda, 2006). Higher N_2O emissions have been reported from corn systems due to greater N application to corn under no-till systems (Mackenzie et al., 1997; Mackenzie et al., 1998). However, a study by Grandy et al. (2006) reported increased SOC and improved soil physical structure and no increased N_2O emissions under no-till regime. They also reported that increased SOC storage can offset N_2O emissions under no-till management systems.

The Natural Resources Conservation Services (NRCS) focuses its efforts on global climate change by: 1) quantifying the effects of conservation practices on GHG emissions and SOC sequestration; 2) refining incentives in conservation programs to address the impacts of climate change on agriculture; 3) developing and encouraging use of conservation practices that reduce GHG emissions; and 4) enhancing opportunities to increase farm profitability on the emerging voluntary emission trading markets (USDA-NRCS, 2011a). Conservation agricultural practices have a potential to reduce atmospheric concentrations of GHGs by storing SOC, reducing GHG emissions, improving N fertilizer use, and reducing fossil fuel combustion.

Proposed management practices will help producers save money and time while improving their environment around them and their community livelihoods. The COMET-VR model was developed to help producers, farmers, and scientists estimate and report stored SOC and GHG emission reductions under exiting agricultural conditions and conservation management practices. The model allows users to quantify their SOC changes and provides them with the ability to determine the effect of their production practices on SOC levels and CO_2 and N_2O emissions (USDA-NRCS, 2012). As part of NRCS policy, producers who can use the model can be given a one-time incentive of $500 under the NRCS Conservation Security Program (CSP) (USDA-NRCS, 2012).

Soil erosion reduces soil productivity when clay and sodium-saturated subsoil is exposed and subsequently reduces infiltration, increases surface runoff, and accelerates erosion on down slope soils (National Soil Erosion-Soil Productivity Research Planning Committee, 1981). The RUSLE2 model was developed to help farmers, scientists, and land managers to estimate soil losses under conditions related to cropping systems, management strategies, and erosion control practices (Angima et al., 2003). The Soil Conditioning Index (SCI) and Soil Tillage Intensity Rating (STIR) programs in the RUSLE2 model were developed to predict the effects of cropping systems on SOC conditions (Warren Wilson College, 2012) and tillage disturbance rating (USDA-NRCS, 2008a, 2011b), respectively.

Objectives

The objectives of this study were to determine the ability of: 1) COMET-VR model to estimate SOC and CO_2 and N_2O emissions under no-till management; 2) RUSLE2 model to quantitatively predict soil losses in no-till production; and 3) SCI and STIR programs to predict SOC conditions and calculate soil disturbance ratings, respectively.

MATERIALS AND METHODS

COMET-VR Modeling Procedure

The COMET-VR model was originally developed for the US Corn Belt region and therefore did not have cropping systems in the northern Great Plains. The COMET-VR was used to evaluate SOC storage and GHG emissions under rotations with winter wheat (*Triticum aestivum* L.) and rotations without winter wheat. The SOC values and GHG emissions reported in each rotation were values accumulated over eleven years under no-till management at the CCSP site.

Rotations with winter wheat were:

- Spring wheat-winter wheat-corn-soybean (SW-WW-C-S)
- Spring wheat-winter wheat-flax-corn-corn-soybean (SW-WW-F-C-C-S)
- Winter wheat-cover crop-corn-soybean (WW-CC-C-S)
- Spring wheat-winter wheat-alfalfa-alfalfa-corn-soybean (SW-WW-A-A-C-S)

Rotations without winter wheat were:

- Spring wheat-corn-soybean (SW-C-S)
- Spring wheat-soybean (SW-S)
- Corn-soybean (C-S)

All simulations were based on the number of crops in each cropping rotation (Tables 9-15). Crops in each rotation were split into two-crop simulations each. Crop rotations that had more crops had more simulations than crop rotations that had fewer crops. Crops were split because the COMET-VR model had limited number of rotations and, therefore, did not reflect all possible combinations of crop rotations at the CCSP site. Different rates of N fertilizer for different crops were entered into the COMET-VR screen, based on the information obtained from the CCSP site.

Different rates of N fertilizer entered for individual crops or combination of crops may have influenced the COMET-VR outputs, especially N_2O values. The outputs were reported as soil and biomass SOC, soil and biomass CO_2 emission equivalents, percent uncertainty, annual N_2O emissions, and N_2O-based CO_2 emission equivalents. The COMET-VR converted a megagram (Mg) soil and biomass SOC into soil and biomass CO_2 emission equivalents using 3.667 Mg of CO_2 per Mg of SOC. Annual N_2O emissions were converted into N_2O-based CO_2 emission equivalents using the global warming potential (GWP) value of 310.

The model-based outputs were computed on a yearly basis (Mg/yr). The simulated values for all simulations were summed for each rotation. The total simulated values were multiplied by 10 years to present SOC sequestration levels and GHG emissions over the next decade for each of the seven crop rotations. The simulated values were also divided by 10 hectares (the area of the CCSP site) for comparison with the field-based SOC values on a per hectare basis. The COMET-VR was able to determine an uncertainty value for the SOC and CO_2 emission equivalents. The uncertainty value (±19) for SOC and CO_2 emission equivalents was consistent for all simulations for the seven crop rotations.

The uncertainty value showed that modeled SOC estimates could vary by +19 to -19% of the simulated value. But the model was unable to determine the uncertainty value for the annual N_2O and N_2O-based CO_2 emission equivalents. This was partly attributed to lack of sufficient field data based on the location, soil type, and the management information that was provided on the COMET-VR data entry screens for the CCSP site. Simulations that had continuous corn, continuous winter wheat, corn-winter wheat, corn-soybean, and continuous soybean had greater stored SOC levels and N_2O emissions than simulations that had continuous corn-spring wheat, continuous spring wheat, soybean-spring wheat, soybean-winter wheat, spring wheat-barley, and pulse-winter wheat.

RUSLE2, SCI, and STIR Modeling Procedure

RUSLE2 1.26.6.4 was used to compute soil losses under the winter wheat rotations and control rotations previously described. The Soil Conditioning Index (SCI) and Soil Tillage Intensity Rating (STIR) programs in RUSLEL2 were used to predict the effects of the rotations on SOC conditions and soil disturbance ratings, respectively. The RUSLE2 model was first programmed using relevant information in North Dakota.

Information included precipitation, temperature, soil, topography, land use, cover management, and supporting practices for all counties in North Dakota. After RUSLE2 1.26.6.4 was downloaded, a profile was created under profile worksheet. Location, topography, soil, cover management, and supporting practices were included in the profile. The profile was also used to store the built-base management sequences. When the profile was used, seven steps were executed to determine soil losses, sediment yields, SOC conditions, and soil disturbance ratings.

Step 1: Choose Location to Set Climate

Sargent County was the location where the CCSP site at Forman was located. Therefore, it was selected in the list of all counties in North Dakota.

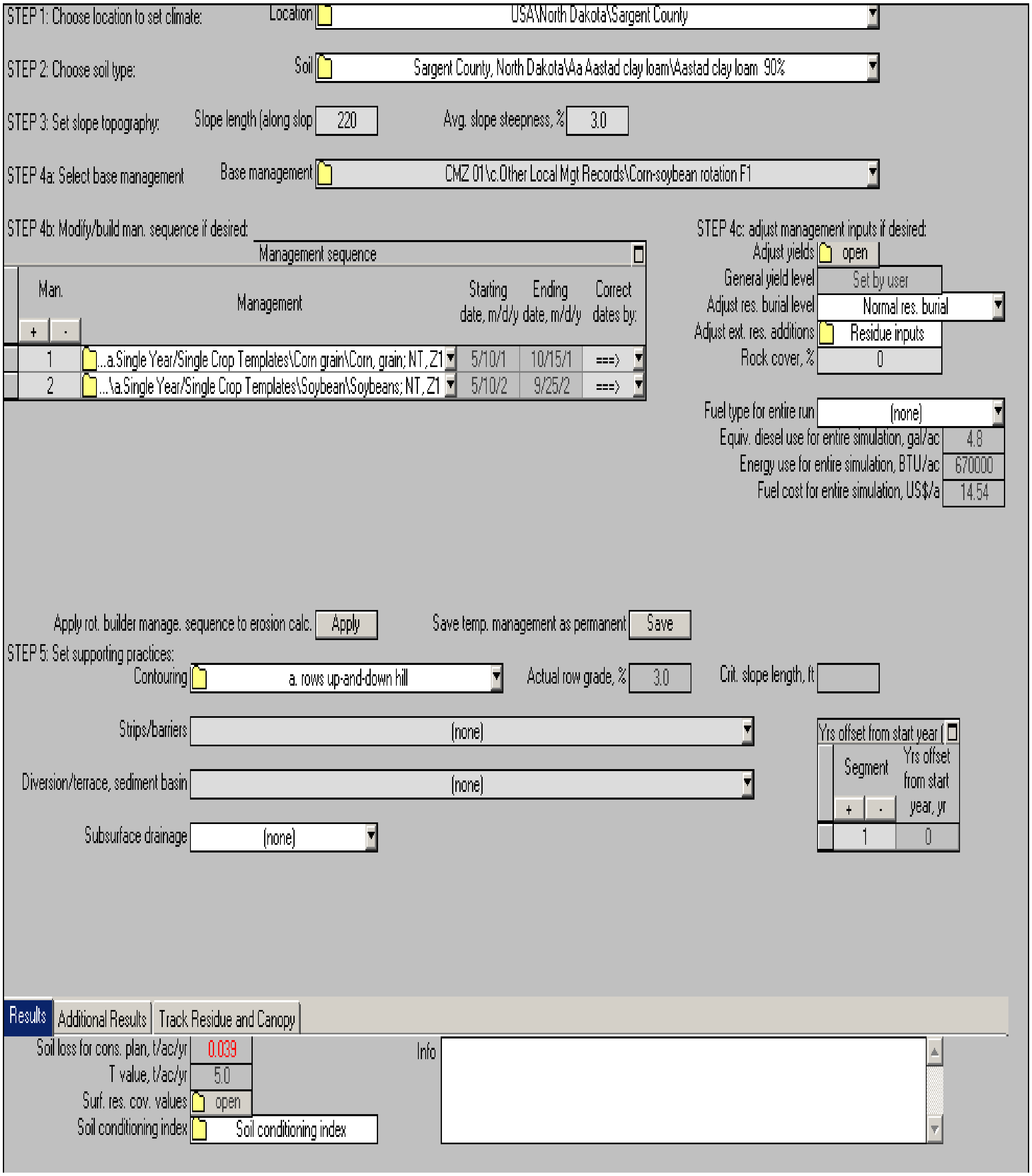
Step 2: Choose Soil Type

Aa Aastad clay loam/Aastad clay loam 90% was selected in the soil screen under Sargent County because it was the dominant soil type at the CCSP farm. Clay loam was chosen because it was a dominant soil texture in the C-S and SW- WW-F-C-C-S rotations sampled in 2006 (Augustin, 2009).

Step 3: Set Slope Topography

Default slope steepness and slope length were changed in the topography screen. Slope length of 67 m (220 ft.) and slope steepness of 3% and 6% were used to compute soil loss estimates in (Fig.5). Both slopes were used because the slope of majority of plots ranged from 3% to 6% at the CCSP site. These slopes were also used to evaluate the impacts of different slopes on soil erosion rates and SOC conditions as determined by RUSLE2 and SCI, respectively. Each rotation was run for both 3% and 6% slopes and slope length of 67 m (220 ft.). For example, the C-S rotation was first run for 3% slope and 67 m (220 ft.) slope length (Fig.

5). The C-S rotation was again run for 6% slope and 67 m (220 ft.) slope length in (Fig. 6). The same procedure was used to compute soil loss estimates for other six crop rotations.



STEP 1: Choose location to set climate: Location: USA\North Dakota\Sargent County

STEP 2: Choose soil type: Soil: Sargent County, North Dakota\Aa Aastad clay loam\Aastad clay loam 90%

STEP 3: Set slope topography: Slope length (along slop: 220 Avg. slope steepness, %: 3.0

STEP 4a: Select base management: Base management: CMZ 01\c.Other Local Mgt Records\Corn-soybean rotation F1

STEP 4b: Modify/build man. sequence if desired:

Management sequence

Man.	Management	Starting date, m/d/y	Ending date, m/d/y	Correct dates by:
1	...a.Single Year/Single Crop Templates\Corn grain\Corn, grain; NT, Z1	5/10/1	10/15/1	===>
2	...\a.Single Year/Single Crop Templates\Soybean\Soybeans; NT, Z1	5/10/2	9/25/2	===>

STEP 4c: adjust management inputs if desired:

Adjust yields: open

General yield level: Set by user

Adjust res. burial level: Normal res. burial

Adjust ext. res. additions: Residue inputs

Rock cover, %: 0

Fuel type for entire run: (none)

Equiv. diesel use for entire simulation, gal/ac: 4.8

Energy use for entire simulation, BTU/ac: 670000

Fuel cost for entire simulation, US$/a: 14.54

Apply rot. builder manage. sequence to erosion calc. Apply

Save temp. management as permanent Save

STEP 5: Set supporting practices:

Contouring: a. rows up-and-down hill Actual row grade, %: 3.0 Crit. slope length, ft:

Strips/barriers: (none)

Diversion/terrace, sediment basin: (none)

Subsurface drainage: (none)

Yrs offset from start year

Segment	Yrs offset from start year, yr
1	0

Results | Additional Results | Track Residue and Canopy

Soil loss for cons. plan, t/ac/yr: 0.039

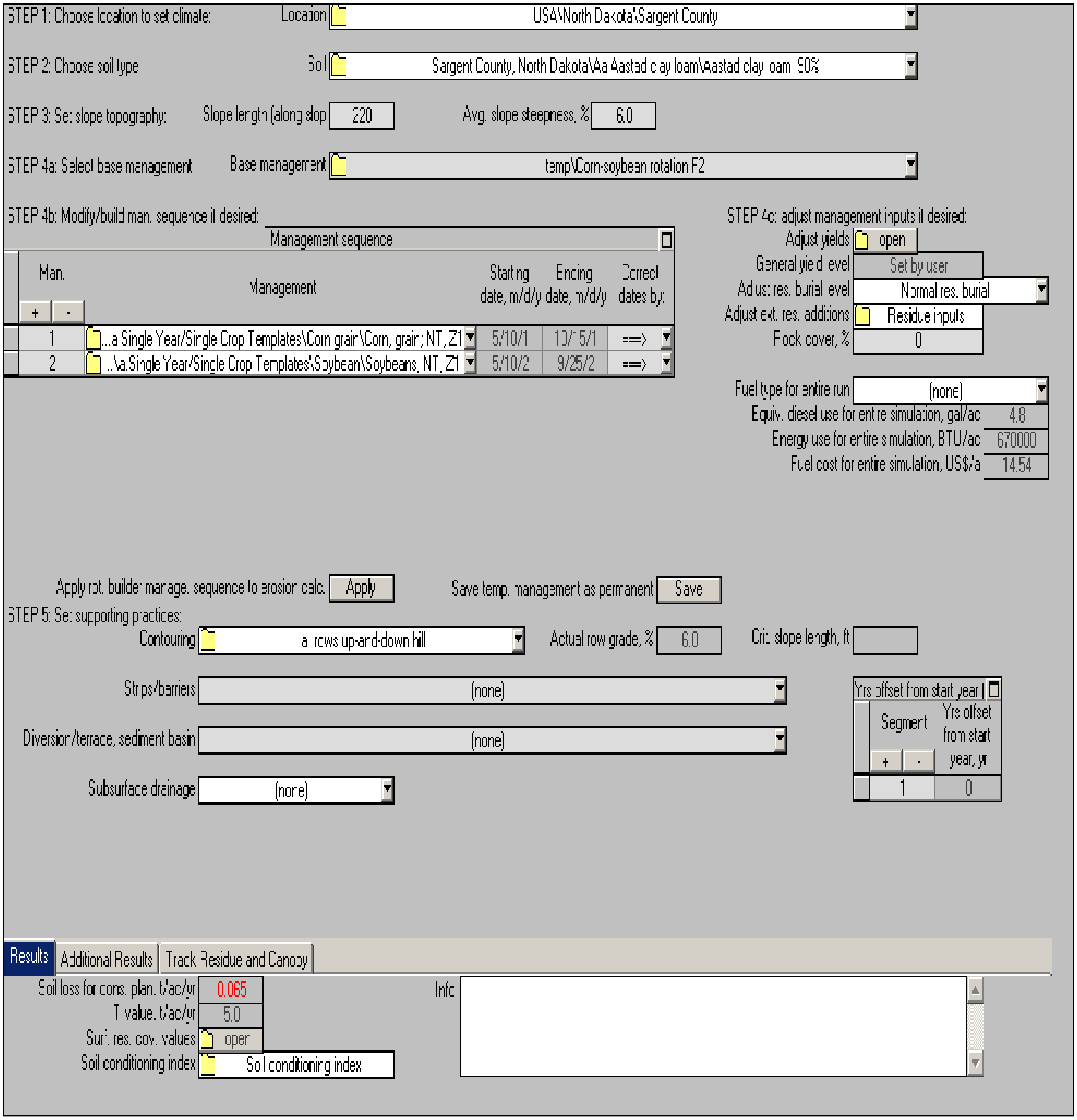
T value, t/ac/yr: 5.0

Surf. res. cov. values: open

Soil conditioning index: Soil conditioning index

Info

Figure 5. Diagram of the RUSLE2 profile for the C-S rotation (3% slope).



STEP 1: Choose location to set climate: Location USA\North Dakota\Sargent County

STEP 2: Choose soil type: Soil Sargent County, North Dakota\Aa Aastad clay loam\Aastad clay loam 90%

STEP 3: Set slope topography: Slope length (along slop 220 Avg. slope steepness, % 6.0

STEP 4a: Select base management Base management temp\Corn-soybean rotation F2

STEP 4b: Modify/build man. sequence if desired:

Management sequence

Man.	Management	Starting date, m/d/y	Ending date, m/d/y	Correct dates by:
1	...a.Single Year/Single Crop Templates\Corn grain\Corn, grain; NT, Z1	5/10/1	10/15/1	===>
2	...\a.Single Year/Single Crop Templates\Soybean\Soybeans; NT, Z1	5/10/2	9/25/2	===>

STEP 4c: adjust management inputs if desired:

Adjust yields open
General yield level Set by user
Adjust res. burial level Normal res. burial
Adjust ext. res. additions Residue inputs
Rock cover, % 0
Fuel type for entire run (none)
Equiv. diesel use for entire simulation, gal/ac 4.8
Energy use for entire simulation, BTU/ac 670000
Fuel cost for entire simulation, US$/a 14.54

Apply rot. builder manage. sequence to erosion calc. Apply
Save temp. management as permanent Save

STEP 5: Set supporting practices:

Contouring a. rows up-and-down hill
Actual row grade, % 6.0
Crit. slope length, ft
Strips/barriers (none)
Diversion/terrace, sediment basin (none)
Subsurface drainage (none)

Yrs offset from start year (

Segment	Yrs offset from start year, yr
1	0

Soil loss for cons. plan, t/ac/yr 0.065
T value, t/ac/yr 5.0
Surf. res. cov. values open
Soil conditioning index Soil conditioning index

Figure 6. Diagram of the RUSLE2 profile for the C-S rotation (6% slope).

Step 4a: Select Base Management

There were three major crop management zones (CMZ 01, CMZ 02, and CMZ 03) available in the RUSLE2 1.26.6.4 profile screen for North Dakota. Sargent County in North Dakota was included under crop management zone (CMZ 01). In the base management screen, a single year/single crop template was selected under CMZ 01. Under the single year/single crop template, each crop was selected from the crop menu list to build base management sequences.

Step 4b: Modify Management Sequence if Desired

Each crop management sequence was modified and built to fit each crop rotation in the RUSLE2 profile screen. Under the single year/single crop template in CMZ01, each crop was "clicked" twice to provide different management options such as plow-based, fallow, and no-till. No-till operation was selected for all crops to build all management sequences. Under the management screen, there were plus (+) and minus (-) signs. To add a crop to the base management sequence, a plus (+) sign button was clicked. To delete a crop from the base management sequence, a minus (-) sign button was clicked.

For the WW-CC-C-S rotation, pea was substituted for cover crop since this was the cover crop used in the site (Fig. 7). For the SW-WW-A-A-C-S rotation, alfalfa was not included in the CMZ 01data pool. Therefore, alfalfa under forage rotation under multi-year rotation templates in CMZ 03 was selected to build the base management for the SW-WW-A-A-C-S rotation.

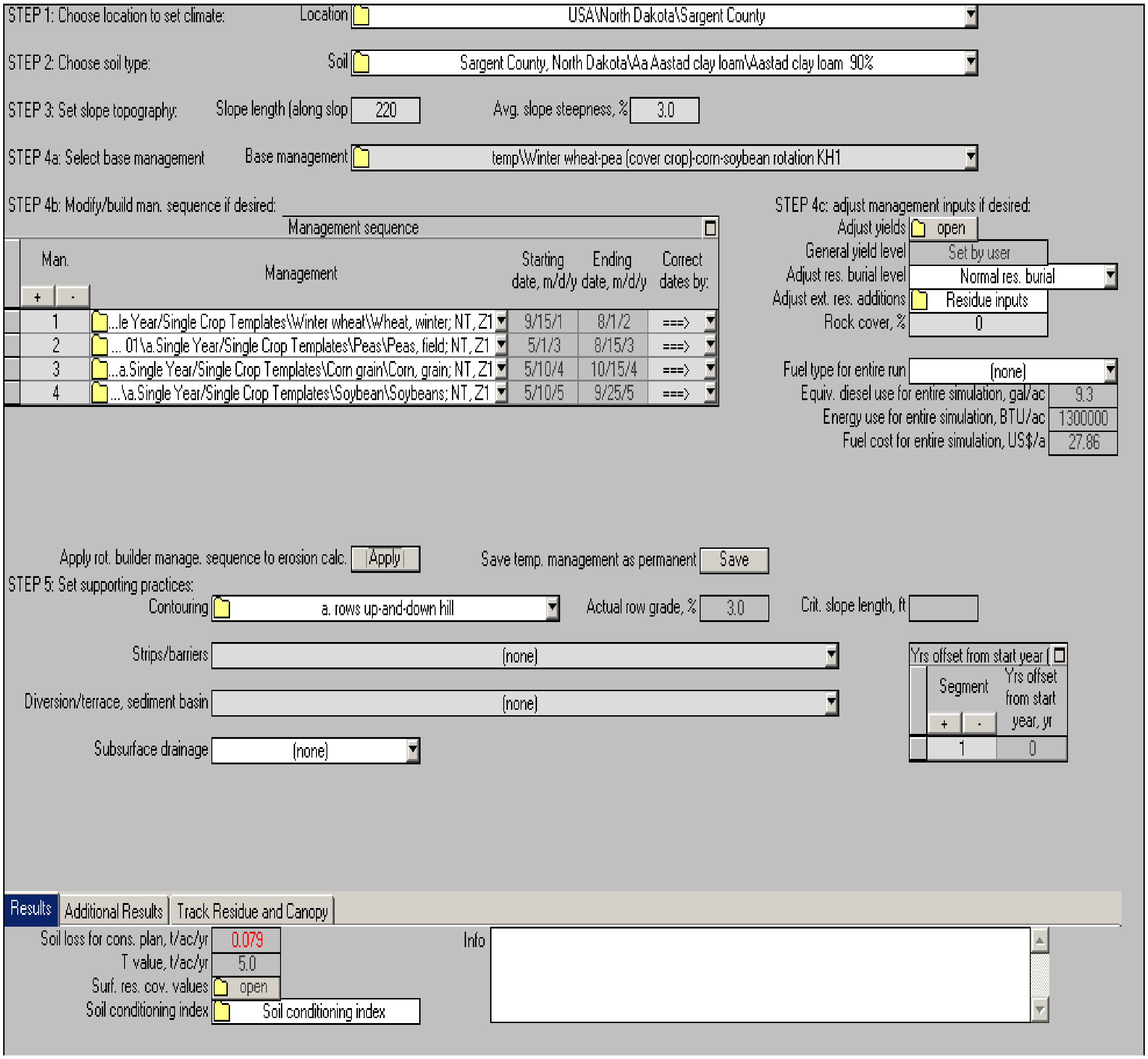
Step 4c: Adjust Management Input if Desired

Yields were adjusted for the built-management sequences by clicking the "open" button in the "adjust yield" screen (Fig. 7). Default yields were replaced with the actual CCSP site yields between 2006 and 2010 (Cooper, 2006, 2007, 2008, 2009, and 2010). The five-year yields for seven crops (alfalfa, corn, flax, pea, soybean, spring wheat, and winter wheat) were averaged for inclusion in the model.

The average yields were: Alfalfa (6.9 Mg/ha= 3.1 tons/acre), corn (10017 kg/ha = 159 bu/acre), flax (1134 kg/ha = 18 bu/acre), pea (1890 kg/ha = 30 bu/acre), soybean (2709 kg/ha = 43 bu/acre), spring wheat (3906 kg/ha = 62 bu/acre), and winter wheat (4536 kg/ha = 72 bu/acre), respectively. The average yields were substituted for the default yields to calculate soil loss, SCI, and STIR.

Step 4d: Apply Rotation Builder Management Sequence

The input information was sent to the erosion calculator by clicking “apply” button in the profile screen. The input information was used to calculate the outputs such as soil loss, SCI, and STIR.



STEP 1: Choose location to set climate: Location USA\North Dakota\Sargent County

STEP 2: Choose soil type: Soil Sargent County, North Dakota\Aa Aastad clay loam\Aastad clay loam 90%

STEP 3: Set slope topography: Slope length (along slop 220 Avg. slope steepness, % 3.0

STEP 4a: Select base management Base management temp\Winter wheat-pea (cover crop)-corn-soybean rotation KH1

STEP 4b: Modify/build man. sequence if desired: Management sequence

Man.	Management	Starting date, m/d/y	Ending date, m/d/y	Correct dates by:
1	...le Year/Single Crop Templates\Winter wheat\Wheat, winter; NT, Z1	9/15/1	8/1/2	===>
2	... 01\a.Single Year/Single Crop Templates\Peas\Peas, field; NT, Z1	5/1/3	8/15/3	===>
3	...a.Single Year/Single Crop Templates\Corn grain\Corn, grain; NT, Z1	5/10/4	10/15/4	===>
4	...\a.Single Year/Single Crop Templates\Soybean\Soybeans; NT, Z1	5/10/5	9/25/5	===>

STEP 4c: adjust management inputs if desired:
Adjust yields open
General yield level Set by user
Adjust res. burial level Normal res. burial
Adjust ext. res. additions Residue inputs
Rock cover, % 0
Fuel type for entire run (none)
Equiv. diesel use for entire simulation, gal/ac 9.3
Energy use for entire simulation, BTU/ac 1300000
Fuel cost for entire simulation, US$/a 27.86

Apply rot. builder manage. sequence to erosion calc. Apply
Save temp. management as permanent Save

STEP 5: Set supporting practices:
Contouring a. rows up-and-down hill
Actual row grade, % 3.0
Crit. slope length, ft
Strips/barriers (none)
Diversion/terrace, sediment basin (none)
Subsurface drainage (none)

Segment	Yrs offset from start year, yr
1	0

Soil loss for cons. plan, t/ac/yr 0.079
T value, t/ac/yr 5.0
Surf. res. cov. values open
Soil conditioning index Soil conditioning index

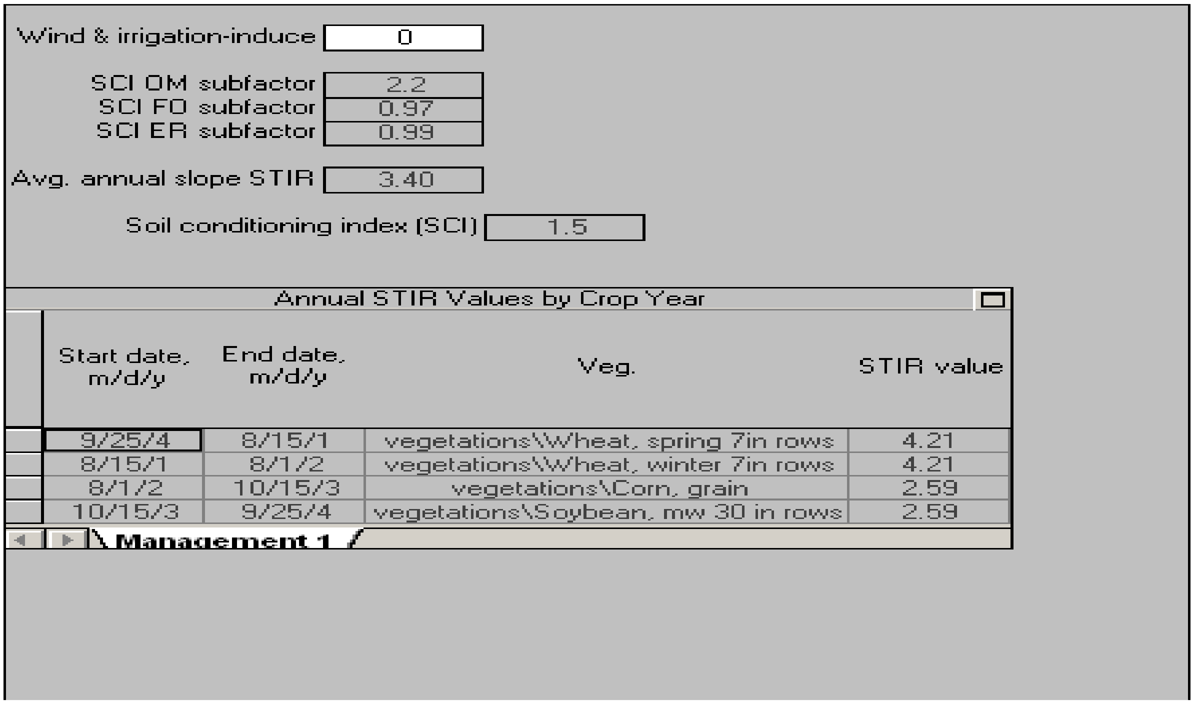
Figure 7. Diagram of the RUSLE2 profile for the WW-CC-C-S rotation (3% slope).

Step 5: Set Supporting Practices

Supporting practices included contouring, strips/barriers, diversions/terraces, and subsurface drainage. Row up-and-down hill was selected for the contouring and “none” was selected for the strips/barriers, diversions/terraces, and subsurface drainage (Figs. 5-8). Row up-and-down hill was considered as the most common contouring practice in the northern Great Plains. “None” was selected for other supporting practices because CCSP site did not have such supporting practices. The long, narrow nature of the plots at the CCSP site precludes deliberate contour seeding operations.

Step 6: Check the SCI and STIR Values

The SCI and STIR values were checked by clicking the “yellow” button in the SCI screen (Figs. 5-7). Figure 8 shows organic matter (OM), field operation (FO), and erosion (ER) that SCI used to qualitatively predict the consequences of the built base management sequences on SOC conditions. Figure 8 also shows SCI and STIR outputs for the SW-WW-C-S rotation.



Wind & irrigation-induce: 0

SCI OM subfactor: 2.2
SCI FO subfactor: 0.97
SCI ER subfactor: 0.99

Avg. annual slope STIR: 3.40

Soil conditioning index (SCI): 1.5

Annual STIR Values by Crop Year

Start date, m/d/y	End date, m/d/y	Veg.	STIR value
9/25/4	8/15/1	vegetations\Wheat, spring 7in rows	4.21
8/15/1	8/1/2	vegetations\Wheat, winter 7in rows	4.21
8/1/2	10/15/3	vegetations\Corn, grain	2.59
10/15/3	9/25/4	vegetations\Soybean, mw 30 in rows	2.59

Figure 8. Diagrammatic view of the modeled SCI and STIR values.

Step 7: Print Report

Under the file menu, “print report” was clicked to print the computed results. Under the “print report” menu list, “NRCS profile with SCI STIR fuel useportrait 0806. pro.dot” was clicked to print the results into the Microsoft word document. The “print report” provided a summary of input information and output values for soil loss, sediment delivery, SCI, and STIR.

RESULTS AND DISCUSSION

COMET-VR Data

The SW-WW-C-S rotation was split into four crop pair simulations (Table 9). The C-WW (0.19 Mg/ha/yr) and C-S (0.16 Mg/ha/yr) simulations had greater SOC values than the SW-WW (0.05 Mg/ha/yr) and S-WW (0.03 Mg/ha/yr) simulations. The model may have assumed greater residue biomass input into the C-WW and C-S simulations which resulted in greater SOC values in the systems. The uncertainty (±19%) and N_2O emission (0.002 Mg/ha/yr) values were consistent for all the simulations in the SW-WW-C-S rotation.

Table 9. COMET-VR estimated SOC, CO_2 flux equivalents, N_2O and N_2O-based CO_2 for individual simulations of crop pairs as well as their aggregated projections for the next ten-year period for the SW-WW-C-S rotation.

Simulations[†]	Soil & Biomass SOC	Soil & Biomass CO_2 Flux Equivalents	Annual N_2O Emissions	N_2O-based CO_2 Flux Equivalents
	-Mg/ha/yr-	-Mg/ha/yr-	-Mg/ha/yr-	-Mg/ha/yr-
SW-WW	0.05	-0.17	0.002	0.50
C-WW	0.19	-0.70	0.002	0.61
C-S	0.16	-0.57	0.002	0.62
S-WW	0.03	-0.13	0.002	0.50
Total	0.43	-1.57	0.008	2.23
10-Year Total	4.3	-15.7	0.080	22.3

[†] SW=spring wheat; WW=winter wheat; C=corn; and S=soybean; SW-WW-C-S = spring wheat-winter wheat-corn-soybean.

The SW-C-S rotation was split into three crop pair simulations (Table 10). The C-S (0.16 Mg/ha/yr) simulation had greater SOC value than the C-SW (0.09 Mg/ha/yr) and C-SW (0.09 Mg/ha/yr) simulations. Greater SOC value was partially attributed to greater residue biomass input into the C-S rotation which contributed to higher SOC in the system. The N_2O emission (0.002 Mg/ha/yr) and uncertainty (±19%) values were consistent for all simulations in the SW-C-S rotation.

Table 10. COMET-VR estimated SOC, CO_2 flux equivalents, N_2O and N_2O-based CO_2 for individual simulation of crop pairs as well as their aggregated projections for the next ten-year period for the SW-C-S rotation.

Simulations†	Soil & Biomass SOC	Soil & Biomass CO_2 Flux Equivalents	Annual N_2O Emissions	N_2O-based CO_2 Flux Equivalents
	-Mg/ha/yr-	-Mg/ha/yr-	-Mg/ha/yr-	-Mg/ha/yr-
C-SW	0.09	-0.31	0.002	0.62
C-S	0.16	-0.60	0.002	0.62
C-SW	0.09	-0.31	0.002	0.62
Total	0.34	-1.22	0.006	1.86
10-Year Total	3.40	-12.2	0.060	18.6

†C=corn; WW=winter wheat; S=soybean; SW-C-S = spring wheat-corn-soybean.

In the SW-S rotation, winter wheat was substituted for spring wheat because spring wheat-soybean sequence was not in the model crop rotations (Table 11). Therefore, the SW-S sequence was simulated as the S-WW simulation. The S-WW simulation had SOC value (0.03 Mg/ha/yr) similar to other sequences that had S-WW simulations. The N_2O emission (0.002 Mg/ha/yr) and uncertainty (±19%) values were consistent and similar to other simulations in other rotations.

The C-S rotation was in the COMET-VR cropping rotations (Table 12). Therefore, the C-S rotation was simulated as the C-S system. The C-S simulation had SOC level (0.16 Mg/ha/yr) similar to other simulations that had C-S simulations in other rotations. The N_2O emission (0.002

Mg/ha/yr) and uncertainty (±19%) values were consistent and similar to other simulations in other crop rotations.

Table 11. COMET-VR estimated SOC, CO_2 flux equivalents, N_2O and N_2O-based CO_2 for individual simulation of crop pairs as well as their aggregated projections for the next ten-year period for the SW-S rotation.

Simulation[†]	Soil & Biomass SOC	Soil & Biomass CO_2 Flux Equivalents	Annual N_2O Emissions	N_2O-based CO_2 Flux Equivalents
	-Mg/ha/yr-	-Mg/ha/yr-	-Mg/ha/yr-	-Mg/ha/yr-
S-WW	0.03	-0.13	0.002	0.50
Total	0.03	-0.13	0.002	0.50
10-year Total	0.30	-1.30	0.020	5.00

[†] S=soybean; WW=winter wheat; SW-S = spring wheat-soybean; CO_2 =

Table 12. COMET-VR estimated SOC, CO_2 flux equivalents, N_2O and N_2O-based CO_2 for individual simulation of crop pairs as well as their total projections for the next ten-year period for the C-S rotation.

Simulation[†]	Soil & Biomass SOC	Soil & Biomass CO_2 Flux Equivalents	Annual N_2O Emissions	N_2O-based CO_2 Flux Equivalents
C-S	-Mg/ha/yr-	-Mg/ha/yr-	-Mg/ha/yr-	-Mg/ha/yr-
	0.16	-0.60	0.002	0.62
Total	0.16	-0.60	0.002	0.62
10-Year Total	1.6	-6.0	0.020	6.20

[†] C=corn; S = soybean; C-S = corn-soybean.

The SW-WW-F-C-C-S rotation was split into six crop pair simulations (Table 13). Flax was not in the COMET-VR crops. Thus, barley was used as the only proxy crop that represented a lower residue producing crop. This may not truly represent the very low residue production of flax but barley was the closest in the library of COMET-VR crops. Therefore, the SW-B sequence was substituted for the WW-F simulation because flax was not in the COMET-VR crop rotations. The C-WW (0.19 Mg/ha/yr), continuous corn (0.30 Mg/ha/yr), and C-S (0.16 Mg/ha/yr) simulations had greater SOC values than the SW-WW (0.05 Mg/ha/yr), SW-B (0.08

Mg/ha/yr), and S-WW (0.03 Mg/ha/yr) simulations. The N_2O emission (0.002 Mg/ha/yr) and uncertainty (±19%) values were consistent and similar to other simulations in other rotations.

Table 13. COMET-VR estimated SOC, CO_2 flux equivalents, N_2O and N_2O-based CO_2 for individual simulations of crop pairs as well as their aggregated projections for the ten-year period for the SW-WW-F-C-C-S rotation.

Simulations†	Soil & Biomass SOC	Soil & Biomass CO_2 Flux Equivalents	Annual N_2O Emissions	N_2O-based CO_2 Flux Equivalents
	-Mg/ha/yr-	-Mg/ha/yr-	-Mg/ha/yr-	-Mg/ha/yr-
SW-WW	0.05	-0.17	0.002	0.50
SW-B	0.08	-0.29	0.002	0.45
C-WW	0.19	-0.70	0.002	0.61
Cont. C	0. 30	-0.98	0.002	0.78
C-S	0.16	-0.60	0.002	0.62
S-WW	0.03	-0.13	0.002	0.50
Total	0.78	-2.87	0.012	3.46
10-Year total	7.80	-28.7	0.12	34.6

†SW=spring wheat; b=barley; Cont. C= continuous corn; WW=winter wheat; S=soybean; SW-WW-F-C-C-S = spring wheat-winter wheat-flax-corn-corn-Soybean.

The WW-CC-C-S rotation was split into four crop pair simulations (Table 14). Cover crop option was not in the COMET-VR crop rotations.

Table 14. COMET-VR estimated SOC, CO_2 flux equivalents, N_2O and N_2O-based CO_2 for individual simulations of crop pairs as well as their aggregated projections for the next ten-year period for the WW-CC-C-S rotation.

Simulations†	Soil & Biomass SOC	Soil & Biomass CO_2 Flux Equivalents	Annual N_2O Emissions	N_2O-based CO_2 Flux Equivalents
	-Mg/ha/yr-	-Mg//ha/yr-	-Mg/ha/yr-	-Mg/ha/yr-
P-WW	0.06	-0.21	0.001	0.42
C-WW	0.19	-0.70	0.002	0.61
C-S	0.16	-0.60	0.002	0.62
S-WW	0.03	-0.10	0.002	0.50
Total	0.44	-1.61	0.007	2.15
10-Year total	4.40	-16.1	0.070	21.5

†P = pulse; C = corn; S = soybean; WW = winter wheat; WW-CC-C-S = winter wheat-cover crop-corn-soybean.

Therefore, pulse was substituted for cover crop in the P-WW simulation since it was most similar to the pea and radish cover crops. The C-S (0.16 Mg/ha/yr) and C-WW (0.19 Mg/ha/yr) simulations showed greater SOC value than the P-WW (0.06 Mg/ha/yr) and S-WW (0.03 Mg/ha/yr) simulations. Greater SOC value in the C-S and C-WW simulations was associated with high residue crops such as corn and wheat in the systems. The N_2O emission (0.002 Mg/ha/yr) and uncertainty (±19%) values were consistent for all the simulations in the WW-CC-C-S rotation.

The SW-WW-A-A-C-S rotation was split into six crop pair simulations (Table 15). The SW-B sequence was used because the SW-WW sequence was not in the COMET-VR crop rotations. The P-WW sequence was substituted for the WW-A simulation because alfalfa was not in the COMET-VR crops and crop rotations. Pulse represented a low residue producing legume crop; therefore, it was substituted for alfalfa.

Table 15. COMET-VR estimated SOC, CO_2 flux equivalents, N_2O and N_2O-based CO_2 for individual simulations of crop pairs as well as their aggregated projections for the next ten year period for the SW-WW-A-A-C-S rotation.

Simulations[†]	Soil & Biomass SOC	Soil & Biomass CO_2 Flux Equivalents	Annual N_2O Emissions	N_2O-based CO_2 Flux Equivalents
	-Mg/ha/yr-	-Mg/ha/yr-	-Mg/ha/yr-	-Mg//ha/yr-
SW-B	0.08	-0.29	0.002	0.50
P-WW	0.06	-0.21	0.001	0.42
Cont. S	0.12	-0.03	0.002	0.51
C-S	0.16	-0.57	0.002	0.62
C-S	0.16	-0.60	0.002	0.62
S-WW	0.03	-0.13	0.002	0.50
Total	0.61	-1.83	0.011	3.17
10-Year total	6.10	-18.3	0.11	31.7

[†] C = corn; P = pulse; WW = winter wheat; Cont. S = continuous soybean; SW = spring wheat; B = barley; SW-WW-A-A-C-S = spring wheat-winter wheat-alfalfa-alfalfa-corn-soybean.

Continuous soybean was substituted for continuous alfalfa in the continuous S simulation because alfalfa was not in the COMET-VR crops and crop rotations. Soybean was also substituted for alfalfa because both crops are legumes and low residue producing crops. This, again, illustrates the limitation of the COMET-VR library of crops in attempting to use this model for a wide range of cropping systems. The C-S simulation (0.16 Mg/ha/yr) had greater SOC value than the SW-B (0.08 Mg/ha/yr), P-WW (0.06 Mg/ha/yr), and S-WW (0.03 Mg/ha/yr) simulations. The model may have assumed greater residue C input to the C-S simulation due to greater residue biomass produced by corn which resulted in higher SOC in the system.

All the simulations had similar N_2O emission values (0.002 Mg/ha/yr), except for the P-WW (0.001 Mg/ha/yr) simulation (Table 15). Pulse crops such as pea and soybean generally require lower supplemental N fertilizer compared to corn and wheat. Therefore, the model may have assumed a lower N input into the P-WW simulation, which resulted in a lower N_2O value in the system compared to the other simulations that did not have pulse crops. The uncertainty (±19%) value was consistent for all the simulations.

Simulation of individual crops or combinations of crops showed greater soil and biomass CO_2 flux equivalents (positive SOC storage) for the continuous corn, corn-soybean, corn-spring wheat, and corn-winter wheat simulations than the spring wheat-winter wheat, soybean-winter wheat, spring wheat-barley, pulse-winter wheat, and continuous soybean simulations (Tables 9-15). These crop simulations mimicked actual cropping rotations and also represented stored SOC or CO_2 removed from the atmosphere. Negative CO_2 flux equivalents showed CO_2 removed from the atmosphere and stored as SOC (Table 9-15). Negative CO_2 emission equivalents have been estimated using the COMET-VR model to predict the potential of conservation management practices to store SOC and reduce GHG emissions (Rosenzweig et al., 2010). Therefore, negative CO_2 emission equivalents represented positive SOC storage.

The continuous corn simulation (-0.98 Mg/ha/yr) had the greatest negative CO_2 emissions (positive SOC storage) (Table 13). The corn-winter wheat simulation (-0.70 Mg/ha/yr) and corn-soybean simulation (-0.60 Mg/ha/yr) had the second and third greatest negative CO_2 emissions (positive SOC storage), respectively, (Tables 12-14). The COMET-VR model may have assumed greater residue biomass input into these simulations which increased SOC in the systems. Therefore, higher simulated SOC levels in the systems were attributed to greater residue C as evidenced by the amount of residue dry matter weight (Table 6 and 7) (Paper 2).

The continuous soybean simulation (-0.03 Mg/ha/yr) (a proxy for the alfalfa-alfalfa treatment) had the lowest negative CO_2 emission (positive SOC storage) (Table 15). Low-residue yielding crops such as alfalfa and soybean generally produce lower residue biomass compared to high-residue yielding crops such as corn and wheat. Therefore, the COMET-VR model may have assumed lower residue C input into the soybean simulation which resulted in lower SOC in the system.

The N_2O is a product of nitrification (NH_3 or NH_4^+ oxidation) and denitrification (NO_3-N reduction). Denitrification is a microbial process that reduces soil NO_3-N or NO_2 to NO, N_2O, and N_2 by denitrifying bacteria under anaerobic conditions (Xu et al., 1998). Positive N_2O emissions and CO_2-based N_2O emission equivalents represented N released as N_2O to the atmosphere (Table 9-15). The N_2O emissions were multiplied by 310 to determine how much CO_2 equivalents would be required to produce a similar warming effect. Therefore, the N_2O emissions and CO_2-based N_2O emission equivalents represented approximate N released as N_2O to the atmosphere from the seven rotations.

The continuous corn simulation (0.78 Mg CO_{2e}/ha/yr) had the greatest N_2O emission equivalents while the corn-soybean simulation (0.61 Mg CO_{2e}/ha/yr) and corn-winter wheat simulation (0.61 Mg CO_{2e}/ha/yr) had the second greatest N_2O emission equivalents (Table 13-14). The COMET-VR model estimated greater N_2O emissions for the continuous corn simulation because greater amount of N fertilizer was entered into the model screen for the system. Greater N_2O emissions in the corn-soybean and corn-winter systems were also related to higher amount of N fertilizer entered into the model screen for these systems. Greater N_2O emissions from corn systems have been associated with greater fertilizer N application to corn **(**Mackenzie et al., 1997). The N_2O emissions from different crop systems were attributed to different fertilizer N rates applied to corn (170 kg N/ha), winter wheat (83 kg N/ha), and soybean (0 kg N/ha) as well as residue C in each crop system (Drury et al., 2008). The N_2O emission of 1.32 kg N_2O/ha was reported when corn, soybean, and winter wheat were not planted in rotation compared to 1.03 kg N_2O/ha when these crops were planted in rotation (Drury et al., 2008). Greater N_2O emissions have been reported in the continuous corn followed by the corn-soybean and corn-soybean-alfalfa rotations (MacKenzie et al., 1998). This shows that crop rotations can reduce N_2O emissions due to low requirement of mineral N compared to monoculture systems that may require high N fertilizer rates. Crop rotation systems can also reduce residual soil NO_3-N accumulation and excess soil moisture due to frequent crop production.

The continuous soybean simulation (0.51 Mg CO_{2e}/ha/yr) had the lowest N_2O emissions compared with other crop simulations (Table 15). The COMET-VR model simulated lower N_2O emissions for the continuous soybean because lower amount of N fertilizer was entered into the model screen for the system. Lower N_2O emissions also have been reported in soybean plots compared to the continuous corn, corn-soybean rotation, and corn-soybean-alfalfa systems

(Mackenzie et al., 1998). The N_2O emissions have been directly associated with the quantity of residue C, N fertilizer, soil NO_3-N, and mineralized SOC in the cropping systems. This was the reason why the COMET-VR model simulated greater N_2O emissions for high-N consuming crops such as corn and wheat systems and lower N_2O emissions for low-N consuming crops such as soybean system.

Management practices such as fertilizer N (timing, type, application method, and rate), crop type, crop rotation, tillage, and residue management influence N_2O emissions from cropping systems (Parkin and Kaspar, 2006; Drury et al., 2008). Judicious management practices and appropriate N fertilizer use can minimize N_2O emissions. Nitrogen uptake is generally low at the beginning of the growing season, more rapid during growing stage, and rapidly reduces as crops reach their maturity (Millar et al., 2010). Applying fertilizer N to high-N requiring crops at their rapid growing stage can increase N use efficiency and reduce soil NO_3-N and N_2O losses to the environment. Previous crop residue N and residual soil NO_3-N from the previous year should also be accounted for in order to avoid N over-fertilization.

Use of N inhibitors (nitrapyrin, dicyandamide, and agrotain) (Havlin et al., 2005), controlled-release N fertilizers (Jones et al., 2013), and low-N consuming corn and wheat varieties with high yielding potential can increase N use efficiency and reduce N_2O emissions and NH_3 volatilization. Planting soybean after corn can reduce N_2O emissions because soybean most often requires low or no supplemental N fertilizer. Direct field measurements of N_2O emissions should be determined in plots cropped with different crops during different months and seasons using gas flux chambers. Crops, residue types, months, seasons (fall, spring, and summer) that produce greater N_2O emissions may be determined under cropping systems using gas flux chambers.

The model-based and actual SOC levels were also reported for each of the seven crop rotations (Table 16). Greater diversified rotations containing winter wheat had greater SOC levels than lower diversified rotations containing no winter wheat. The WW-CC-C-S (4.40 Mg/ha), SW-WW-F-C-C-S (7.80 Mg/ha), SW-WW-C-S (4.30 Mg/ha), SW-WW-A-A-C-S (6.10 Mg/ha), and SW-C-S (3.40 Mg/ha) rotations had greater modeled SOC than the C-S (1.60 Mg/ha) and SW-S (0.30 Mg/ha) rotations. The COMET-VR model may have assumed greater residue C input into high-diversity systems which increased SOC in the systems. Greater simulations in the rotations containing winter wheat also resulted in higher SOC in the systems.

The modeled SOC values were compared to the annual SOC values obtained from actual field sampling and extended for a ten-year period similar to the extended period for the COMET-VR (Table 16).

Table 16. Crop rotation treatments, COMET-VR SOC, actual lab SOC and ΔSOC projected for a ten-year period.

Crop Rotation Treatments[†]	COMET-VR SOC	Actual Lab SOC	(Actual minus COMET) ΔSOC
	-Mg/ha-	-Mg/ha-	-Mg/ha-
SW-WW-C-S	4.30	50.0	45.7
SW-C-S	3.40	64.0	60.6
SW-S	0.30	40.0	39.7
C-S	1.60	23.0	21.4
SW-WW-F-C-C-S	7.80	24.0	16.2
WW-CC-C-S	4.40	26.0	21.6
SW-WW-A-A-C-S	6.10	48.0	41.9

[†] SW-WW-C-S = spring wheat-winter wheat-corn-soybean; SW-C-S = spring wheat-corn- soybean; SW-S = spring wheat-soybean; C-S = corn-soybean; SW-WW-F-C-C-S = spring wheat-winter wheat-flax-corn-corn-soybean; WW-CC-C-S = winter wheat-cover crop-corn-soybean; SW-WW-A-A-C-S = spring wheat-winter wheat-alfalfa-alfalfa-corn-soybean.

The model-based SOC levels were lower than the actual SOC levels, which showed the model underestimated SOC in the seven rotations. Underestimation of actual SOC levels was due to the fact that the model did not contain most of crops and crop rotations grown at the CCSP site, since the COMET-VR was developed for the Corn Belt region. Another explanation for lower modeled SOC values was that the model did not account for diverse crop rotations and residue retention to build SOC under no-till management at the CCSP site. This shows that the COMET-VR model has a limited capability to accurately account for the contribution of no-till management practices to SOC.

Ten-year projection of simulated negative CO_2 emissions (positive SOC storage) showed greater total positive SOC levels in the SW-WW-F-C-C-S (-28.7 Mg/ha) and SW-WW-A-A-C-S (-18.3 Mg/ha) and lower SOC in the SW-S (-1.30 Mg/ha) and C-S (-0.60 Mg/ha) rotations (Table 17). The model might have assumed a greater residue production in rotations containing winter wheat compared with rotations containing no winter wheat. Therefore, greater SOC levels in rotations containing winter wheat were attributed to greater crop diversity which increased residue production in the systems. The SW-WW-F-C-C-S (-28.7 Mg/ha/yr) rotation also had a greater positive SOC level than the SW-WW-CS (-15.7 Mg/ha/yr), WW-CC-C-S (-16.1 Mg/ha/yr), and SW-WW-A-A-C-S (-18.3 Mg/ha/yr) rotations. Greater SOC level in the SW-WW-FX-C-C-S was perhaps due to a greater production of corn and wheat residue biomass which resulted in higher SOC in the system.

The N_2O-based CO_2 equivalents (CO_{2e} emissions) also showed greater emissions in the SW-WW-F-C-C-S (34.6 Mg/ha) and SW-WW-A-A-C-S (31.7 Mg/ha) rotations compared to the SW-S (5.00 Mg/ha) and C-S (6.20 Mg/ha) rotations (Table 17). Greater N_2O emissions from the SW-WW-F-C-C-S and SW-WW-A-A-C-S rotations were due to greater number of simulations due to greater crop diversity in the systems compared to the SW-S and C-S rotations. Because denitrifying bacteria often require N and mineralizable SOC for N_2O emissions, greater corn and wheat residue C and fertilizer N input into the SW-WW-FX-C-C-S and SW-WW-A-A-C-S rotations might have increased N_2O emissions from the systems.

Table 17. Crop rotation treatments, COMET-VR SOC, soil & biomass CO_2 flux equivalents, annual N_2O emissions and N_2O-based CO_2 based equivalents projected for a ten-year period.

Crop Rotation Treatments[†]	COMET-VR SOC	Soil & Biomass CO_2 Flux Equivalent	N_2O Emission	N_2O-based CO_2 Flux Equivalent	N_2O Losses
	-Mg/ha-	-Mg/ha-	-Mg/ha-	-Mg/ha-	-Mg/ha-
SW-WW-C-S	4.30	-15.7	0.08	22.3	0.05
SW-C-S	3.40	-12.2	0.06	18.6	0.04
SW-S	0.30	-1.30	0.02	5.00	0.01
C-S	1.60	-6.00	0.02	6.20	0.01
SW-WW-F-C-C-S	7.80	-28.7	0.12	34.6	0.08
WW-CC-C-S	4.40	-16.1	0.07	21.5	0.04
SW-WW-A-A-C-S	6.10	-18.3	0.11	31.7	0.07
Total	10.5	-98.3	0.48	140	0.31

[†] SW-WW-C-S = spring wheat-winter wheat-corn-soybean; SW-C-S = spring wheat-corn-soybean; SW-S = spring wheat-soybean; C-S = corn-soybean; SW-WW-F-C-C-S = spring wheat-winter wheat-flax-corn-corn-soybean; WW-CC-C-S = winter wheat-cover crop-corn-soybean; SW-WW-A-A-C-S = spring wheat-winter wheat-alfalfa-alfalfa-corn-soybean.

Also, the total positive SOC level (-98.3 Mg CO_{2e}/ha) (Table 17) at the CCSP site (area = 10 ha) in Sargent County, North Dakota was compared with the total simulated SOC level in ten counties of Hudson Valley (area = 176, 042 ha), New York. The total SOC under conservation/no-till and rotation grazing in Hudson Valley was reported as -3.51 Mg CO_{2e}/ha/yr (Rosenzweig et al., 2010). But for comparison with this data, -3.51 Mg CO_{2e}/ha/yr was multiplied by 10 years to obtain 35.1 Mg CO_{2e}/ha. Difference showed 47% greater positive SOC level (-63.2 Mg CO_{2e}/ha) in Sargent County than in Hudson Valley region. High-residue no-till management might have increased SOC level at the CCSP site compared with Hudson Valley region. Additional factors other than conservation tillage systems might have contributed to this difference in SOC levels between two locations. For example, the entire area (area = 176, 042 ha) of Hudson Valley was not under conservation tillage and rotational grazing systems while the entire area (area = 10 ha) was continuously no-tilled at the CCSP site. These two locations may also have different climates that may have influenced SOC levels in each cropping system in each location.

Furthermore, the total positive SOC level (-98.3 Mg CO_{2e}/ha) was subtracted from the total N_2O-based CO_2 (140 Mg CO_{2e}/ha) to determine a warming potential of N_2O (Table 17). Difference (140 – 98.3) showed that N_2O emission equivalent was greater by 41.7 Mg CO_{2e}/ha than SOC storage at the CCSP site. Greater N_2O emissions may have been due to greater residue C, mineralizable SOC, residual NO_3-N, and moisture content under no-till management at the CCSP site. This excess amount of N_2O (41.7 Mg CO_{2e}/ha) can be reduced by adopting N fertilizer and N_2O emission reduction protocol recommended by Millar et al. (2010). This stored SOC (-98.3 Mg CO_{2e}/ha) could also be remitted to the atmosphere if no-till management at the CCSP site is changed to conventional tillage in the future.

Table 17 shows ten-year projection of simulated N released as N_2O emissions from the seven cropping systems. The SW-WW-F-C-C-S (0.08 Mg N_2O/ha), SW-WW-A-A-C-S (0.07 Mg N_2O/ha), SW-WW-C-S (0.05 Mg N_2O/ha), and WW-CC-C-S (0.04 Mg N_2O/ha) rotations had greater N_2O emissions compared with the SW-S (0.01 Mg N_2O/ha) and C-S (0.01 Mg N_2O/ha) rotations. The model may have assumed that greater crop diversity increased residual soil NO_3-N and mineralizable SOC and that lower crop diversity reduced soil NO_3-N and mineralizable SOC in the cropping systems. Therefore, greater N_2O emissions in some rotations were likely due to more simulations and greater crop diversity in the systems while lower N_2O emissions in some rotations were likely due to fewer simulations and lower crop diversity in the systems. Greater N_2O emissions from greater diverse cropping rotations were also attributed to greater N fertilizer values entered to the COMET-VR model during the simulation. This was another likely reason why greater diverse cropping rotations such as SW-WW-F-C-C-S, SW-WW-A-A-C-S, and SW-WW-C-S rotations had greater N_2O emissions compared to lower diverse cropping rotations such as SW-S and C-S rotations.

RUSLE2 Data

Table 18 shows the RUSLE2 modeled soil losses for the seven crop rotations. The SW-WW-C-S, SW-WW-F-C-C-S, and SW-WW-A-A-C-S rotations containing winter wheat resulted in slightly lower soil losses than the SW-C-S, SW-S, and C-S rotations containing no winter wheat for 3% and 6% slopes. Winter wheat has been reported to produce greater residue biomass per unit of grain yield compared with spring wheat, thereby providing greater soil surface protection against wind and water erosion than spring wheat residue (Black and Bauer, 1983). It has been reported that winter wheat provides a better soil surface cover and has the ability to anchor corn and soybean residues, increase water infiltration, and reduce rill and inter-rill erosion (Singer et al., 2005). It has also been reported that wheat residue is more effective in protecting soil surface and reducing soil erosion than cornstalks or sorghum residue (Allison, 1973). Wheat stubble is more effective in reducing surface runoff and soil erosion because it stands straight on the soil surface while corn and sorghum residue lies flat on the soil surface. Orientation and type of crop residue has an important impact in reducing or increasing surface runoff and soil erosion in the field. The RUSLE2 model may have also assumed that greater crop diversity in rotations containing winter wheat produced larger residue biomass which increased soil surface protection against wind and water erosive forces compared to lower crop diversity in rotations containing no winter wheat. Therefore, lower soil losses for the SW-WW-C-S, SW-WW-F-C-C-S, and SW-WW-A-A-C-S rotations were probably due to greater wheat residue in the systems compared with the SW-C-S, SW-S, and C-S rotations that had lower or no wheat residue in the systems. Although corn residue was produced in greater quantity and frequency in the C-S rotation, this system resulted in greater soil losses probably due to the fact that corn residue laid flat on the soil surface. This showed the importance of crop residue orientation in the field.

Table 18. Crop rotation treatments, Slope 1(3%) and Slope 2 (6%) soil losses, and SCI and STIR values as determined by RUSLE2.

Crop Rotation Treatments[†]	Slope 1 (3%)	Slope 2 (6%)	SCI[‡]	STIR[§]
	--kg/ha/yr--	--kg/ha/yr--	------	------
SW-WW-C-S	67.0	112	1.50	3.40
SW-C-S	112	179	1.20	3.13
SW-S	157	267	1.10	3.40
C-S	135	247	1.00	2.59
SW-WW-F-C-C-S	90.0	157	1.30	3.40
WW-CC-C-S	202	359	0.95	2.72
SW-WW-A-A-C-S	45.0	90.0	1.50	2.59
Average	112	202	1.22	3.03

[†] SW-WW-C-S = spring wheat-winter wheat-corn-soybean; SW-C-S = spring wheat-corn-soybean; SW-S = spring wheat-soybean; C-S = corn-soybean; SW-WW-F-C-C-S = spring wheat-winter wheat-flax-corn-corn-soybean; WW-CC-C-S = winter wheat-cover crop-corn-soybean; SW-WW-A-A-C-S = spring wheat-winter wheat-alfalfa-alfalfa-corn-soybean.
[‡] SCI=Soil Conditioning Index; [§] STIR=Soil Tillage Intensity Rating.

Similarly, OM in form of surface-retained residue has also been reported to be more effective in preventing soil erosion compared to soil-incorporated residue and highly decomposed SOM that has been made part of soil (Allison, 1973). Nyakatawa et al. (2001) reported three to five times higher soil losses under conventional system than no-till and mulch-till systems. Plant roots and residues reduce soil erosion by improving soil structure, increasing water infiltration, and increasing soil aggregation under no-till regimes. High residue no-till management, improved soil structure, and increased infiltration rate contributed to low soil losses for the seven crop rotations at the CCSP site. Reduced soil losses can reduce SOC mineralization and CO_2 evolution. Greater production of winter wheat residue has the potential to reduce wind and water erosion, increase water infiltration, improve soil structure and aggregation, and reduce SOC losses. Lower soil losses in the rotations containing winter wheat can also increase nutrients retention and reduce contamination of surface water sources associated with surface runoff and sediment loadings.

The WW-CC-C-S rotation had greater soil losses than other rotations for 3% slope (202 kg/ha/yr) and 6% slope (359 kg/ha/yr) (Table 18). The RUSLE2 model may have assumed low residue input into the rotation. Greater soil losses were attributed to low residue surface cover due to low residue producing crops such as field pea and soybean in the rotation. Greater soil losses in the WW-CC-C-S rotation were perhaps the reason why the SOC level (8.41 kg/m^2) was lower in the system (Table 4, Paper 1). However, actual effects of cover crops might not have been treated well within the RUSLE2 model because “cover crop” was simulated as a pea for the WW-CC-C-S rotation. This shows that limitations in the RUSLE2 model might have overestimated soil losses in the WW-CC-C-S rotation.

Statistical analysis showed a high correlation ($r = 1.00$) of soil loss for 3% and 6% slopes. It has been reported that soil erosion increases as the slope of field increases (Allison, 1973). This was likely the reason why the RUSLE2 model estimated lower soil losses for 3% slope compared to 6% slope. This analysis showed that slope steepness has an important effect in reducing or increasing soil erosion rate and SOC losses.

Table 18 also shows the Soil Conditioning Index (SCI) and the Soil Tillage Intensity Rating (STIR) values. The SCI values represented the effects of crop rotations on SOC conditions. Generally, positive SCI value predicts the potential of cropping systems to build SOC levels. The SW-WW-C-S (1.50), SW-WW-F-C-C-S (1.30), and SW-WW-A-A-C-S (1.50) rotations containing winter wheat had slightly greater positive SCI values than the SW-C-S

(1.20), SW-S) (1.10), and C-S (1.00) rotations containing no winter wheat. The most likely explanation for greater positive SCI values in the rotations containing winter wheat was greater crop diversity compared to lower crop diversity in the rotations no containing winter wheat. The SCI model may have assumed a greater production of residue biomass in the rotations containing winter wheat which resulted in greater positive SCI values in the systems. The WW-CC-C-S rotation (0.95) had a lower positive SCI value than other rotations. This was likely due to low production of residue biomass by low residue pea and soybean crops which might have decreased the potential of the system to build SOC. Another explanation for lower positive SCI values in the WW-CC-C-S rotation was that field pea was substituted for cover crops in RUSEL2 model. Therefore, the model might not have accounted for the contribution of cover crops to increase SOC in the system. Overall, positive SCI values showed the potential of the seven rotations to increase SOC levels over the time. Positive SCI values are also indicators of high-residue conditions and judicious conservation management practices at the CCSP site.

The simulated STIR values for the seven rotations are also shown in Table 18. The C-S (2.59) and SW-WW-A-A-C-S (2.59) rotations had a lower STIR value than other rotations. It has been reported that STIR values can be lowered by using soil conserving crops such as alfalfa and grass (USDA-NRCS, 2008a; USDA-NRCS 2011b). Therefore, lower STIR value (2.59) in the SW-WW-A-A-C-S rotation was attributed to two continuous years of alfalfa crop in the rotation. A STIR value would have been expected to be greater in the WW-CC-C-S rotation due to additional soil surface disturbance from cover crop seeding into wheat stubble. But because pea was substituted for cover crops in the RUSLE2 model, the STIR program did not reflect the effects of cover crops in the system. This was the reason why the WW-CC-C-S rotation had a lower STIR value than other rotations, with the exception of the C-S and SW-WW-A-A-C-S rotations.

Also, the average STIR value (3.03) for the seven rotations was much lower than the STIR value (26.0) reported in Allen County, Ohio, under the corn-soybean rotation in which corn was mulch-tilled and soybean was no-tilled (USDA-NRCS, 2004). The C-S rotation, which was similar to C-S rotation in Allen County, also showed much lower STIR value (2.59) than the STIR value (26.0) reported in Allen County, Ohio. This shows that no-till operation contributed to low STIR values at the CCSP site compared with the STIR value under mulch-tilled and no-till corn-soybean systems at Allen County, Ohio. But differences in STIR values for these two locations (Sargent County, North Dakota and Allen County, Ohio) might have been influenced by different climatic conditions at the two different locations that have different amounts of rainfall as well as frequency and intensity of rainfall. Additional factors (soil texture and mineralogy, depth of tillage, percent of soil surface area disturbed, residue amount, and types of machinery) might have also contributed to differences in STIR values in two locations. Overall, the STIR values for the seven rotations were much lower than the STIR value (15 or less) recommended for no-till operations (USDA-NRCS, 2008a; USDA-NRCS, 2011b). Low STIR values can reduce sheet and rill erosion, increase SOC/SOM, reduce SOC oxidation, reduce SOC emissions to the atmosphere, and improve infiltration rate as reported by USDA-NRCS (2008a) and USDA-NRCS (2011b).

SUMMARY AND CONCLUSIONS

The COMET-VR simulations had greater SOC levels in continuous corn, continuous winter wheat, corn-winter wheat, corn-soybean, and continuous soybean. The model may have assumed greater surface residue input into these systems which increased SOC levels in the systems. Crop simulations with greater SOC levels may be appropriate for SOC sequestration. The continuous spring wheat, soybean-spring wheat, soybean-winter wheat, corn-spring wheat, spring wheat-barley, and pulse-winter wheat simulations had much lower SOC levels. These crops or crop combinations may not be suitable for SOC sequestration due to low production of residue biomass. The COMET-VR model estimated greater SOC levels for the SW-WW-C-S, SW-WW-F-C-C-S, WW-CC-C-S, and SW-WW-A-A-C-S rotations than the SW-C-S, SW-S, and C-S rotations. This was attributed to more simulations in the rotations containing winter wheat than the rotations containing no winter wheat. A comparison of the COMET-VR simulated SOC levels and actual SOC levels showed that the model underestimated SOC in the seven rotations. This shows that mode should be improved so that it accounts for the impacts of conservation management practices on SOC in cropping systems.

The RUSLE2 model associated soil losses with different slopes, with 3% slope resulting in lower soil losses than 6% slope. Soil losses were strongly correlated (r = 1.00) for 3% and 6% slopes. The SW-WW-C-S, SW-WW-F-C-C-S, and SW-WW-A-A-C-S rotations had lower soil losses than the SW-C-S, SW-S, and C-S rotations for 3% and 6% slopes. The RUSLE2 model assumed greater wheat residue production in rotations with winter wheat which provided greater soil surface cover and subsequently reduced soil losses. However, the WW-CC-C-S rotation had slightly greater soil losses than other rotations for 3% and 6% slopes due to low-residue yielding crops such as pea and soybean in the rotation. The model also did not account for the effects of cover crops in the rotation because pea was substituted for cover crops in the RUSLE2 model which might have overestimated soil losses in the system.

Overall, the RUSLE2 modeled results showed that slope steepness was an important factor in increasing or decreasing soil losses under the seven rotations**.** High residue no-till management, improved soil aggregation and tilth, increased infiltration rate, and low soil disturbance contributed to low soil losses for 3% and 6% slopes at the CCSP site. Low soil losses showed low impairment of water quality in surrounding water resources due to reduced surface runoff. Low soil losses also indicated low SOC mineralization and low SOC losses due to reduced erosion rate on the soil surface.

The SCI associated high-residue no-till production with positive SCI values. Generally, positive SCI value shows increasing SOC trends and negative index rating shows decreasing SOC trends. The SCI values were positive for the seven crop rotations, indicating that the rotations had a greater potential to increase SOC levels. The SW-WW-C-S, SW-WW-F-C-C-S, and SW-WW-A-A-C-S rotations had slightly greater SCI values than the SW-C-S, SW-S, and C-S rotations. Greater SCI values were due to greater cropping diversity in rotations with winter wheat compared to lower cropping diversity in rotations without winter wheat. Although the main purpose of the SCI was to predict the effects of the seven crop rotations on the SOC conditions, the SCI values were not related to field-based SOC values. Because SCI did not determine bulk density, infiltration rate, pH, soil biota, and nutrient level, these parameters should be separately determined to evaluate overall condition of soil quality, fertility, and productivity.

The modeled STIR values were much lower than the recommended STIR value (15 or less) for the no-till operations. Low STIR values were due to low soil disturbance on the soil surface due to no-till management at the CCSP site. Low STIR values reflected efficacious soil management practices. Low STIR values were also indicators of improved soil quality, increased SOC content, reduced SOC oxidation, improved soil structure and tilth, and increased infiltration rate.

Although low STIR values reflected no-till management conditions, they did not relate to SOC levels for 2006/2010 and 2012 in each rotation. It was also difficult to relate the number of crops and rate of soil surface disturbance in each crop rotation to the STIR values. For example, the SW-S rotation had slightly greater STIR value than the SW-C-S, WW-CC-C-S, and SW-WW-A-A-C-S rotations. However, as a soil-conserving crop, two alfalfa crops in the SW-WW-A-A-C-S rotation contributed to lower STIR value compared with the rotations in which alfalfa was not included.

Recommendations for Future Research Trials

- Because the U.S Government may require farmers to use the COMET-VR model for estimating and reporting their SOC storage or GHG emissions under their agricultural management practices, it is important that the model be greatly improved to allow farmers and scientists to use it in a more friendly manner. Lack of other regions' crops and cropping rotations in the COMET-VR model library can pose a major challenge to the government to encourage farmers to use the model. The model was originally developed for the Corn Belt region. This has omitted majority of crops and cropping rotations in other regions in the United States. For example, most crops and crop management sequences at the Conservation Cropping Systems project (CCSP) site were not found in the model. Although the NRCS has announced that it will give a $500 to each of the first time users of the model, lack of crops and crop rotations can be a disincentive to farmers whom the government may require to use this model. Therefore, inclusion of crops and crop rotations can make the model more applicable to all regions in U.S.A.

- Another issue with the model is that it has not been widely used since it was developed. Therefore, there is a limited information out there for potential users to reference. Lack of already modeled information makes it difficult for scientists, farmers, and land resources managers to benchmark their modeled results. This issue is again attributable to the fact that the information in the model library is very limited and, therefore, does not reflect the diversity of crops and cropping systems in other regions in the United States. Thus, the model needs improvement by including crops and rotation sequences in other regions. When the model is improved and validated for the general use in the United States, the government should also employ extension scientists who are familiar with the model to train farmers how to use the model and how to report their SOC storage and GHG emissions under their farming practices. This information should also be published and made accessible to other farmers who may be required by the government to use the model. Sharing this information can help farmers and scientists justify their findings.
- The RUSLE2 model was originally developed for high-rainfall regions in U.S because these regions tend to experience high soil erosion rate (T. Alme, personal communication). This may make the model underestimate soil losses in low-rainfall regions. Therefore, the model capability should be improved to accurately estimate soil losses in both low-rainfall and high-rainfall regions in U.S.A.
- Future research should determine pre-treatment (baseline) soil losses under conventional systems and compare them to soil losses under no-till systems. This comparison method would be the only way to show that high residue no-till regimes

can reduce soil losses compared to conventional systems. The SCI and STIR programs incorporated in RUSLE2 should also be improved so that their simulated values reflect a number of crops in each rotation as well as cropping complexity and diversity in each system. The SCI program developed to predict SOC conditions in cropping systems should have the capability to reflect the amount of SOC level in in SCI values in each crop rotation. The STIR program developed to determine soil surface disturbance rating should also have the capability to relate STIR values to crop rotation diversity and number of tillage practices in each cropping system. If done in this way, the SCI and STIR values will account for the reality under different cropping systems.

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GENERAL SUMMARY AND CONCLUSIONS

This study evaluated the impact of winter wheat on SOC levels under high residue no-till cropping systems as part of SOC sequestration monitoring program in the Northern Great Plains. It determined the contribution of long-term no-till production to SOC sequestration and soil quality. Data obtained from this study are important for the management of winter wheat and other crops. The impact of winter wheat on SOC was evaluated by field-based analysis (Paper 1). Aboveground aged and fresh residues were analyzed to determine residue biomass, residue C:N ratios, residue C and N contents, and supplemental N fertilizer requirements (Paper 2). The COMET-VR and RUSLE2 models were used to estimate SOC and GHG (CO_2 and N_2O) emissions and predict soil losses, respectively, (Paper 3). The Soil Conditioning Index (SCI) and Soil Tillage Intensity Rating (STIR) in the RUSLE2 model were used to predict SOC conditions and soil surface disturbance ratings, respectively, (Paper 3).

Baseline soil samples were taken in 2006 and 2010 to monitor SOC trends at the CCSP site. The SW-WW-FX-C-C-S rotation containing winter wheat and the C-S rotation containing no winter wheat were sampled in 2006 to establish initial SOC levels. The SW-WW-C-S, SW-WW-CC-S, and SW-WW-A-A-C-S rotations containing winter wheat and the SW-C-S and SW-S rotations containing no winter wheat were sampled in 2010 for the same purpose. In 2012, the last sampling was conducted on all rotations sampled in 2006 and 2010 to continue monitor SOC trends.

The analysis of the 2006 and 2010 SOC data showed no significant difference between the rotations probably due to relatively similar climatic conditions and soil mineralogy. Analysis of the 2012 SOC data showed a greater SOC level in the C-S rotation than the SW-WW-CC-S rotation. Greater SOC in the C-S rotation was associated with a greater cumulative residue biomass produced and returned to the system by corn. Corn was more frequently cropped in the C-S rotation than other crops in the rotations containing winter wheat. Soybean residue with high residue C content was also produced and returned in greater quantity and frequency to the C-S rotation. Therefore, greater frequent production of corn and soybean residue C contributed to greater SOC in the C-S rotation. Analyses showed that restoration and maintenance of SOC can be achieved by greater frequent production of high-residue crops such as corn and winter wheat. Although rotations that contained winter wheat had a neutral impact on SOC and SOC levels in these rotations were not significantly greater than SOC level in the C-S rotation, these rotations have benefits such as increased profitability and reduced N-denitrification associated with reduced wetness during fall and spring seasons. The rotations containing winter wheat can also increase N and water use efficiency due to earlier growth.

The WW-CC-C-S rotation had lower SOC than other rotations for the 2012 SOC data analysis. Lower SOC level in the WW-CC-C-S rotation was attributable to low residue-crops such as cover crops (field pea and radish) which produced low residue biomass in the system. Production of corn and soybean residue was lower in the SW-WW-CC-S rotations compared to production of corn and soybean residue in the C-S rotation. Production of winter wheat and spring wheat residue was also lower in the SW-WW-CC-S rotation than production of corn residue in the C-S rotation. Therefore, lower production of corn, spring wheat, winter wheat residue in the WW-CC-C-S rotation contributed to lower SOC in the rotation. This shows restoration and maintenance of SOC cannot only be increased by greater crop intensity and diversity but can also be increased by greater production of high residue crops such as corn and wheat in no-till cropping systems. Also, as evidenced by low SOC in the WW-CC-C-S rotation, low residue crops such as alfalfa, soybean, and cover crops (pea and radish) may not be suitable for SOC sequestration. But cover crops have the agronomic and environmental benefits such as increasing nutrient supplying power of soil, reducing N (N_2O and NO_3-N) losses to the environment, and capturing and retaining residual inorganic N in their tissues for subsequent crop use.

Residue samples were collected in the spring 2011 and fall 2012. Aged residue was sampled in the spring 2011 and fresh residue was sampled in the fall 2012. These residue samples were evaluated to determine residue biomass, C:N ratios, C and N contents, and supplemental N fertilizer requirements. Aged residue biomass was greater in the C-S rotation and lower in the SW-WW-A-A-C-S rotation. Fresh residue biomass was greater in the C-S rotation and lower in the SW-WW-A-A-C-S rotation. The main reason for greater residue biomass in the C-S rotation was greater frequent production of corn residue in the system. Production of soybean residue was greater in the C-S rotation which contributed to greater total residue biomass in the system. Low residue crops such as two alfalfa crops and soybean in the SW-WW-A-A-C-S rotation contributed to low residue input into the system. Production of corn and wheat residue was also low in the SW-WW-A-A-C-S rotation which decreased residue biomass in the system.

Aged residue C and N contents were greater in the C-S rotation and lower in the SW-WW-A-A-C-S rotation. Greater residue C and N concentrations in the C-S rotation were associated with greater residue biomass produced in the system due to greater frequent production of corn. There was lower residue C and N concentrations in the SW-WW-A-A-C-S rotation due to lower residue biomass produced by low residue crops such as two alfalfa crops and soybean in the system. Analysis showed that greater residue biomass added greater residue C and N to the systems while lower residue biomass added lower residue C and N to the systems.

Therefore, crop rotations that had greater residue biomass added greater residue C and N to the systems compared with the rotations that had lower residue biomass. This was the likely reason why the SW-WW-A-A-C-S rotation that had lower residue biomass resulted in proportionally lower residue C and N contents in the system. Fresh residue C and N concentrations were greater in the SW-C-S and C-S rotations and lower in the SW-S and SW-WW-A-A-C-S rotations. The main reason for greater residue C and N concentrations in the SW-C-S and C-S rotations was greater production of residue biomass in the systems by corn and wheat. Soybean residue was also produced in greater quantity which increased residue C and N in the systems. The main explanation for lower residue C and N contents in the SW-S and SW-WW-A-A-C-S rotations was lower production of residue biomass in the systems by soybean and wheat. Corn residue was also produced in much lower quantity in the SW-WW-A-A-C-S rotation which reduced residue C and N in the system.

Analyses of aged and fresh residue C:N ratios showed greater C:N ratio in the C-S rotation and lower C:N ratio in the SW-WW-A-A-C-S rotation. Greater C:N ratio in the C-S rotation was attributed to greater corn residue with corresponding lower N content in the system. The main reason for the lower C:N ratio in the SW-WW-A-A-C-S rotation was production of alfalfa and soybean residue with corresponding greater N content in the system. The amount of residue biomass produced in each system also influenced the C:N ratio in that system. This was the likely reason why the C-S rotation that had greater residue biomass resulted in wider C:N ratio. The fresh crop residues sampled in the 2012 fall showed narrower C:N ratios for legume crops and wider C:N ratios for non-legume crops. Winter wheat had the greatest C:N ratio and pea and radish had the lowest C:N ratios. Analyses of fresh residue C:N ratios showed that legumes can increase residue N mineralization and non-legumes can promote residue N immobilization.

Supplement N fertilizer requirements were evaluated for each of the seven rotations to determine the amount of additional N fertilizer that can be applied to subsequent crops to reduce residue N depletion associated with microorganisms decomposing high C residues. The SW-WW-C-S and SW-S rotations had greater total supplemental N fertilizer requirements for the aged residue while the SW-C-S and C-S rotations had greater total supplemental N fertilizer requirements for the fresh residue. These rotations required a greater amount of supplemental N fertilizer due to greater C:N ratios and residue biomass in the systems. The SW-WW-A-A-C-S rotation required a lower amount of supplemental N fertilizer for both aged and fresh residue because lower residue biomass with greater N content was produced in the system. Lower supplemental N fertilizer requirement in the SW-WW-A-A-C-S rotation was also attributed to high-N residue produced by two alfalfa crops and soybean in the system.

The COMET-VR model estimated greater SOC levels in rotations containing winter wheat and lower SOC levels in rotations containing no winter wheat. The main reason for greater SOC levels in the SW-WW-C-S, SW-WW-F-C-C-S, WW-CC-C-S, and SW-WW-A-A-C-S rotations was that these systems had more simulations compared with the SW-S and C-S rotations. However, the modeled SOC values were lower when compared with the field-based SOC values which showed the COMET-VR model underestimated the actual SOC in high-residue no-till management. This drawback in the model shows the model capability should be improved and validated to accurately simulate SOC levels in no-till cropping systems.

The RUSLE2 model estimated lower soil losses for the SW-WW-C-S, SW-WW-F-C-C-S, and SW-WW-A-A-C-S rotations containing winter wheat and greater soil losses for the SW-

C-S, SW-S, and C-S rotations containing no winter wheat for 3% and 6% slopes. The likely reason for lower soil losses in the rotations containing winter wheat was production of winter wheat residue in the systems. Winter wheat generally produces greater residue than spring wheat and therefore provides greater soil surface protection against wind and water erosion than spring wheat residue. Wheat residue also stands straight on the soil surface which provides a better protection against wind and water erosive forces in cropping systems. These conditions contributed to lower soil losses in the rotations that contained winter wheat than rotations that did not contain winter wheat or had spring wheat in the systems. The RUSLE2 model also may have associated greater crop diversity in the rotations that contained winter wheat with greater surface cover which decreased soil losses. Lower soil losses in the rotations with winter wheat showed that these systems can increase nutrient retention and reduce surface runoff. Lower soil losses can also reduce SOC mineralization and increase SOC retention. The WW-CC-C-S rotation had greater soil losses than other rotations for 3% and 6% slopes due to low residue crops such as field pea and soybean in the rotation. However, the fact that field pea was substituted for cover crops in the WW-CC-C-S rotation might have overestimated soil losses in the system.

The Soil Conditioning Index and Soil Tillage Intensity Rating in RUSLE2 predicted positive SOC conditions and low soil disturbance ratings, respectively. Positive SCI values were attributed to increased SOC associated with greater residue production and retention in no-till cropping systems. Positive SCI values showed the potential of the seven crop rotations to increase SOC at the CCSP site. Low STIR values were attributed to less soil surface disturbance which reflected the efficacy of actual soil management practices in no-till cropping systems at the CCSP site. These low STIR values showed the potential of the seven crop rotations to reduce sheet and rill erosion, increase SOC/SOM, reduce SOC mineralization, reduce SOC emissions, and improve infiltration rate and aggregation.

Conclusions from this study show that greater crop diversity does not necessarily lead to greater SOC and residue biomass in cropping systems. The SW-WW-F-C-C-S and SW-WW-A-A-C-S rotations did not result in greater SOC and residue biomass in the systems than the SW-C-S and C-S rotations. This shows that SOC and residue biomass cannot only be increased by increasing a number of crops but can also be increased by producing high residue crops such as corn and wheat in greater quantity and frequency in the cropping systems. A comparison of rotations that contained winter wheat and rotations that contained no winter wheat was difficult because SOC and residue biomass data were cumulative across all plots within the seven rotation treatments. It was also difficult to compare SOC and residue biomass in low diversity system such as C-S rotation with SOC and residue biomass in high diversity system such as SW-WW-F-C-C-S rotation. No valid comparison could be made between the two systems because corn and soybean residues were each produced in greater quantity and frequency in the C-S rotation compared to the SW-WW-F-C-C-S rotation in which corn, soybean, and wheat residues were each produced in lower quantity and frequency.

Future research trials should consider the impacts of high-diversity cropping systems on the individual crops. Crops that require a specific observation such as winter wheat in this study should be cropped in low-diversity rotations as winter wheat-soybean or winter wheat-alfalfa in order to accurately assess its contribution to SOC sequestration and residue biomass production. If cropped in this way, it may be easier to make a valid comparison between winter wheat system such as winter wheat-soybean rotation and corn system such as corn-soybean rotation.

APPENDIX A

Table A1. Plot, crop treatment, treatment replication, latitude, longitude, depth, bulk density and SOC values for 2006 and 2010.

Plot	Crop Treatment	Treatment Repl.	Latitude (N)	Longitude (W)	Depth	Bulk Density	2006 and 2010 SOC
					-cm-	-g/cm^3-	-kg/m^2-
18	A	1	46º 05’. 042”	097º 38’. 095”	0-30	1.43	8.37
19	A	1	46º 05’.032”	097º 38’ .109”	0-30	1.35	8.72
20	A	1	46º 05’.026”	097º 38’.085”	0-30	1.27	8.83
21	A	1	46º 05’ .019”	097º 38’ .074”	0-30	1.26	8.67
91	A	2	46º 05’ .181”	097º 38’ .290”	0-30	1.39	8.89
92	A	2	46º 05’ .170”	097º 38’ .270”	0-30	1.26	7.91
93	A	2	46º 05’ .162”	097º 38’ .273”	0-30	1.29	8.16
94	A	2	46º 05’ .153”	097º 38’ .274”	0-30	1.26	5.99
188	A	3	46º 05’ .065”	097º 38’ .540”	0-30	1.29	7.40
189	A	3	46º 05’ .058”	097º 38’ .541”	0-30	1.30	6.14
190	A	3	46º 05’ .058”	097º 38’ .539”	0-30	1.30	8.07
191	A	3	46º 05’ .045”	097º 38’ .541”	0-30	1.15	4.45
39	D	1	46º 05’ .053”	097º 38’ .145”	0-30	1.34	8.16
40	D	1	46º 05’ .061”	097º 38’ .146”	0-30	1.30	8.95
41	D	1	46º 05’ .071”	097º 38’ .144”	0-30	1.30	9.33
83	D	2	46º 05’ .262”	097º 38’ .281”	0-30	1.27	10.3
127	D	2	46º 05’ .265”	097º 38’ .379”	0-30	1.15	6.24
164	D	2	46º 05’ .150”	097º 38’ .452”	0-30	1.25	5.85
200	D	3	46º 04’ .950”	097º 38’ .512”	0-30	1.17	8.98
201	D	3	46º 04’ .937”	097º 38’ .535”	0-30	1.24	7.97
225	D	3	46º 04’ .960”	097º 38’ .591”	0-30	1.35	6.91
48	E	1	46º 04’ .984”	097º 38’ .156”	0-30	1.31	8.08
49	E	1	46º 04’ .972”	097º 38’ .157”	0-30	1.27	8.44
60	E	2	46º 05’ .171”	097º 38’ .221”	0-30	1.28	7.91
61	E	2	46º 05’ .161”	097º 38’ .200”	0-30	1.34	8.66
214	E	3	46º 05’ .065”	097º 38’ .564”	0-30	1.20	6.26
215	E	3	46º 05’ .055”	097º 38’ .564”	0-30	1.30	7.78
50	F	1	46º 04’ .975”	097º 38’ .169”	0-30	1.34	8.67
59	F	1	46º 05’ .045”	097º 38’ .541”	0-30	1.17	10.7
62	F	2	46º 05’ .179"	097º 38’ .215”	0-30	1.21	10.0
79	F	2	46º 05’.152"	097º 38’ .208”	0-30	1.11	6.50
158	F	3	46º 05’ .205"	097º 38’ .449”	0-30	1.31	4.72
159	F	3	46º 05’ .213"	097 38 .457”	0-30	1.30	7.87
52	I	1	46º 05’ .249"	097º 38’ .221”	0-30	1.23	7.98
53	I	1	46º 05’ .243"	097º 38’ .218”	0-30	1.14	8.09
54	I	1	46º 05’ .212”	097º 38’ .219”	0-30	1.16	6.78
55	I	1	46º 05’ .224”	097º 38’ .218”	0-30	1.22	6.83
56	I	1	46º 05’ .212”	097º 38’ .219”	0-30	1.14	6.05
57	I	1	46º 05’ .224”	097º 38’ .218”	0-30	1.16	7.47
118	I	2	46º 05’ .135”	097º 38’ .336”	0-30	1.13	8.46
119	I	2	46º 05’ .083”	097º 38’ .340”	0-30	1.16	8.26
120	I	2	46º 05’ .212”	097º 38’ .219”	0-30	1.28	7.27
121	I	2	46º 05’ .125”	097º 38’ .332”	0-30	1.11	6.83
122	I	2	46º 05’ .093”	097º 38’ .330”	0-30	1.14	7.28
123	I	2	46º 05’ .106”	097º 38’ .332”	0-30	1.25	8.46

Table A1. Plot, crop treatment, treatment replication, latitude, longitude, depth, bulk density and SOC values for 2006 and 2010 (continued).

Plot	Crop Treatment	Treatment Repl.	Latitude (N)	Longitude (N)	Depth	Bulk Density	2006 and 2010 SOC
					-cm-	-g/cm^3-	-kg/m^2-
204	I	3	46º 05’ .167”	097º 38’ .569”	0-30	1.15	6.91
205	I	3	46º 05’ .138”	097º 38’ .567”	0-30	1.21	7.87
206	I	3	46º 05’ .145”	097º 38’ .573”	0-30	1.22	5.54
207	I	3	46º 05’ .159”	097º 38’ .571”	0-30	1.17	6.72
208	I	3	46º 05’ .138”	097º 38’ .567”	0-30	1.28	7.06
42	KH	1	46º 05’ .044”	097º 38’ .145”	0-30	1.36	8.26
72	KH	1	46º 05’ .053”	097º 38’ .210”	0-30	1.31	10.9
73	KH	1	46º 05’ .045”	097º 38’ .219”	0-30	1.31	6.07
136	KH	2	46º 05’ .175”	097º 38’ .389”	0-30	1.32	7.80
137	KH	2	46º 05’ .163”	097º 38’ .389”	0-30	1.12	6.80
138	KH	2	46º 05’ .154”	097º 38’ .384”	0-30	1.14	10.3
178	KH	3	46º 05’ .166”	097º 38’ .535”	0-30	1.39	5.84
179	KH	3	46º 05’ .156”	097º 38’ .534”	0-30	1.26	7.50
180	KH	3	46º 05’ .147”	097º 38’ .534”	0-30	1.17	7.80
32	N	1	46º 05’ .135”	097◦ 38’ .167”	0-30	1.21	8.27
33	N	1	46º 05’ .133”	097º 38’ .166”	0-30	1.26	8.54
34	N	1	46º 05’ .119”	097º 38’ .157”	0-30	1.23	9.07
35	N	1	46º 05’ .112”	097º 38’ .144”	0-30	1.14	6.50
58	N	1	46º 05’ .191”	097º 38’ .960”	0-30	1.39	10.7
80	N	1	46º 04’ .975”	097º 38’ .210”	0-30	1.24	8.56
167	N	2	46º 05’ .125”	097º 38’ .443”	0-30	1.22	5.22
168	N	2	46º 05’ .114”	097º 38’ .458”	0-30	1.30	9.11
169	N	2	46º 05’ .106”	097º 38’ .460”	0-30	1.29	6.87
170	N	2	46º 05’ .097”	097º 38’ .448”	0-30	1.21	6.83
171	N	2	46º 05’ .089”	097º 38’ .452”	0-30	1.26	6.62
172	N	2	46º 05’ .078”	097º 38’ .458”	0-30	1.22	8.92
216	N	3	46º 05’ .045”	097º 38’ .568”	0-30	1.27	9.44
217	N	3	46º 05’ .037”	097° 38’ .570”	0-30	1.26	10.5
218	N	3	46º 05’ .028”	097° 38’ .572”	0-30	1.25	7.77
219	N	3	46º 05’ .017”	097° 38’ .576”	0-30	1.06	6.35
220	N	3	46º 05’ .009”	097° 38’ .580”	0-30	1.07	6.63
221	N	3	46º 05’ .000”	097° 38’ .577”	0-30	1.17	8.60

Table A2. Plot, crop treatment, treatment replication, latitude, longitude, depth, bulk density and SOC values for 2012.

Plot	Crop Treatment	Treatment Repl.	Latitude (N)	Longitude (W)	Depth	Bulk Density	2012 SOC
					-cm-	-g/cm^3-	-kg/m^2-
18	A	1	46º 05’.042”	097º 38’. 095”	0-30	1.18	9.51
19	A	1	46º 05’.032”	097º 38’ .109”	0-30	1.29	8.80
20	A	1	46º 05’.026”	097º 38’.085”	0-30	1.20	10.1
21	A	1	46º 05’.019”	097º 38’.074”	0-30	1.30	9.07
91	A	2	46º 05’.181”	097º 38’.290”	0-30	1.170	9.06
92	A	2	46º 05’.170”	097º 38’.270”	0-30	1.12	8.45
93	A	2	46º 05’.162”	097º 38’.273”	0-30	1.15	5.20
94	A	2	46º 05’.153”	097º 38’.274”	0-30	1.25	9.72
188	A	3	46º 05’.065”	097º 38’.540”	0-30	1.24	8.36
189	A	3	46º 05’.058”	097º 38’.541”	0-30	1.09	7.92
190	A	3	46º 05’.058”	097º 38’.539”	0-30	1.28	8.56
191	A	3	46º 05’.045”	097º 38’.541”	0-30	1.14	8.89
39	D	1	46º 05’ .053”	097º 38’ .145”	0-30	1.20	9.63
40	D	1	46º 05’ .061”	097º 38’ .146”	0-30	1.25	9.81
41	D	1	46° 05’ .071”	097º 38’ .144”	0-30	1.23	9.47
83	D	2	46° 05’ .262”	097º 38’ .281”	0-30	1.14	9.48
127	D	2	46º 05’ .265”	097º 38’ .379”	0-30	1.31	9.41
164	D	2	46º 05’ .150”	097º 38’ .452”	0-30	1.17	10.0
200	D	3	46º 04’ .950”	097º 38’ .512”	0-30	1.13	8.63
201	D	3	46º 04’ .937”	097º 38’ .535”	0-30	1.21	8.62
225	D	3	46º 04’ .960”	097º 38’ .591”	0-30	1.17	9.13
48	E	1	46º 04’ .984”	097º 38’ .156”	0-30	1.16	5.11
49	E	1	46º 04’ .972”	097º 38’ .157”	0-30	1.20	10.3
60	E	2	46º 05’ .171”	097º 38’ .221”	0-30	1.08	8.25
61	E	2	46º 05’ .161”	097º 38’ .200”	0-30	1.19	8.55
214	E	3	46º 05’ .065”	097º 38’ .564”	0-30	1.24	9.75
215	E	3	46º 05’ .055”	097º 38’ .564”	0-30	1.28	9.90
50	F	1	46º 04’ .975”	097º 38’ .169”	0-30	1.17	9.95
59	F	1	46º 05’ .045”	097º 38’ .541”	0-30	1.34	10.4
62	F	2	46º 05’ .179"	097º 38’ .215”	0-30	1.21	9.30
79	F	2	46º 05’.152"	097º 38’ .208”	0-30	1.07	8.09
158	F	3	46º 05’ .205"	097º 38’ .449”	0-30	1.07	9.66
159	F	3	46º 05’ .213"	097 38 .457”	0-30	1.30	9.45
52	I	1	46º 05’ .249"	097º 38’ .221”	0-30	1.31	9.68
53	I	1	46º 05’ .243"	097º 38’ .218”	0-30	1.23	9.38
54	I	1	46º 05’ .212”	097º 38’ .219”	0-30	1.22	8.84
55	I	1	46º 05’ .224”	097º 38’ .218”	0-30	1.13	9.07
56	I	1	46º 05’ .212”	097º 38’ .219”	0-30	1.11	7.98
57	I	1	46º 05’ .224”	097º 38’ .218”	0-30	1.11	9.38
118	I	2	46º 05’ .135”	097º 38’ .336”	0-30	1.22	7.86
119	I	2	46º 05’ .083”	097º 38’ .340”	0-30	1.14	4.22
120	I	2	46º 05’ .212”	097º 38’ .219”	0-30	0.99	9.31
121	I	2	46º 05’ .125”	097º 38’ .332”	0-30	1.16	8.98
122	I	2	46º 05’ .093”	097º 38’ .330”	0-30	1.14	9.33
123	I	2	46º 05’ .106”	097º 38’ .332”	0-30	1.15	8.16
203	I	3	46º 05’ .176”	097º 38’ .573”	0-30	1.17	9.03
204	I	3	46º 05’ .167”	097º 38’ .569”	0-30	1.16	9.18
205	I	3	46º 05’ .138”	097º 38’ .567”	0-30	1.28	9.70

Table A2. Plot, crop treatment, treatment replication, latitude, longitude and depth, bulk density and SOC values for 2012 (continued).

Plot	Crop Treatment	Treatment Repl.	Latitude (N)	Longitude (W)	Depth	Bulk Density	2012 SOC
					-cm-	-g/cm^3-	-kg/m^2-
207	I	3	46º 05’ .159”	097º 38’ .571”	0-30	1.23	7.05
208	I	3	46º 05’ .138”	097º 38’ .567”	0-30	1.28	10.3
42	KH	1	46º 05’ .044”	097º 38’ .145”	0-30	1.17	9.52
72	KH	1	46º 05’ .053”	097º 38’ .210”	0-30	1.11	7.76
73	KH	1	46º 05’ .045”	097º 38’ .219”	0-30	1.22	8.70
136	KH	2	46º 05’ .175”	097º 38’ .389”	0-30	1.19	8.00
137	KH	2	46º 05’ .163”	097º 38’ .389”	0-30	1.15	8.48
138	KH	2	46º 05’ .154”	097º 38’ .384”	0-30	1.05	8.19
178	KH	3	46º 05’ .166”	097º 38’ .535”	0-30	1.28	9.26
179	KH	3	46º 05’ .156”	097º 38’ .534”	0-30	1.13	7.86
180	KH	3	46º 05’ .147”	097º 38’ .534”	0-30	1.15	7.98
32	N	1	46º 05’ .135”	097◦ 38’ .167”	0-30	1.10	10.3
33	N	1	46º 05’ .133”	097º 38’ .166”	0-30	1.15	10.0
34	N	1	46º 05’ .119”	097º 38’ .157”	0-30	1.18	10.3
35	N	1	46º 05’ .112”	097º 38’ .144”	0-30	1.44	10.2
58	N	1	46º 05’ .191”	097º 38’ .960”	0-30	1.15	9.14
80	N	1	46º 04’ .975”	097º 38’ .210”	0-30	1.10	8.62
167	N	2	46º 05’ .125”	097º 38’ .443”	0-30	1.31	8.44
168	N	2	46º 05’ .114”	097º 38’ .458”	0-30	1.15	8.26
169	N	2	46º 05’ .106”	097º 38’ .460”	0-30	1.12	7.26
170	N	2	46º 05’ .097”	097º 38’ .448”	0-30	1.21	8.04
171	N	2	46º 05’ .089”	097º 38’ .452”	0-30	1.16	8.00
172	N	2	46º 05’ .078”	097º 38’ .458”	0-30	1.20	8.54
216	N	3	46º 05’ .045”	097º 38’ .568”	0-30	1.20	9.94
217	N	3	46º 05’ .037”	097° 38’ .570”	0-30	1.24	9.36
218	N	3	46º 05’ .028”	097° 38’ .572”	0-30	1.09	8.71
219	N	3	46º 05’ .017”	097° 38’ .576”	0-30	1.10	8.73
220	N	3	46º 05’ .009”	097° 38’ .580”	0-30	1.38	10.2
221	N	3	46º 05’ .000”	097° 38’ .577”	0-30	0.94	7.61

Table A3. Plot number, Plot replication, residue dry matter weight, residue C, residue C used by microbes, N in residue, N deficit in residue and residue C:N ratio for the aged residue spring 2010.

Plot Number	2010 Spring Aged Residue Treatment	Plot Repl	Residue Dry matter Weight	Residue C	Residue C used by microbes	Residue N needed by microbes	Residue N	Residue-N Deficit	C:N Ratio
			-Mg/ha-	-kg C/ha-	-kg C/ha-	-kg N/ha	-kg N/ha-	-kg N/ha-	----
18	A	1	11.9	5014	1755	219	1001	-119	48.6
19	A	1	8.37	3464	1213	152	41.8	-110	35.3
20	A	1	7.15	3036	1063	133	52.6	-80.3	45.6
21	A	1	14.0	6095	2133	267	147	-119	69.3
91	A	2	10.0	4271	1495	187	105	-81.9	65.5
92	A	2	8.23	3441	1204	151	81.5	-69.0	58.5
93	A	2	11.4	4433	1551	194	91.5	-102	45.5
94	A	2	3.01	1283	449	56.1	21.6	-34.6	43.3
188	A	3	13.3	5425	1899	237	113	-125	51.2
189	A	3	20.4	8767	3070	384	191	-192	58.3
190	A	3	9.16	3713	1299	162	57.4	-105	38.3
191	A	3	4.23	1819	637	79.6	20.8	-58.8	33.7
39	D	1	9.38	4037	1413	177	97.2	-79.4	59.6
40	D	1	6.19	2630	920	115	48.1	-67.0	44.7
41	D	1	5.60	2604	911	114	37.6	-76.3	41.4
83	D	2	7.38	2876	1007	126	65.5	-60.3	46.1
127	D	2	15.3	6428	2250	281	151	-130	59.9
164	D	2	9.22	3588	1256	157	53.2	-104	33.9
200	D	3	10.4	4293	1502	188	76.2	-112	45.6
201	D	3	7.01	2989	1046	131	61.6	-69.2	53.2
225	D	3	10.9	4749	1662	208	109	-99.0	60.3
48	E	1	5.07	2097	734	91.7	-0.22	-91.9	23.1
49	E	1	7.01	3000	1050	131	44.6	-86.6	38.3
60	E	2	11.2	4655	1629	204	87.4	-116	43.4
61	E	2	8.22	3393	1188	148	48.4	-100	36.3
214	E	3	9.48	3631	1271	159	56.4	-102	33.6
215	E	3	12.4	5186	1815	91.8	91.8	-135	42.0
50	F	1	6.57	2890	1011	67.6	67.6	-58.9	62.6
59	F	1	7.86	3236	1133	88.9	88.9	-52.7	74.3
62	F	2	19.3	8039	2814	352	202	-149	68.1
79	F	2	9.21	3979	1393	174	99.2	-74.8	65.9
158	F	3	17.4	7499	2625	328	188	-140	69.1
159	F	3	10.3	4465	1563	195	101	-94.3	59.6
52	I	1	8.70	3691	1292	161	80.4	-81.0	50.8
53	I	1	3.85	1586	555	69.4	27.2	-42.2	37.7
54	I	1	7.22	3017	1056	132	70.2	-61.8	59.7
55	I	1	11.2	4585	1605	201	122	-78.9	72.1
56	I	1	14.1	5730	2006	251	163	-87.2	76.5
57	I	1	5.40	2238	783	97.9	48.3	-49.6	51.3
118	I	2	7.09	2828	990	124	63.1	-60.7	54.1
119	I	2	4.23	1702	596	74.5	28.6	-45.9	40.4
120	I	2	6.16	2207	772	96.5	60.2	-36.3	52.4

Table A3. Plot number, Plot replication, residue dry matter weight, residue C, residue C used by microbes, N in residue, N deficit in residue and residue C:N ratio for the aged residue spring 2010 (continued).

Plot Number	2010 Spring Aged Residue Treatment	Plot Repl	Residue Dry matter Weight	Residue C	Residue C used by microbes	Residue N needed by microbes	Residue N	Residue-N Deficit	C:N Ratio
			-Mg/ha-	-kg C/ha-	-kg C/ha-	-kg N/ha	-kg N/ha-	-kg N/ha-	----
122	I	2	17.0	7177	2512	314	184	-130	64.2
123	I	2	9.00	3771	1320	165	60.8	-104	41.4
203	I	3	8.31	3574	1251	156	82.5	-73.9	60.5
204	I	3	1.85	796	279	34.8	13.6	-21.2	42.0
205	I	3	7.09	3016	1055	132	69.9	-62.0	62.3
206	I	3	11.1	4719	1652	206	113	-93.8	61.1
207	I	3	11.1	4507	1578	197	96.0	-101	49.8
208	I	3	7.13	2945	1031	129	55.3	-73.6	43.3
42	KH	1	7.35	3162	1107	138	62.0	-76.3	50.7
72	KH	1	3.37	1427	500	62.4	30.4	-32.1	50.1
73	KH	1	6.24	2700	945	118	76.7	-41.5	95.3
136	KH	2	3.91	1680	588	73.5	29.1	-44.4	43.9
137	KH	2	12.2	5199	1820	227	121	-107	58.8
138	KH	2	7.48	3076	1076	135	62.0	-72.6	45.2
178	KH	3	7.11	3132	1096	137	71.0	-66.0	62.2
179	KH	3	10.45	4311	1509	189	94.2	-94.3	49.6
180	KH	3	8.58	3617	1266	158	69.5	-88.8	45.3
32	N	1	4.74	2012	704	88.0	25.2	-62.9	33.8
33	N	1	9.06	3765	1318	165	72.7	-92.0	48.0
34	N	1	1.63	682	239	29.8	0.88	-30.0	24.6
35	N	1	1.63	682	239	29.8	0.88	-29.0	24.6
58	N	1	5.40	2208	773	96.6	39.7	-56.9	41.4
80	N	1	1.09	483	169	21.1	8.14	-13.0	47.1
167	N	2	1.52	647	227	28.3	8.74	-19.6	38.7
168	N	2	1.74	750	262	32.8	10.38	-22.4	40.9
169	N	2	6.72	2909	1018	127	8.24	-119	25.8
170	N	2	8.39	3604	1261	158	81.3	-76.4	57.4
171	N	2	3.48	1509	528	66.0	1.66	-64.3	26.5
172	N	2	3.48	1509	528	66.0	1.66	-64.3	26.5
216	N	3	3.07	1286	450	56.3	18.9	-37.4	37.6
217	N	3	4.46	1913	669	83.7	23.6	-60.0	36.8
218	N	3	8.17	3264	1143	143	57.0	-84.9	39.5
219	N	3	5.81	2418	846	106	40.3	-65.4	43.3
220	N	3	2.90	1219	427	53.3	0.44	-52.9	25.1
221	N	3	2.90	1219	427	53.3	0.44	-52.9	25.1

Table A4. Plot number, plot replication, residue dry matter weight, residue C, residue C used by microbes, N in residue, N deficit in residue and residue C:N ratio for the fresh residue fall 2012.

Plot Number	2012 Fall Fresh Residue Treatment	Plot Repl	Residue Dry Matter Weight	Residue C	Residue C used by microbes	Residue N needed by microbes	Residue N	Residue-N deficit	C:N Ratio
			-Mg/ha-	-kg C/ha-	-kg C/ha-	-kg N/ha-	-kg N/ha-	-kg N/ha-	----
18	A	1	10.9	4841	1694	212	113	-98.3	68.5
19	A	1	6.65	2946	1031	129	73.0	-55.9	73.5
20	A	1	9.86	4451	1558	195	104	-91.2	69.4
21	A	1	4.13	1831	641	80.1	365	-43.6	54.4
91	A	2	7.65	3340	1169	146	77.6	-68.5	63.8
92	A	2	8.04	2802	981	123	37.9	-84.6	42.8
93	A	2	8.00	3621	1267	158	80.9	-77.6	66.4
94	A	2	10.1	4480	1568	196	98.6	-97.4	61.8
188	A	3	14.3	6139	2149	269	144	-124	62.4
189	A	3	7.80	3445	1205	151	72.6	-78.1	57.5
190	A	3	7.40	3262	1142	143	67.3	-75.5	55.1
191	A	3	13.9	6083	2129	266	134	-132	59.4
39	D	1	7.76	3389	1186	148	80.1	-68.2	65.4
40	D	1	10.0	4260	1491	186	95.3	-91.1	57.2
41	D	1	13.6	5833	2042	255	126	-130	56.1
83	D	2	13.8	5995	2098	262	137	-125	62.0
127	D	2	10.6	4520	1582	198	89.7	-108	50.4
164	D	2	7.14	3016	1056	132	59.2	-72.7	48.6
200	D	3	8.51	3706	1297	162	82.1	-80.0	59.2
201	D	3	13.5	5949	2082	260	126	-134	58.1
225	D	3	8.39	3724	1303	163	88.6	-74.3	68.9
48	E	1	10.8	4806	1682	210	104	-106	59.1
49	E	1	7.03	3104	1087	136	63.9	-71.9	55.8
60	E	2	5.00	2207	772	96.5	48.2	-48.3	60.9
61	E	2	7.04	3079	1078	135	73.4	-61.3	66.4
214	E	3	7.31	3192	1117	140	55.1	-84.5	46.1
215	E	3	6.26	2717	951	119	63.4	-55.4	63.3
50	F	1	6.78	3002	1051	131	70.8	-60.5	67.7
59	F	1	14.0	6155	2154	269	160	-111	78.0
62	F	2	9.13	4085	1430	179	96.0	-82.7	69.1
79	F	2	11.4	4910	1719	215	99.4	-115	51.5
158	F	3	8.75	3934	1377	172	84.9	-87.2	61.6
159	F	3	11.5	4934	1727	216	112	-104	58.5
52	I	1	11.4	4966	1738	217	115	-102	63.6
53	I	1	6.73	3150	1103	138	65.2	-72.6	64.0

Table A4. Plot number, plot replication, residue dry matter weight, residue C, residue C used by microbes, N in residue, N deficit in residue and residue C:N ratio for the fresh residue fall 2012 (continued).

Plot Number	2012 Fall Fresh Residue Treatment	Plot Repl	Residue Dry Matter Weight	Residue C	Residue C used by microbes	Residue N needed by microbes	Residue N	Residue-N deficit	C:N Ratio
			-Mg/ha-	-kg C/ha-	-kg C/ha-	-kg N/ha-	-kg N/ha-	-kg N/ha-	----
55	I	1	8.86	3885	1360	170	86.8	-83.1	60.9
56	I	1	6.53	2925	1023	128	72	-56	74.8
57	I	1	8.21	3626	1269	159	96.3	-62.4	83.8
118	I	2	6.61	2448	857	107	30.6	-76.5	45.8
119	I	2	6.51	3032	1061	133	63	-69.7	63.7
120	I	2	10.9	4638	1623	203	86.8	-116	46.7
121	I	2	6.1	2623	918	115	65.8	-49	69.3
122	I	2	10.1	4233	1481	185	107	-78.4	64.7
123	I	2	8.79	3833	1341	168	69.9	-97.7	48.2
203	I	3	11.1	4824	1688	211	105	-106	58.3
204	I	3	5.21	2426	849	106	52.3	-53.9	66.8
205	I	3	7.39	3182	1114	139	74.3	-64.9	62.1
206	I	3	10.2	4450	1575	197	107	-89.6	67.6
207	I	3	9.82	4233	1482	185	97.3	-87.9	60.8
208	I	3	11.3	4930	1726	216	92.8	-123	50
42	KH	1	8.45	3517	1231	154	83.5	-70.4	58.4
72	KH	1	11.4	4975	1741	218	132	-86	80.2
73	KH	1	7.68	3438	1203	150	68.6	-81.8	55.4
136	KH	2	11.4	5058	1770	221	128	-93.6	76.9
137	KH	2	5.84	2538	888	111	55.9	-55.1	58.6
138	KH	2	7.79	3334	1167	16	73.6	-72.3	56.6
178	KH	3	13.5	5995	2098	262	158	-104	84.5
179	KH	3	5.31	2408	843	105	57	-48.3	71.9
180	KH	3	7.89	3484	1219	152	76.4	-76	60.4
32	N	1	7.44	3206	1122	140	54.6	-85.7	44.6
33	N	1	6.86	3035	1062	133	55.7	-77	49.9
34	N	1	8.27	3668	1284	160	82.7	-77.8	63.4
35	N	1	9.46	4127	1444	181	79.2	-101	50.6
58	N	1	3.25	1422	498	62.2	23.6	-38.6	18
80	N	1	4.66	2077	727	90.9	22.6	-68.3	20.4
167	N	2	1.53	631	221	27.6	13.7	-13.9	51.5
168	N	2	2.79	1173	411	51.3	18	-33.3	44.3
169	N	2	14.4	6230	2181	273	142	-131	60.4
170	N	2	7.17	3096	1084	135	71.1	-64.3	60.9
171	N	2	6.24	2787	975	122	62.3	-59.6	63.5
172	N	2	13.2	5826	2039	255	118	-137	55

Table A4. Plot number, plot replication, residue dry matter weight, residue C, residue C used by microbes, N in residue, N deficit in residue and residue C:N ratio for the fresh residue fall 2012 (continued).

Plot Number	2012 Fall Fresh Residue Treatment	Plot Repl	Residue Dry Matter Weight	Residue C	Residue C used by microbes	Residue N needed by microbes	Residue N	Residue-N deficit	C:N Ratio
			-Mg/ha-	-kg C/ha-	-kg C/ha-	-kg N/ha-	-kg N/ha-	-kg N/ha-	----
218	N	3	9.82	4277	1497	187	87.3	-99.8	53.7
219	N	3	8.34	3643	1275	159	78.5	-80.8	57.7
220	N	3	3.56	1232	431	53.9	15.4	-38.5	43.8
221	N	3	10.7	2159	756	94.5	57	-37.5	45.3

Table A5**.** Fuel estimated values used in the COMET-VR.

Source of Fuel	Colorado State University fuel estimates
	---L/ha---
No-till planter	3.27
Grain drill	3.27
Combine, small grains	9.35
combine , beans	10.3
combine, corn	15.0
Cutterbar	3.27
Rake, single	2.34
Baler	4.21
Sprayer	0.94
Total	52.0

Table A6. CCSP N fertilizer values used in the COMET-VR modeling.

Nitrogen Fertilizer Source	CCSP N Fertilizer Rates
Crops	---kg/ha---
Barley	250
Corn	200
Continuous corn	220
Dry pea (pulse)	80
Flax	56
Soybean	12
Spring Wheat	250
Winter Wheat	230

Table A7**.** Example of COMET-VR CENTURY online C Storage Report-2007 for the no-till production system at the CCSP site.

COMET-VR 2 Century Online C Storage report-2013 United States Department of Agriculture (USDA)

Session ID: 820450096 CCSP

1. Parcel Description:

Name: Parcel1, Sargent County, North Dakota;

Size: 10 Hectares;

Type: Agriculture;

LRR: F;

MLRA: 055B;

Soil: clay loam;

Hydric: N;

2. Parcel Management History:

Historic: Upland Cropland, non-irrigated;

1970's to 1990's: Continuous winter wheat, non-irrigated, intensive tillage;

Base (last decade Mgmt): Corn-winter wheat, non-irrigated, no-tillage system;

Report Period (next decade): Corn-winter wheat, non-irrigated, no-tillage system;

3. Carbon and Biomass Storage report:

A). Baseline:

Total tonnes C storage per year for the parcel 1: 1.92, percent uncertainty: 19;

Total tonnes net CO_2 equivalent flux per year for the parcel 1: -7.04;

B). Projection:

Total tonnes C storage per year for the parcel 1: 1.92, uncertainty: 19;

Total tonnes net CO_2 equivalent flux per year for the parcel 1: -7.04;

4. Important Comments:

For SOC storage, a positive value shows SOC sequestration and a negative value shows a soil carbon loss;

For SOC flux, a positive value shows an emission of GHG to the atmosphere and a negative value indicates a removal of GHG from the atmosphere;

One tonne of C is equivalent to 3.667 tonnes of CO_2;

Table A7. Example of COMET-VR CENTURY online C Storage Report-2007 for the no-till production system at the CCSP site (continued).

5. Direct and Indirect Nutrient Emission Report:

A). Baseline:

Total direct and indirect kg N/yer for the parcel 1: 19.8; percent uncertainty: Undetermined;

Total direct and indirect tonnes net CO_2 equivalent flux per year for the parcel: 6.13;

B). Projection:

Total direct and indirect kg N/yer for the parcel 1: 19.8; percent uncertainty: Undetermined;

Total direct and indirect tonnes net CO_2 equivalent flux per year for the parcel: 6.13;

There was no N_2O projection warning message;

The N_2O flux is converted to into tonnes of CO_2 using the global warming potential (GWP) of 310

Table A8. CCSP crop yield values for seven crops used in RUSLE2 version 1.26.6.4.†

Years	Alfalfa	Corn	Flax	Pea	Soybean	Spring wheat	Winter wheat
-yr-	-ton/ac-	-Bu/ac-	-bu/ac-	-bu/ac-	-Bu/ac-	-bu/ac-	-bu/ac-
2006	0	191	9	30	51	62	62
2007	3.5	149	14	30	46	54	73
2008	3.0	135	24	30	28	70	85
2009	5.0	167	28	30	45	65	65
2010	4.0	154	15	30	44	58	77
Average	3.1	159	18	30	43	62	72

†Based on actual annual average yields.

Table A9. Crop Rotation: Inputs and results (outputs) from RUSLE 2 version 1.26.6.4 profile erosion calculation record for soil losses for 3% slope and a 220 foot (68 m) long.

File: Profiles\Sargent County Work

Access Group: R2_NRCS_Fld_Office

Inputs:

Location Name	Soil Type	Slope length	slope steepness (%)
North Dakota\Sargent County	Aa Aastad clay loam\Aastad clay loam 90%	220	3.0

Crops	Management	Crop Yields --bu/ac--
Spring Wheat	Spring wheat-winter wheat-corn-soybean	62.0
Winter wheat	Spring wheat-winter wheat-corn-soybean	72.0
Corn	Spring wheat-winter wheat-corn-soybean	159
Soybean	Spring wheat-winter wheat-corn-soybean	43.0

Contouring	Strips/barriers	Diversion/terrace, sediment basin	Subsurface drainage
rows up-and-down hill	--none--	--none--	--none--

Soil Loss Ouputs:

T value	Soil loss erod. portion	Detachment on slope	Soil loss for cons. plan	Sediment delivery	Net C factor	Net K factor
-ton/ac/yr-	-ton/ac/yr-	-ton/ac/yr-	-ton/ac/yr-	-ton/ac/yr-	-ton/ac/yr-	-ton/ac/yr-
5.00	0.03	0.03	0.03	0.03	0.01	0.22

Table A9. Crop Rotation: Inputs and results (outputs) from RUSLE 2 version 1.26.6.4 profile erosion calculation record for soil losses for 3% slope and a 220 foot long (continued).

SCI and STIR Outputs:

Soil conditioning index (SCI)†	Avg. annual slope STIR
--unitless—	--unitless-
1.50	3.40

†The SCI is the Soil Conditioning Index rating. If the calculated index is a negative value, soil organic matter levels are predicted to decline under that production system. If the index is a positive value, soil organic matter levels are predicted to increase under that system.

The STIR value is the Soil Tillage Intensity Rating. It utilizes the speed, depth, surface disturbance percent and tillage type parameters to calculate a tillage intensity rating for the system used in growing a crop or a rotation. STIR ratings tend to show the differences in the degree of soil disturbance between systems. The kind, severity and number of ground disturbing passes are evaluated for the entire cropping rotation as shown in the management description.

APPENDIX B

Abbreviation	Definition
CC	Cover Crop
CEC	Cation exchange capacity
CCSP	Conservation Cropping Systems Project
CMZ	Crop Management Zone
COMET-VR	CarbOn Management Evaluation Tool for Voluntary Reporting
CRM	Crop Residue Management
CSRA	Carbon Sequestration Rural Appraisal
CSP	Conservation Security Program
CTIC	Conservation Tillage Information Center
MLRA	Major Land Resource Area
EIA	Energy Information Administration
ASSCII	American Standard Code for Information and Interchange
SOM1C (1)	C in surface microbe pool (g/m^2)
C:N	Carbon and Nitrogen Ratio
DOE	Department of Energy
ER	Erosion
FO	Field Operation
OC	Organic Carbon
OM	Organic Matter
POM	Particulate Organic Matter
TOC	Total Organic Carbon
IC	Inorganic Carbon
O	Oxygen

H	Hydrogen
N	Nitrogen
P	Phosphorous
K	Potassium
S	Sulfur
C	Carbon
%C	Percent Carbon
CH_4	Methane
CO_2	Carbon dioxide
%H_2O	%H_2O (sample moisture) = (Wet weight - Dry Weight)/Wet Weight
GCM	Global Climate Models
LSD	Least Significant Difference
GWP	Global Warming Potential
GHG	Greenhouse Gas
GIS	Geographical Information System
IPCC	Intergovernmental Panel on Climate Change
LRR	Land Resource Region
DMW	Dry Matter Weight
N/A	Not Available
N	Nitrogen
%N	Percent Nitrogen
N_2O	Nitrous Oxide
NRCS	Natural Resources Conservation Services
ND	North Dakota
NDSU	North Dakota State University

CT	Conventional Tillage
NT	No-Till
A	Alfalfa
C	Corn
F	Flax
P	Pulse
P	Pea
SB	Soybean
A = RKLSCP	Soil Loss Equation
A	Predicted long-term Average of annual sheet and rill erosion loss
R	Rainfall and Runoff Erosivity Factor
K	Soil Erodibility Factor
L	Slope Length Factor
S	Slope Steepness Factor
C	Cover Management Factor
P	Supporting Practice Factor
RUSLE2	Revised Universal Soil Loss Equation Version 2
SCI	Soil Conditioning Index
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SW	Spring Wheat
HRWW	Hard Red Winter Wheat
SRWW	Soft Red Winter Wheat
STIR	Soil Tillage Intensity Rating

USDA	United States Department of Agriculture
WW	Winter Wheat

APPENDIX C

Abbreviation	Unit
Ac	Acre
Bu	Bushel
bu/ac	Bushel per acre
Ton	Tonne
Ton/ac/yr	Tonne Per acre per year
Ton/ac	Tonne Per acre
Pg	Picrogram
Gt	Gigatonne
Tg	Teragram
ppbv	Parts Per billion by volume
ppmv	Parts Per million by volume
ft^2	Square feet
Ft	Feet
kg	Kilogram
kg/m^2	Kilogram per Square meter
g	Gram
g/m^2	Gram per Square Meter
Ha	Hectare
Lbs	Pounds
m	Meter
cm	Centimeter
m^2	Square Meter
m^{-2}	Per square Meter

Abbreviation	Unit
m^{-3}	Per Cubic Meter
Mg	Megagram
Mg/ha	Megagram Per Hectare
Mg/ha/yr	Megagram Per Hectare Per year
Mt	Metric Tonne