SOIL EROSION AND ORGANIC MATTER VARIATIONS FOR CENTRAL GREAT PLAINS CROPPING SYSTEMS UNDER RESIDUE REMOVAL

R. G. Nelson, J. Tatarko, J. C. Ascough II

ABSTRACT. *Removal of crop residues for bioenergy, feedstock, or other purposes should be done with caution to avoid excessive soil erosion or loss of soil organic matter (SOM). This study examined average annual changes in soil erosion from rainfall and wind forces and trends in soil organic matter as a function of commodity and/or bioenergy-based crop rotations, yield variations, and different field management practices, including residue removal across all land capability class (LCC) I to VIII soils in selected areas of the U.S. Central Great Plains (CGP). Specifically, comparisons were made between various rotations including corn, winter wheat, sorghum, cotton, fallow, and canola, subject to reduced tillage and no-till management practices. The purpose was to assess cropping options, field management, and soil sustainability to provide a geospatial assessment for use in soil conservation planning and possible bioenergy resource assessments in the CGP. Soil erosion and SOM (proxied by a soil conditioning index, SCI) were analyzed on individual soil map unit components using the RUSLE2 and WEPS models. Results were grouped by LCC and organized with respect to three different spatial resolutions: field scale (individual soil type), field scale aggregated to county level, and field scale aggregated to regional level. Analyses indicate variation in soil erosion and SCI trends as a function of crop type, rotation, and field management practices across different soil types within a single county and at the regional level. Considerable variation in removable residue amounts also occurred across different rotations, especially with respect to crop type, rotation, soil type, and tillage. Results obtained in this study should help advance the overall knowledge base of both public and private-focused commodity and bioenergy crop production agriculture and soil sustainability by providing small informational resolution (i.e., soil type) data on soil erosion and health trends that could have a pronounced effect on producer economics and long-term land sustainability.*

Keywords. *Bioenergy, Modeling, Residue removal, RUSLE2, Soil conditioning index, Soil erosion, WEPS.*

The geo-climatic makeup of the U.S. agricultural sector is extremely diverse, which can have a profound effect on crop production variability as well as long-term environmental quality. Sustainable agricultural production, primarily in terms of soil quality, is a key to ensuring reliable food, feed, and fiber supplies (USDA-NRCS, 2011a). In addition, agriculture, both in the U.S. and globally, has significant potential to contribute to the generation and production of biomass resources for alternative energy. Parts of the U.S. Central Great Plains (CGP), comprising northern Texas, western Oklahoma, Kansas, Nebraska, and eastern Colorado in this study, offer unique agricultural practices, land management, and environmental sustainability in terms of soils, climate, and water availability. Individual soils are often designated within the NRCS by land capability class (LCC) and ranked from I to VIII depending on local soil characteristics such as soil reaction (pH), surface texture class (silt loam, clay loam, etc.), available water capacity, and drainage class (USDA-NRCS, 2013). Well over 50% of the soils in certain regions of the CGP are LCC IV to VII, which implies that they are subject to certain geo-climatic limitations (related to field topography, soil characteristics, and geographic location) that affect their capacity for cultivated crop production (USDA-NRCS, 2009).

Given the diversity of geo-climatic land bases and potential feedstocks within the CGP, it is important to identify sustainable production scenarios that provide optimal resource utilization while maintaining or enhancing soil and environmental quality as much as possible on a localized (soil type) basis. Use of certain alternate cropping and tillage systems, including crop rotations and field management operations, may help alleviate long-term sustainability concerns and provide improvement to the soil and land base. The amount of soil erosion loss and trends in soil productivity from agricultural cropland can be a function of many factors, including crop, rotation, field management practices (e.g., tillage), and timing of operations. Other factors

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include soil physical characteristics (soil erodibility), field topology (slope), localized climate (precipitation, wind, temperature, solar radiation, etc.), and residue orientation (standing vs. flat).

Water and wind erosion simulation models are valuable tools for estimating potential soil loss under given climate, soil, and management practices. The Revised Universal Soil Loss Equation 2 (RUSLE2) (Renard et al., 1997; Dabney et al., 2012) and its predecessor, the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978), have been used in a wide variety of applications. The applications primarily involve cultivated field crop production and are focused on making water erosion and soil quality estimations with respect to changes in crop management. Use of these models has generally occurred in the U.S., but they have also been applied elsewhere (e.g., Yu, 2005; Zhang et al., 2010; Nunes et al., 2009). Dabney et al. (2012) also used RUSLE2 to: (1) evaluate the sensitivity of erosion estimates to possible climate change scenarios, (2) demonstrate the ability to evaluate alternative management adaptations, and (3) compare predictions with observations of runoff and sediment yield from a small research watershed in Iowa. The Wind Erosion Prediction System (WEPS) (Wagner, 2013) was developed to replace the older Wind Erosion eQuation (WEQ) (Woodruff and Siddoway, 1965) and for the NRCS to estimate soil loss from wind forces as affected by agricultural crop production; however, it has also been used for other applications. For example, van Donk et al. (2008) used WEPS to make comparisons of simulated residue cover in south-central North Dakota for 50 two-year cropping sequences from nine different crop species subject to no-till field management.

As a measure of the trend in SOM, the USDA-NRCS developed the concept of a soil conditioning index (SCI) (Hubbs et al., 2002; Zobeck et al., 2007). The SCI is a prediction tool used in conservation planning to estimate whether applied conservation practices will result in decreased, maintained, or increased levels of SOM. If the SCI is negative, the level of SOM is predicted to decline under the production system. If the SCI is positive, the SOM (and thus soil quality) is predicted to increase under the system. The SCI is a function of three interrelated parameters directly related to soil quality: (1) organic matter, in terms of the amount of organic material returned to the ground during the year; (2) field operations that stimulate organic matter decomposition; and (3) erosion, which involves removal of organic matter across field boundaries. SCI is used throughout this article as a proxy for SOM, and both RUSLE2 and WEPS calculate SCI as part of their simulations.

Agricultural crop residues, a subset of the biomass resource base, are cellulosic biomass materials that remain in the field after the harvest of agricultural crops and currently qualify as a sustainable bioenergy feedstock under the Renewable Fuel Standard 2 (RFS2) (EISA, 2007). However, residues play an important role in maintaining or improving soil quality, protecting the soil surface from water and wind erosion, and helping to maintain nutrient levels (Skidmore et al., 1979; Wilson et al., 2004; Lal, 2005). Residue available for removal from cropland is directly influenced by grain yield, crop rotation, field management practices within a rotation (e.g., tillage and pest management), climate, and soil physical characteristics such as erodibility and topography.

Tillage management systems have been found to affect soil erodibility and SOM. In a field study on long-term experimental plots, Blanco-Canqui et al. (2009) found that no-till management (compared to conventional, moldboard, and reduced tillage) enhanced near-surface aggregate properties to reduce water erodibility but had little or no effect on wind-erodible aggregate properties. They also found an increase in soil organic carbon under no-till, which was presumed to contribute to greater aggregate resistance to rainfall erosion. Field wind tunnel tests conducted by Van Pelt et al. (2013) on two Central High Plains silt loam soils and long-term (20-year) experimental plots with no-till, reduced tillage, and conventional tillage systems showed wind erosion results similar to those of Blanco-Canqui et al. (2009). Dry aggregate stability was not affected by tillage system type, leading Van Pelt et al. (2013) to conclude that improved wind erosion protection by no-till systems was entirely due to the protection afforded by crop residues.

Nelson (2002) conducted a large-scale crop residue resource assessment accounting for local soil types but not soil carbon or organic matter changes as a function of crop residue removal. This assessment focused on developing a methodology using RUSLE and WEQ to assess the removal of stover and straw from continuous corn and wheat rotations. The methodology was then used to provide estimates of area-weighted, county-level corn stover and spring/winter wheat straw removable for a three-year timeframe in 37 U.S. states east of a line from North Dakota to Texas. Residue removal was confined to amounts that maintained soil erosion below the tolerable loss level (T). Two mulch-till and two no-till tillage systems were used, and soil types were limited to LCC I to IV. Results of this study indicated that an annual average of more than 42 million and 8 million metric tons of corn stover and wheat straw, respectively, were potentially available for removal from 1995-1997 across the 37 states.

Nelson et al. (2004) expanded on the 2002 effort by analyzing six corn rotations as well as spring and winter wheat rotations in the ten largest corn-producing states, providing estimates of stover and straw residues that could be removed while maintaining erosion at less than or equal to T. This study provided the first large-scale look at how residue removal varied at the individual soil type level but did not take into account soil carbon effects. The methodology developed by Nelson et al. (2004) was used within a much larger biomass resource assessment for the whole U.S. (Perlack et al., 2005). That larger analysis indicated that potential maximum residue removable ranged from nearly 5.5 million dry metric tons a year for a continuous corn rotation using conventional tillage in Kansas to more than 97 million dry metric tons a year for a corn-wheat rotation using no-till in Illinois.

Graham et al. (2007) built on the work of Nelson et al. (2004) by expanding the analysis area, but they also eliminated areas due to soil moisture concerns and did not consider soil carbon. Wilhelm et al. (2007) used RUSLE2 and WEPS to investigate erosion due to stover removal and soil organic carbon (SOC) changes in several corn-based production systems throughout the Corn Belt, specifically the amount of stover needed to maintain SOC and not exceed tolerable soil erosion limits. Their estimates indicated that the amount of stover needed to maintain SOC, and thus productivity, is a greater constraint to environmentally sustainable cellulosic feedstock harvest than that needed to control water and wind erosion. English et al. (2013) used an integrated RUSLE2/WEPS framework to evaluate the costs and benefits with corn stover removal, conservation measures, and soil erosion and soil quality in Indiana.

The most comprehensive study to date of crop residue removal for bioenergy production at the soil-type level, with an impact on both soil erosion and soil carbon, was conducted by Muth et al. (2013). Their analysis considered both a "present" situation in 2011 and one projected to 2030. Over 900 crop rotations were analyzed with three different field management practices on LCC I to IV soils involving corn, soybeans, sorghum, small grains, and rice in conjunction with other crops such as soybeans in which residue removal was not considered. Soil erosion and SCI variations with rotation, field management, and residue removal were simulated using RUSLE2 and WEPS. The results showed that over 150 million metric tons of agricultural residues could have been sustainably removed in 2011 across the U.S. Projecting crop yields and land management practices to 2030, Muth et al. (2013) determined that over 207 million metric tons of agricultural residues could be sustainably removed for bioenergy production at that time. The analysis and data from Muth et al. (2013) were used by the U.S. Department of Energy in the revised "U.S. Billion Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry" (USDOE, 2011).

The goal of this study is to build on the methodology developed by Muth et al. (2013) and examine average annual changes in soil erosion (from rainfall and wind forces) and SCI as a function of commodity type and/or bioenergy-based cropping rotation, current and projected yields, and different field management practices on all LCC I to VIII soils in selected areas of the CGP. The specific study objective was to use the RUSLE2 and WEPS simulation models to explore changes in soil erosion (from water and wind) and SCI for selected commodity and bioenergy-based rotations pertinent to the CGP, which are subject to both reduced tillage and no-till practices under residue removal and no residue removal. Comparisons were made between crop rotations based on exceeding the NRCS tolerable soil loss limit and whether or not SCI was trending positive or negative. The models were run across all LCC I to VIII soil types in the CGP areas of eastern Colorado, western Kansas, Nebraska, Oklahoma, and northwest Texas. This study expands on the methodology presented by Muth et al. (2013) and other studies in the following ways:

- Additional crop rotations were developed and analyzed specific to the CGP.
- Canola, which qualifies as a bioenergy crop under the RFS2, was added to certain rotations where applicable within the CGP.
- Soil erosion and change in SCI specific to each individual cropping rotation, field management practice (reduced tillage and no-till), and agricultural crop residue removal (where applicable) were estimated for all LCC I to VIII soil types.

Materials and Methods

Assessment and Analysis Aggregation

Soil erosion and SCI analyses were performed on individual soil map unit components (USDA-NRCS, 1995), and results were grouped according to LCC. Results were organized with respect to (1) field scale (individual soil type), (2) field scale aggregated to county level, and (3) field scale aggregated to regional level. For county-level data by rotation, tillage, and residue or no residue removal, all individual soil type erosion and SCI values were hectare-weighted by SSURGO (USDA-NRCS, 1995) unit area within the county, summed over all county soil types, and divided by the total map unit area. Data were also obtained for trends by individual LCC in the same manner.

Regional assessments were made according to crop management zones (CMZ). Aggregation across a CMZ involved the same methodology as county-level aggregation except across all counties within the CMZ. A CMZ refers to an area in which similar crops are grown under similar climatic conditions. A CMZ map for the U.S. was delineated in 2001-2004 by the National Soil Survey Center in Lincoln, Nebraska, and was designed to organize sets of crop management scenario templates for use in implementing the RUSLE2 and WEPS models (D.T. Lightle, NRCS water erosion specialist retired, personal communication). The CMZ map (fig. 1) provided the basis in this study for standard sets of crop management scenarios (crops, crop rotations, and field management practices) for use in areas with similar agriculture to provide a level of consistency between counties and field offices within the same CMZ. Many of the rotations were developed by local and regional NRCS personnel over a 30-year period.

Information sources considered in developing the CMZ map included USLE Erosivity Index distribution data and figure 9 from USDA Agriculture Handbook 537 (Wischmeier and Smith, 1978), the C-factor zone map previously used in implementing RUSLE, National Agriculture Statistics Service (NASS) data on major crops grown (USEPA, 2011), and the usual planting and harvest dates for these crops within the crop-reporting regions (USDA-NASS, 1997). In addition, land resource regions and major land resource areas (USDA-NRCS, 2006), as well as USDA plant hardiness zones (USDA-ARS, 2012) were considered in establishing CMZ zone boundaries. Input and concurrence were received from all NRCS state agronomists and regional RUSLE2 coordinators during the process in establishing and normalizing the boundaries to county boundaries and major topographic features to aid in the implementation of RUSLE2 and WEPS in NRCS field

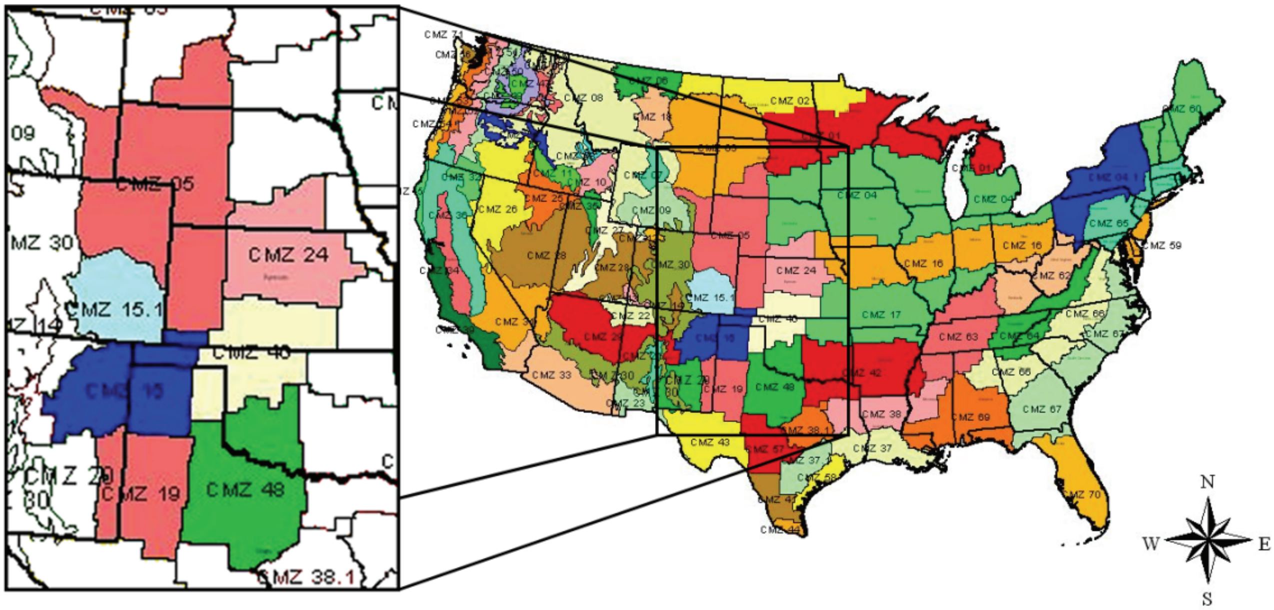

Figure 1. The six USDA-NRCS crop management zones (CMZs) analyzed in this study for the CGP. Note that CMZs 15 and 15.1 were combined for this study (source: http://fargo.nserl.purdue.edu/rusle2_dataweb/NRCS_Crop_Management_Zone_Maps.htm).

offices. The area of interest in this study for the CGP was limited to CMZs 5, 15, 15.1, 19, 24, 40, and 48, as shown in figure 1. CMZs 15 and 15.1 were combined into one crop management zone (15) as their crops and rotations were similar. More detailed CMZ maps are available on the RUSLE2 website (http://fargo.nserl.purdue.edu/rusle2_dataweb/NRCS_Crop_Management_Zone_Maps.htm).

RUSLE2 and WEPS Model Descriptions

The RUSLE2 and WEPS models were used to perform all simulations presented in this study. Both models require similar basic inputs that include soil properties, location (e.g., for weather input), and management applied, including operations such as tillage, planting, harvesting, and irrigation. The main reason RUSLE2 and WEPS were selected was their official adoption by the NRCS as superior tools for evaluating commodity crop production system soil conservation plans. This evaluation includes both estimating average annual soil erosion (kg m^{-2}) as well as assessing SCI associated with crop residue removal. Weather files used were those generated by each specific model at each location. For each model, the same weather sequence was applied to both the 2011 and 2030 simulations; the only difference was the use of expected crop yields for each year simulated at each simulation location (see crop yield discussion below). For more information on respective weather model development, databases, and validation, see Skidmore and Tatarko (1990) and van Donk et al. (2005) for WEPS and USDA-ARS (2008) and Dabney et al. (2012) for RUSLE2.

The RUSLE2 model was derived from the original Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1965, 1978), arguably the most widely used soil loss estimation equation in the world. The empirically derived USLE predicts long-term average annual soil loss from sheet and rill erosion based on six factors. These factors account for rainfall and runoff erosivity, the soil erodibility factor, topographic factors that depend on slope length and gradient, a cover and crop management factor, and a soil conservation practice factor. The USLE was originally developed to provide a soil loss estimation method for making land management decisions that would reduce water erosion (Kinnell, 2010). Like the USLE, RUSLE2 is designed to predict long-term annual soil loss but uses a daily time step and different approaches to determining factors such as R (erosivity factor) and K (soil erodibility factor) than are used in the USLE (Foster et al., 2003). RUSLE2 calculates runoff, erosion, and sediment delivery from a variable hillslope profile, using the climate, topography, soils, land management, and concentrated flowpath properties of a site. It also provides an approach to account for deposition resulting from changes in slope gradient on one-dimensional hillslopes (Dabney et al., 2011). Climate data required to simulate weather and calculate sheet and rill erosion and sediment delivery with RUSLE2 are monthly averages for precipitation, temperature, and erosivity density, plus location 10-year, 24-hour precipitation depth (Dabney et al., 2012; USDA-ARS, 2008).

The WEPS model was developed primarily to assist land managers in controlling wind erosion and establishing acceptable field-level conservation plans. WEPS simulates daily field hydrology, plant growth and residue decomposition, land management, and soil surface erodibility to calculate wind erosion loss as affected by local weather (Hagen, 2004; Wagner, 2013). WEPS simulates daily weather stochastically based on historical weather distributions where precipitation, temperature, and solar radiation are simulated by the Cligen climate generator (Meyer, 2004) and wind parameters are simulated by the Windgen climate generator (van Donk et al., 2005). Precipitation, temperature, and solar radiation are the primary drivers for surface physical processes and plant growth and are stochastically generated based on the location's historical weather record. The hydrology submodel simulates soil energy dynamics, including soil temperature and water content within soil layers. The user inputs management practices, which add to or change surface properties. Physical properties of the soil vary as a result of weathering processes between management events. The growth of crops is simulated and plant decomposition is accounted for based on temperature and precipitation. When the surface threshold friction velocity is less than the actual friction velocity, computed from the hourly wind speed and current surface aerodynamic roughness, then soil loss from wind is calculated. WEPS simulations were 50 years per crop rotation year (e.g., a three-year rotation was run for 150 simulation years). Results reported are the average of all 50 simulation years per simulation year.

Crop Rotations and Tillage Inputs

Crop rotations and field management practices (e.g., tillage) relevant to each CMZ were obtained from the RUSLE2 and WEPS management templates and from consultation with other experts within the NRCS. Bioenergy crop rotations were developed in consultation with a number of industry and academic experts. All crop rotations developed were applied at the SSURGO map unit scale across all soils within a CMZ. The following conventional commodity crops were chosen due to their relative number of planted hectares within the region of interest: corn, soybeans, sorghum, winter wheat, and cotton. In addition, fallow is used within many rotations throughout the study area due to moisture concerns and therefore was included as part of some crop rotations, specifically those involving winter wheat. The addition of canola in some rotations was due to it qualifying as a bioenergy crop under the present RFS2 as well as its suitability for production in some analyzed CMZs. Table 1 presents average annual data on hectares planted for a number of crops in each CMZ for 2008-2012 (USDA-NASS, 2012). Data for canola were not available on a county or state basis, and some crops were not grown in some CMZs.

Based on the data presented in table 1, as well as the fact that canola meets the greenhouse gas emissions criteria for conversion to an alternative liquid fuel under the RFS2, the rotations presented in table 2 were used in this study. For each crop rotation presented in table 2, four separate scenarios were evaluated. Two field management practices consisting of reduced-till and no-till systems and rotations were evaluated with and without residue removal.

Rotations varied from one year (continuous) to three years (e.g., CG is a one-year continuous corn, grain rotation; SG-CT is a two-year sorghum, grain-cotton rotation; and SG-FA-WW is a three-year sorghum, grain-fallow-winter wheat rotation). All rotations had at least one crop that produced residues (i.e., corn or sorghum stover, wheat straw). Table 3 presents typical operations used for each crop subject to reduced tillage and residue removal. No-till field management involved only planting and harvesting operations with dates typical for each crop within a particular CMZ.

Table 2. Crop rotations used in this study by CMZ.[a]

CMZ	Crop Rotations
5	CG, CG-FA-WW, SG-FA-WW, WW-FA, WW-CG-CA
15	CG, SG-FA-WW, WW, WW-CG-CA
19	CG, SG-CT, SG-CT-CT, WW-CT, WW-CG-CA
24	CG, CG-SB, SG-FA-WW, SG-SB-WW, WW, WW-WW-CA
40	CG, SG-FA-WW, SG-SB-WW, WW-WW-CA, WW
48	WW, WW-CT-CT, WW-WW-CT, WW-WW-CA

[a] CA = canola; CG = corn, grain; CT= cotton; FA= fallow; SB= soybeans; SG= sorghum, grain; WW= winter wheat.

Table 3. Typical reduced tillage field operations by individual crop.

Crop	Operation
Canola (CA)	Disk, sweep
Corn, grain (CG)	Chisel, sweep, cultivator, tandem disk
Cotton (CT)	Chisel, cultivator, tandem disk
Soybeans (SB)	Chisel, cultivator
Sorghum, grain (SG)	Chisel, cultivator
Winter wheat (WW)	Chisel, cultivator, tandem disk

Residue Removal

For the crops considered in this analysis, stover from corn and sorghum, as well as straw from winter wheat, were residues that could potentially be removed from the field after harvest. Muth et al. (2013) developed four residue removal configurations with differing removal rates expressed as a percentage of residue collected, which ranged from 22% to 83%. Due primarily to the number of soil types and rotations investigated in this study, only one residue collection system was chosen for analysis, moderately high residue harvest (MHH), which had a removal rate of 50%. The MHH system involved a combine harvester residue chopper and spreader and a rake for collecting all residue into a single windrow. Residue was generally collected within a few days after actual grain harvest. All equipment configurations represent current, commercially available technology and include a description of not only amounts of residue available after harvest but also the orientation of the residue (e.g., residue left on the ground flat for rainfall erosion protection or standing stubble that can reduce the kinetic energy from wind forces). Both RUSLE2 and WEPS take into consideration residue orientation after harvest (standing vs. flat), which is extremely important in

Table 1. Average annual crop area (ha) planted in each CMZ from 2008-2012.

Crop	CMZ 5	CMZ 15	CMZ 15.1	CMZ 19	CMZ 24	CMZ 40	CMZ 48
Barley	3,488	0	0	0	0	0	0
Corn	1,545,431	289,407	77,837	133,733	701,920	226,260	1,497
Cotton	1,376	57,935	0	1,459,953	0	24,710	356,625
Oats	1,311	186	0	121	3,140	129	11,833
Rye	0	0	0	0	0	3,683	890
Sorghum	238,401	131,013	20,639	206,317	410,044	211,003	16,762
Soybeans	74,673	4,249	0		633,390	201,234	356
Sunflowers	6,022	1,190	3,974	3,375	2,582	0	121
Winter wheat	2,034,470	730,758	328,621	385,561	1,289,799	1,853,672	1,408,412

Table 4. Land capability class (LCC) area (%) by CMZ.

CMZ	LCC I	LCC II	LCC III	LCC IV	LCC V	LCC VI	LCC VII	LCC VIII
5	0	16.41	22.64	14.16	0.35	41.66	4.78	0
15	0	2.60	19.60	19.78	0.40	44.74	12.88	0
19	0	1.53	55.46	18.80	0.69	16.45	7.07	0
24	4.07	39.47	21.93	12.38	1.48	18.89	1.75	0.03
40	5.11	27.25	26.73	11.34	2.77	20.80	5.95	0.05
48	1.36	26.44	28.76	12.00	3.84	15.20	12.37	0.03
Study region	1.48	17.93	26.24	14.89	1.35	30.57	7.52	0.02

providing accurate estimations of annual losses due to soil erosion.

Soils

Soils data used in the RUSLE2 and WEPS models were derived from the NRCS SSURGO database (USDA-NRCS, 1995), accessed from the NRCS National Soil Information System (NASIS) server (USDA-NRCS, 2011b). SSURGO provides, by county, discrete soil mapping unit components comprising certain soil characteristics such as the number of hectares (acres) of each particular soil type, a slope range, texture, irrigated and non-irrigated land capability class and subclass, tolerable soil loss limit, and soil erodibility parameters with respect to rainfall and wind erosion. Although soil loss tolerance values vary among soil types from 0.224 to 1.12 kg m^{-2} (1 to 5 tons $acre^{-1}$), we chose a constant T value of 1.12 kg m^{-2} to provide consistency in comparisons throughout the soils and spatial scales in this study because it represented over 98% of the T values across all CMZs. Table 4 presents the approximate percentage of area in each CMZ by individual LCC.

Crop Yields for 2011 and 2030

Expected crop yields can be input into the RUSLE2 and WEPS models and are directly correlated to residue production, i.e., as yields increase, the resulting residue produced increases. All simulations in this study were run with two separate sets of crop yields (one for 2011 and one projected to 2030), which is identical to the analysis performed by Muth et al. (2013). Crop yields used in this analysis for corn, grain sorghum, winter wheat, soybeans, and cotton were taken directly from the analysis performed by Muth et al. (2013) and were at the county level. Yields for 2030 were estimated using POLYSYS, a non-linear policy simulation model of the U.S. agricultural sector (USDOE, 2011) that accounts for dynamic international commodity markets. Yield estimates are based on a number of factors including estimated land use changes, energy crop supplies, and commodity prices. These projections may drive some higher-valued crops such as corn with both high-value grain as well as stover to more productive land and lower-valued crops (e.g., grain sorghum) to less productive lands; therefore, in some counties, various crops may have lower yields in 2030 than in 2011, and vice versa. During a WEPS run, yields are allowed to vary from year to year in response to soil hydrology, given precipitation, temperature, and wind effects on available soil moisture, evaporation, and transpiration. But on average, yields for a simulation run are the expected yields entered by the user. In contrast, RUSLE2 uses one average yield for the entire simulation.

A constant residue generation ratio was assumed the same in 2030 as 2011 due to a lack of reliable data concerning future harvest indices. Current and projected yields for canola were provided by faculty members of the Kansas State University Department of Agronomy (personal communication). Table 5 presents the minimum and maximum yields for each crop in each CMZ from POLYSYS projections.

Soil Erosion and SCI Values

For each cropping rotation and its associated management, i.e., reduced till (RT) or no-till (NT), yields for 2011 or 2030, and whether residue was removed or not, a combination of RUSLE2 and WEPS was used to calculate a single average annual value of soil erosion and SCI on all individual soil types. Table 6 presents an example of the type of soil erosion and SCI data output from the RUSLE2 and WEPS runs for a single rotation (corn-fallow-winter wheat), both tillage practices (RT and NT), residue removal

Table 5. Minimum and maximum yields by crop for 2011 and 2030.[a]

			Yield (g m^{-2})					
Year	CMZ		CG	SB	SG	WW	CT	CA
2011	5	Min.	345	-	157	138	-	128
		Max.	1,229	-	571	370	-	128
	15	Min.	307	-	219	100	-	128
		Max.	1,430	-	545	458	-	128
	19	Min.	746	-	138	63	36	128
		Max.	1,367	-	451	288	86	128
	24	Min.	439	107	470	176	-	85
		Max.	1,279	395	690	395	-	85
	40	Min.	414	119	263	132	-	85
		Max.	1,411	382	558	288	-	85
	48	Min.	-	-	-	-	21	85
		Max.	-	-	-	-	110	85
2030	5	Min.	426	-	138	176	-	340
		Max.	1,624	-	533	395	-	340
	15	Min.	483	-	144	188	-	340
		Max.	1,655	-	602	470	-	340
	19	Min.	1,179	-	138	113	47	340
		Max.	1,655	-	458	389	105	340
	24	Min.	577	150	395	213	-	298
		Max.	1,593	445	671	376	-	298
	40	Min.	796	138	251	163	-	298
		Max.	1,743	470	571	270	-	298
	48	Min.	-	-	-	-	9	298
		Max.	-	-	-	-	98	298

[a] CG = corn, grain; SB = soybeans; SG = sorghum, grain; WW = winter wheat; CT = cotton; CA = canola.

Table 6. Example average annual soil erosion and SCI values for one cropping rotation and two tillage practices (RT = reduced tillage and NT = no-till), with and without residue removal, for a Bridgeport silt loam in Thomas County, Kansas.

Crop		Residue	Erosion (kg m^{-2})			
Rotation[a]	Tillage	Removal	Total	Rainfall	Wind	SCI
CG-FA-WW	NT	Yes	0.13	0.05	0.07	0.45
CG-FA-WW	NT	No	0.02	0.01	0.01	0.73
CG-FA-WW	RT	Yes	0.33	0.12	0.22	0.24
CG-FA-WW	RT	No	0.14	0.06	0.08	0.49

[a] CG = corn, grain; FA = fallow; WW = winter wheat.

and no residue removal, and 2011 yields for corn and winter wheat on a Bridgeport silt loam in Thomas County, Kansas. These data were reported for all rotations in each county across all six CMZs.

RESULTS AND DISCUSSION

The RUSLE2 and WEPS simulation results were obtained at an individual field scale (SSURGO map unit component) as well as the county and CMZ level through aggregation of individual soil type data. The full dataset as well as aggregated data for all crop rotations, tillage, residue removal, and yield differences for all five CMZs are available from Tatarko et al. (2015). The results indicate tremendous variation in soil erosion and SCI trends, depending on which rotation was analyzed, the subcounty and regional geographic location of that rotation, and how the field was managed with respect to residue levels. The following three scenarios were examined to provide insight into soil erosion and SCI variations at three different scales:

Scenario 1: Field scale. Comparison of soil erosion loss and SCI trends within a single county by crop rotation, tillage, yield, soil type, and residue removal.

Scenario 2: County scale. Comparison of soil erosion loss and SCI trends within two counties of one CMZ for the following cases: (1) the same crop rotation with and without residue removal on two different LCC soils and a reduced tillage practice, (2) the same crop rotation with and without residue removal for two tillage practices and on two different LCC soils, and (3) different crop rotations on one LCC soil with two different tillage practices.

Scenario 3: CMZ scale. Comparison of aggregated soil erosion loss and SCI trends across each CMZ by rotation for all LCC class soils, both tillage practices, with and without residue removal, and 2011 and 2030 yields.

Scenario 1 should be of interest to those making short-term and long-term decisions at the farm level, such as an individual producer. Scenarios 2 and 3, on the other hand, should be of interest to those making resource-planning decisions on a regional scale, such as an alternative energy company or conservation planners.

As expected under the relative low topography and high wind climate of the CGP, soil loss by wind was the dominant erosion process, accounting for 72.5% of all soil loss compared to 27.5% for water erosion. Only slight differences were observed between 2011 and the relatively higher 2030 yields, where wind erosion accounted for 73.3% of erosion in 2011 and 71.7% using the 2030 yields. Conversely, water erosion consisted of 26.7% of the erosion in 2011 and 28.3% for 2030 yields (data not shown). Tillage practices showed an overall relative increase in water erosion and a decrease in wind erosion under NT compared to RT (water erosion: NT = 44% vs. RT = 24% and wind erosion: NT = 56% vs. RT = 76%, data not shown). This could be a result of NT leaving more standing residue to intercept the wind erosive force compared to RT, resulting in increased flat residue, which would intercept more raindrop impact.

SCENARIO 1: FIELD SCALE

Table 7 contains data taken from RUSLE2 and WEPS simulations for two separate soil types in Thomas County, Kansas, and four crop rotations, two tillage practices (RT and NT), 2011 and 2030 yields, and with and without residue removal

Table 7. Variation in average annual soil erosion (total of wind + water) and SCI for differing crop rotations, tillage practices (RT = reduced tillage and NT = no-till), residue removal, and different LCC soils for Thomas County, Kansas.

		Erosion and SCI for 2011 Yields				Erosion and SCI for Projected 2030 Yields			
		No Residue Removal		Residue Removal		No Residue Removal		Residue Removal	
Soil	Crop Rotation[a]	Erosion (kg m^{-2})	SCI	Erosion (kg m^{-2})	SCI	Erosion (kg m^{-2})	SCI	Erosion (kg m^{-2})	SCI
Ulysses silt loam, 1% to 3% slopes (LCC II)	CG								
	RT	0.06	0.52	0.10	0.27	0.04	0.73	0.07	0.39
	NT	0.01	0.90	0.04	0.58	0.00	1.13	0.03	0.70
	CG-FA-WW								
	RT	0.14	0.49	0.33	0.24	0.08	0.56	0.20	0.32
	NT	0.02	0.73	0.12	0.45	0.01	0.79	0.08	0.50
	CG-CA-WW								
	RT	0.85	0.17	2.06[b]	-0.41	0.60	0.47	1.76[b]	-0.11
	NT	0.03	0.74	0.09	0.52	0.01	0.98	0.05	0.73
	WW-FA								
	RT	0.05	0.53	0.14	0.33	0.05	0.50	0.15	0.32
	NT	0.01	0.65	0.06	0.42	0.01	0.62	0.06	0.41
Colby silt loam, rarely flooded (LCC VI)	CG								
	RT	0.70	0.30	1.19[b]	-0.11	0.44	0.59	0.82	0.13
	NT	0.05	0.89	0.46	0.44	0.02	1.12	0.26	0.62
	CG-FA-WW								
	RT	0.73	0.29	1.56[b]	-0.19	0.62	0.38	1.35[b]	-0.08
	NT	0.07	0.71	0.64	0.27	0.05	0.78	0.52	0.35
	CG-CA-WW								
	RT	1.26[b]	0.03	2.63[b]	-0.61	0.91	0.37	2.17[b]	-0.26
	NT	0.20	0.68	0.75	0.29	0.11	0.94	0.48	0.58
	WW-FA								
	RT	0.46	0.38	1.34[b]	-0.09	0.51	0.34	1.47[b]	-0.15
	NT	0.06	0.63	0.68	0.20	0.08	0.60	0.76	0.16

[a] CA = canola; CG = corn, grain; FA = fallow; WW = winter wheat.
[b] Values for erosion that are above the NRCS tolerable soil loss limit of 1.12 kg m^{-2} (5 tons acre^{-1}).

due removal. The soils are a Ulysses silt loam (LCC 2) and Colby silt loam (LCC 6), and the crop rotations are corn (CG), corn-fallow-winter wheat (CG-FA-WW), corn-canola-winter wheat (CG-CA-WW), and winter wheat-continuous fallow (WW-FA). Soil loss as well as SCI is a function of all factors listed above and possibly others. These data are presented to point out that differences in both soil erosion and SCI can occur when one or more of these factors are varied and to show relative changes.

In general, soil erosion increased and SCI decreased under all rotations as tillage changed from NT to RT, yields increased from 2011 to 2030, residue removal increased, and LCC changed from II to VI (table 7). Although organic matter can affect such factors as soil aggregation, the soil erosion increases and decreasing SCI are likely a reflection of biomass productivity on these field-scale parameters, where higher biomass increases SCI while also providing more cover to reduce erosion. Among the four crop rotations on either soil, differences in the magnitude of soil erosion and value of SCI exist. Continuous CG tended to have the lowest erosion and highest SCI, whereas the CG-CA-WW rotation tended to have the highest erosion and lowest SCI. On both soils, the residue removal cases exceeded T (1.12 kg m^{-2}) for the CG-CA-WW RT rotation. The value of T was exceeded for the CG-CA-WW rotation and corresponded with negative SCI values for all cases where residue was removed, indicating that this would not be a sustainable system. This could be explained by canola (CA) tending to have much lower biomass production than CG and WW. In all cases presented in table 7, employing NT as compared to RT resulted in less soil erosion and greater SCI. In all cases where soil loss was greater than T and SCI values were negative under RT, switching to NT resulted in erosion below T and positive SCI values. This result could have occurred because more residue was available after harvest and throughout the year (due to no-till field management) to protect the field from erosion forces.

Biomass production is directly related to crop yield and therefore has an effect on soil erosion. In general erosion should decrease as yield increases for the same geo-climatic conditions and tillage practices, assuming residue generation remains at the same level. Simulated corn yields in 2011 and 2030 in Thomas County were 759 and 1,054 g m^{-2}, respectively, which means more residue would be present in 2030. In all cases in scenario 1 where corn was part of the rotation, soil erosion values decreased and SCI increased from 2011 to 2030. Simulated winter wheat yields decreased slightly from 282 g m^{-2} in 2011 to 257 g m^{-2} in 2030. For the WW-FA rotation, soil erosion actually increased (and SCI decreased) from 2011 to 2030, at least in part because of the lower yields.

Differences were present between the two soils. For example, on the Ulysses silt loam with 2011 yields and no residue removal, a range of 0.84 kg m^{-2} in soil loss (0.85 kg m^{-2} versus 0.01 kg m^{-2}) occurred among the four rotations. The same trend occurred on the Colby silt loam soil, but the soil erosion values were greater. The Ulysses soil exhibited erosion exceeding T with a corresponding negative SCI on the two residue removal cases under the CG-CA-WW rotation, whereas the Colby soil showed erosion greater than T (and corresponding negative SCI) for seven of eight residue removal cases. The CG rotation showed improvement in erosion and SCI using the 2030 yields (table 7). These results indicate that the CG-FA-WW, CG-CA-WW, and WW-FA rotations are not sustainable on the Colby soil with residue removal. In general, LCC VI soils are defined to have limitations that restrict cultivation for commodity crop production, which could potentially make them more susceptible to erosion.

When residue removal occurred, soil erosion increased in every instance and SCI decreased compared with no removal. Of all 32 residue removal cases shown in table 7, nine exhibited soil losses greater than T with residue removal and negative SCI, whereas the non-removal cases showed only one case with soil loss greater than T and a positive SCI. These results can be attributed to the fact that less residue is present on the field after harvest; however, some of the cases presented here had average annual soil loss less than T even though residue was removed (this is true for other CMZs as well).

The field-scale results mirror soil erosion and/or SCI trends presented in previous studies by Nelson (2002), Nelson et al. (2004), Graham et al. (2007), and Wilhelm et al. (2007). All studies showed tremendous variations in one or more parameters between rotations and tillage practices across the soils investigated. In some cases, differences were at least an order of magnitude. The trends observed in the snapshot of four rotations on two separate soil types in one county were also observed in other instances throughout the six CMZs analyzed, but obviously with different magnitudes of soil erosion and trends in SCI depending on rotations, yields, geo-climatic conditions, and soil properties. In some cases presented, soil loss was not greater than T, and SCI values were positive. However, for specific crop rotations and management practices that an individual producer might consider, simulations of those crops and management practices with RUSLE2 and WEPS are recommended as an efficacious means to assess soil erosion and tilth on individual fields.

SCENARIO 2: COUNTY SCALE

The second scenario involves a comparison of three different crop rotations (CG, SG-FA-WW, and WW) common between two counties in different CMZs: Saline County, Kansas (CMZ 24) and Gray County, Texas (CMZ 40). The purpose of scenario 2 was to demonstrate how differing geo-climatic conditions including soil types, precipitation, temperature, etc., can have an impact on soil erosion and organic matter at a larger scale. Specifically, three different cases provided comparisons of soil erosion and SCI under the following scenarios: (1) one rotation with and without residue removal on two different LCC soils and reduced tillage, (2) one rotation and two residue removal scenarios varied by tillage on two different LCC soils, and (3) three different rotations on one specific LCC soil and both an RT and NT tillage practice with residue removal. Simulated yields for corn, sorghum, and winter wheat in 2011 were 765, 552, and 282 g m^{-2}, respectively, in Saline County and 1,204, 332, and 163 g m^{-2}, respectively, in Gray County. Average annual WEPS-simulated precipitation was

731 mm in Saline County and 548 mm in Gray County.

Table 8 shows the three cases of soil erosion and SCI variations for each rotation aggregated across all LCC II and IV (cases 1 and 2) and LCC VI (case 3) soils in each of the two counties. All soil erosion and SCI values shown in table 8 were calculated as the product of the soil erosion or SCI that occurs on any one particular soil type and the map unit hectares of that soil, summed over all soils of that particular LCC, divided by the sum of the map unit area (hectares) of that LCC. In all examples shown in table 8, soil erosion increased and SCI decreased from LCC II to LCC IV and when the tillage was RT compared to NT. This result was expected, based on the lower "quality" and higher susceptibility to erosion of higher LCC soils (LCC IV versus LCC II) as defined within the LCC system. In some instances, differences in soil erosion loss and SCI trends existed in both the continuous corn (case 1) and continuous wheat (case 2) examples.

For case 1, soil erosion was less in Gray County than in Saline County, with LCC IV exceeding T under residue removal (table 8). This result was at least partly due to the corn yield being much greater in Gray County than in Saline County. Soil erodibility and climate also may have had an effect. The opposite was true in case 2, as the wheat yield was two-thirds greater in Saline County compared to Gray County, but again, other factors such as climate could have impacted this situation. In both counties, 75% of the simulations showed soil loss greater than T and negative SCI for LCC IV under RT. Case 3 involves production of three different crop rotations on LCC VI soils and no residue removal. Again, as in the previous two cases, soil erosion decreased and SCI increased when the tillage changed from RT to NT (table 8). Significant differences in erosion occurred between rotations, especially when RT was used, in which four of six simulations with RT had soil loss greater than T and negative SCI. The effect was much less pronounced for NT, where the SG-FA-WW (sorghum, grain-fallow, winter wheat) rotation in Gray County had total soil loss greater than T but still had a positive SCI. The SG-FA-WW rotation had much higher erosion and smaller SCI values than the continuous corn (CG) and winter wheat (WW) rotations, which demonstrates that rotation and field management practices can make a difference. This particular rotation in Gray County had greater erosion than Saline County, in part due to yield differences in sorghum and wheat. The fallow year also could have been a factor because a continuous crop would have some cover every year, and the cover would probably be less in general during the fallow period.

The results presented in table 8 show pronounced differences between geographic locations within the same cropping rotation produced on the same LCC soil due to climate, yield, timing of operations, and soil characteristics, possibly including field slope and soil susceptibility to erosion forces. These types of observations were found in other locations throughout the six CMZs (data not shown).

Scenario 3: CMZ Scale

Soil erosion and SCI data were aggregated for all soils to a CMZ scale by rotation, LCC, tillage, and whether residue was removed. Table 9 shows aggregated soil erosion and SCI data for five crop rotations in CMZ 40 subject to RT management and residue removal with 2011 and 2030 yields, and table 10 shows erosion and SCI data for six crop rotations in CMZ 24 subject to only 2011 yields and RT and NT management. In table 9, with the exception of the SG-FA-WW rotation, soil erosion decreased and SCI increased from 2011 yields to 2030 yields. This exception is due, at least in part, to the fact that 2030 sorghum yields were predicted to be lower than those in 2011, but the magnitude of erosion was far greater than any other rotation within this particular CMZ. In table 10, for all six crop rotations, soil erosion decreased and SCI increased for NT field management compared to RT.

In a majority of the aggregated data within each of the six CMZs, soil erosion losses tended to increase and the SCI values became more negative as land capability classes progressed from I to VIII, with the exception of LCC V and

Table 8. Selected annual average soil erosion and SCI data from Saline County, Kansas and Gray County, Texas with 2011 yields.

Case 1: Continuous corn (CG) with and without residue removal on two different LCC soils		No Residue Removal		Residue Removal	
		LCC II	LCC IV	LCC II	LCC IV
Saline County, Kansas	Erosion (kg m^{-2})	0.24	0.86	0.33	1.21[a]
	SCI	0.33	0.20	0.13	-0.13
Gray County, Texas	Erosion (kg m^{-2})	0.08	0.31	0.12	0.68
	SCI	0.65	0.48	0.35	0.10

Case 2: Continuous winter wheat (WW) rotation and residue removal with tillage variation		No Residue Removal				Residue Removal			
		Reduced Tillage		No-Till		Reduced Tillage		No-Till	
		LCC II	LCC IV	LCC II	LCC IV	LCC II	LCC IV	LCC II	LCC IV
Saline County, Kansas	Erosion (kg m^{-2})	0.14	0.47	0.02	0.06	0.40	1.32[a]	0.21	0.75
	SCI	0.35	0.31	0.75	0.83	0.05	-0.22	0.39	0.25
Gray County, Texas	Erosion (kg m^{-2})	0.31	2.15[a]	0.04	0.11	0.77	4.02[a]	0.18	0.49
	SCI	0.23	-0.47	0.64	0.57	-0.1	-1.27	0.39	0.25

Case 3: Comparison of three crop rotations on LCC VI and no-till with no residue removal[b]		CG		WW		SG-FA-WW	
		Reduced Tillage	No-Till	Reduced Tillage	No-Till	Reduced Tillage	No-Till
Saline County, Kansas	Erosion (kg m^{-2})	1.34[a]	0.17	0.72	0.09	2.37[a]	0.43
	SCI	-0.07	0.68	0.13	0.71	-0.53	0.38
Gray County, Texas	Erosion (kg m^{-2})	0.40	0.02	1.19[a]	0.18	4.09[a]	1.14[a]
	SCI	0.48	1.01	-0.11	0.56	-1.17	0.08

[a] Values for erosion that are above the NRCS tolerable soil loss limit of 1.12 kg m^{-2} (5 tons acre^{-1}).

[b] CG = corn, grain; FA = fallow; SG = sorghum, grain; WW = winter wheat.

Table 9. Soil average annual erosion (kg m^{-2}) and SCI comparison by land capability class (LCC) for five crop rotations in CMZ 40 under reduced tillage and residue removal with 2011 and 2030 yields.

Crop Rotation[a]		LCC I	LCC II	LCC III	LCC IV	LCC V	LCC VI	LCC VII	LCC VIII
Reduced tillage with residue removal: 2011 yields									
CG	Erosion	2.56	2.75	8.78	16.16	10.34	13.74	20.86	14.87
	SCI	-0.05	0.05	-0.42	-1.04	-0.61	-0.82	-1.40	-0.92
SG-FA-WW	Erosion	8.97	14.50	40.16	70.60	39.84	49.46	62.80	58.77
	SCI	-0.54	-0.94	-2.97	-5.38	-2.97	-3.70	-4.77	-4.46
SG-SB-WW	Erosion	1.92	3.23	7.77	11.99	5.89	13.16	21.73	24.34
	SCI	0.03	-0.03	-0.39	-0.74	-0.27	-0.82	-1.51	-1.72
WW	Erosion	3.78	7.00	20.81	36.10	20.51	23.93	34.44	32.69
	SCI	-0.14	-0.35	-1.44	-2.67	-1.46	-1.70	-2.54	-2.44
WW-WW-CA	Erosion	4.72	8.87	26.53	46.55	25.81	32.54	40.43	37.16
	SCI	-0.15	-0.45	-1.85	-3.44	-1.81	-2.32	-2.95	-2.71
Reduced tillage with residue removal: 2030 yields									
CG	Erosion	1.04	1.37	3.27	4.87	2.12	5.72	10.66	11.41
	SCI	0.18	0.27	0.15	-0.02	0.17	-0.05	-0.46	-0.57
SG-FA-WW	Erosion	8.97	15.25	41.04	70.63	38.95	51.36	62.83	66.66
	SCI	-0.54	-1.01	-3.04	-5.38	-2.89	-3.85	-4.77	-5.08
SG-SB-WW	Erosion	1.75	2.99	6.76	10.08	4.52	12.12	20.04	22.89
	SCI	0.05	0.00	-0.30	-0.58	-0.16	-0.73	-1.36	-1.59
WW	Erosion	3.29	6.84	17.84	28.66	13.39	19.38	26.38	26.54
	SCI	-0.09	-0.33	-1.19	-2.07	-0.88	-1.32	-1.89	-1.93
WW-WW-CA	Erosion	1.95	3.82	9.13	14.30	7.31	12.72	19.07	19.68
	SCI	0.20	0.09	-0.33	-0.76	-0.22	-0.62	-1.12	-1.18

[a] CA = canola; CG = corn, grain; FA= fallow; SB= soybeans; SG= sorghum, grain; WW= winter wheat.

Table 10. Soil average annual erosion (kg m^{-2}) and SCI comparison by land capability class (LCC) for six crop rotations in CMZ 24 under reduced tillage and no till with residue removal and 2011 yields.

Crop Rotation[a]		LCC I	LCC II	LCC III	LCC IV	LCC V	LCC VI	LCC VII	LCC VIII
Reduced tillage with residue removal: 2011 yields									
CG	Erosion	1.01	1.61	3.66	4.69	0.99	8.07	14.98	0.38
	SCI	0.23	0.15	0.00	-0.07	0.17	-0.35	-0.89	0.45
CG-SB	Erosion	1.50	2.46	5.36	6.97	1.67	11.33	19.49	1.19
	SCI	0.08	-0.02	-0.24	-0.36	0.02	-0.71	-1.34	0.24
SG-FA-WW	Erosion	6.46	7.98	13.27	18.48	7.47	26.33	44.11	26.75
	SCI	-0.30	-0.41	-0.82	-1.22	-0.38	-1.85	-3.24	-1.85
SG-SB-WW	Erosion	1.76	2.60	5.66	7.45	1.90	12.15	20.64	4.04
	SCI	0.02	-0.04	-0.27	-0.40	0.01	-0.79	-1.44	-0.08
WW	Erosion	2.00	2.18	4.78	6.49	1.64	11.82	18.14	8.54
	SCI	0.06	0.06	-0.14	-0.26	0.09	-0.69	-1.18	-0.38
WW-WW-CA	Erosion	8.11	7.97	11.85	16.90	7.46	23.19	34.83	31.01
	SCI	-0.39	-0.37	-0.67	-1.05	-0.34	-1.56	-2.47	-2.13
No-till with residue removal: 2011 yields									
CG	Erosion	0.43	0.67	1.49	1.91	0.44	3.50	6.93	0.13
	SCI	0.58	0.52	0.47	0.45	0.51	0.30	0.04	0.77
CG-SB	Erosion	0.76	1.18	2.69	3.47	0.70	6.18	11.11	0.26
	SCI	0.43	0.37	0.26	0.21	0.39	-0.01	-0.39	0.61
SG-FA-WW	Erosion	6.10	7.28	10.69	14.39	8.45	20.72	34.82	20.85
	SCI	-0.08	-0.16	-0.43	-0.71	-0.26	-1.22	-2.32	-1.19
SG-SB-WW	Erosion	0.64	0.90	2.02	2.57	0.54	4.75	8.89	0.27
	SCI	0.41	0.39	0.31	0.28	0.41	0.09	-0.22	0.51
WW	Erosion	0.74	1.02	2.28	2.88	0.60	5.35	10.39	0.34
	SCI	0.42	0.42	0.32	0.29	0.44	0.08	-0.31	0.52
WW-WW-CA	Erosion	0.89	1.15	2.54	3.30	0.85	5.70	10.41	2.21
	SCI	0.42	0.41	0.31	0.26	0.42	0.06	-0.31	0.37

[a] CA = canola; CG = corn, grain; FA= fallow; SB= soybeans; SG= sorghum, grain; WW= winter wheat.

VIII soils (data not shown). LCC V and VIII generally did not follow this trend because these LCCs are limited by high rock content or are subject to being wet, which limits wind and water erosion losses (they also have other limitations to productivity). In addition, a common trend of less erosion and greater SCI values was observed when yields increased from 2011 to 2030 and when the tillage went from RT to NT within a crop rotation. It should be noted that these aggregated data are intended to show only how individual rotations may interact with soils, climate, and topography across an entire CMZ. As observed for scenarios 1 and 2, much fluctuation can exist between individual soil types within a CMZ for the same rotation, and different crop rotations affect erosion and SCI on the same soil type.

Removable Residues

Table 11 presents the potential range of removable residue quantities (kg ha^{-1}) at harvest within each of the six CMZs by commodity or bioenergy crop for 2011 and 2030. These quantities are intended to provide insight that could factor into the economics of including the bioenergy crops in rotational choices. The values show residue that could be

Table 11. Single-year and average annual (AA) minimum and maximum removable residue (kg ha^{-1}) by commodity and bioenergy crop.[a]

CMZ	Year	CG Min.	CG Max.	SG Min.	SG Max.	WW Min.	WW Max.	AA Min.	AA Max.
5	2011	1,846	6,651	1,915	3,823	1,775	4,327	1,846	6,655
	2030	2,224	8,536	1,319	3,629	2,190	6,203	2,226	8,540
15	2011	1,803	7,844	2,065	4,856	1,545	6,131	1,107	7,850
	2030	2,661	9,339	1,835	6,061	2,446	7,966	1,300	9,343
19	2011	3,447	7,353	1,850	4,291	1,545	5,218	515	6,936
	2030	5,294	8,790	2,118	4,911	1,773	6,307	706	8,462
24	2011	2,028	6,189	2,621	3,965	1,996	4,817	1,015	6,193
	2030	2,527	7,636	2,224	4,020	2,182	4,625	1,263	7,641
40	2011	1,982	6,769	2,184	4,390	1,521	3,649	1,131	6,773
	2030	3,368	8,407	2,117	4,384	1,791	3,828	1,272	8,411
48	2011	-[b]	-	-	-	1,167	2,597	431	2,604
	2030	-	-	-	-	1,236	3,854	493	3,866

[a] CG = corn, grain; SG = sorghum, grain; WW = winter wheat.

[b] No CG and SG data were available for CMZ 48 as these crops were not in the candidate rotations.

removed from any one specific agricultural field within a particular CMZ, subject to limitations that when residue is removed the average annual soil loss was less than or equal to T and the SCI was greater than or equal to zero. Other cases occurred in which residue was removed but the soil loss was greater than T and/or the SCI value was negative; these amounts were not counted in table 11.

Two sets of removable residue quantities are shown in table 11: one for the minimum and maximum amounts that occurred in any one single rotation year across all soil types within each CMZ, and the other set is the average annual minimum and maximum amount over a three-year rotation period within that CMZ. For example in CMZ 40, for any one of the four rotations containing winter wheat (table 2), in 2030, the minimum removable wheat straw quantity was estimated to be 1,791 kg ha^{-1} and the maximum was 3,828 kg ha^{-1} subject to soil erosion less than or equal to T and SCI greater than or equal to zero (table 11). Average annual residue amounts within a CMZ for any rotation on any soil type were the sum of all sustainably available residues on that soil type across the three-year period divided by 3. The minimum and maximum values were the minimum and maximum of all values across all rotations in that CMZ. For example, the average annual values of 1,272 and 8,411 kg ha^{-1} in CMZ 40 reflect the respective minimum and maximum removable residue amounts from corn, sorghum, or winter wheat that could possibly occur annually over the three-year period.

SUMMARY AND CONCLUSIONS

This analysis was performed at three different spatial scales: field scale (individual soil type), county scale, and CMZ scale. Average annual changes in rainfall and wind induced soil erosion and SOM (proxied by SCI) were simulated for over 140 different conventional and bioenergy-related cropping scenarios and field management practices (tillage and residue removal) on LCC I to VIII soils in selected areas of the U.S. Central Great Plains (CGP). The RUSLE2 and WEPS models performed all simulations for soil erosion, and SCI trends were calculated within WEPS and RUSLE2 as a measure of soil quality. Crop rotations comprised combinations of corn, winter wheat, sorghum, cotton, canola, and fallow with two separate sets of crop yields: one for 2011 and one projected to 2030. Tillage practices consisted of reduced tillage and no-till scenarios, and residue removal for corn/sorghum stover and wheat straw was based on current commercially available equipment with a residue collection rate of 50%. Soil erosion values varied from under 0.224 kg m^{-2} (1 ton acre^{-1}) to considerably greater than the tolerable soil loss, and SCI values had a wide range above and below zero. Throughout all CMZs, rotations, and field management practices, variation in soil erosion and SCI existed across all LCC I to VIII soils at the field scale depending on crops, rotation, tillage, and yields.

The analysis in this study provided a wider breadth of crops and rotational combinations than earlier studies; however, all analyses showed considerable variation in removable residue amounts across different rotations, especially with respect to the various tillage operations, and were comparable to results of earlier studies. The following general conclusions can be made concerning the estimates of soil erosion losses and SCI trends obtained in this study:

- Soil erosion and changes in SCI are strong functions of crop rotation, soil type (e.g., LCC), and tillage operations used, such as field cultivation, disking, etc. Differences exist across different soil types in a single county and across all counties within a CMZ.
- Crop rotation made a difference in the magnitude of soil erosion and SCI trends, both on individual soil types and across a county. Rotations with low-residue crops (e.g., canola and cotton) had soil erosion greater than T and negative SCI, whereas crops grown in continuous rotation (i.e., corn and, to a lesser extent, winter wheat) exhibited soil erosion less than T.
- Soil erosion was greater when the RT scenario was employed versus the NT scenario.
- Soil erosion losses and SCI increased and decreased, respectively, as LCC increased, with the general exception of LCC V because its limitations (rock and flooding) resist erosion.
- Soil erosion increased and SCI decreased as a function of residue removal because less residue is available during certain periods of a rotational cycle to protect the ground from rainfall impact, runoff, and wind forces. Corn and sorghum stover, as well as winter wheat straw, could potentially be removed in

selected regions of the study area while maintaining soil erosion limits below the tolerable loss limit T and positive SCI trends.

A strength of this study is that it provides a detailed evaluation of soil erosion from rainfall and wind as well as SCI on all LCC soils in the CGP. A practical limitation of this study is that it was strictly simulation based; however, every effort was made to ensure accuracy of all cropping scenarios, field management operations and timing, and reasonable yields used in the simulations in order to accurately reflect what may actually happen on a field-by-field basis within a CMZ. Both RUSLE2 and WEPS are nationally accepted tools by which researchers, government agencies, etc., are able to assess erosion impacts related to a number of potential crop production scenarios. Furthermore, both models have been shown (through extensive validation studies in the literature) to reasonably (although not perfectly) predict real-world conditions for the output responses analyzed in this study. In addition, because only a single crop residue harvest scenario was used, the analysis did not take into consideration other field management practices that might be prevalent; furthermore, the analysis assumed the crop rotations would be the same in 2030, as would residue-to-yield ratios.

Results obtained in this study should help advance the overall knowledge base of both public and private-focused commodity and bioenergy crop production agriculture and soil sustainability by providing small informational resolution (i.e., soil type) data on soil erosion and health trends that could have a pronounced effect on producer economics and long-term land sustainability. For erosion and SCI estimates on specific crops, soils, management practices, and locations, it is recommended that the WEPS and RUSLE2 models be run for site-specific results. Future research might include field verification of the results obtained herein, an evaluation of dedicated herbaceous energy crops such as a mixed prairie grasses or sweet/photoperiod sorghums, and investigating the optimization of removable residue amounts on individual soil types while keeping erosion at or below T and SCI positive or neutral.

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