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Sustainable agricultural residue removal for bioenergy: A spatially comprehensive US national assessment

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HIGHLIGHTS

- ▶ We perform an assessment of US agricultural residue availability for bioenergy.
- ▶ The assessment considers multiple sustainability factors using an integrated model.
- ▶ The study is spatially comprehensive for the US at an analysis scale of 10–100 m.
- ▶ More than 150 million metric tons of residue were sustainably available in 2011.
- ▶ More than 207 million metric tons of available residue are projected in 2030.

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ABSTRACT

This study provides a spatially comprehensive assessment of sustainable agricultural residue removal potential across the United States for bioenergy production. Earlier assessments determining the quantity of agricultural residue that could be sustainably removed for bioenergy production at the regional and national scale faced a number of computational limitations. These limitations included the number of environmental factors, the number of land management scenarios, and the spatial fidelity and spatial extent of the assessment. This study utilizes integrated multi-factor environmental process modeling and high fidelity land use datasets to perform the sustainable agricultural residue removal assessment. Soil type represents the base spatial unit for this study and is modeled using a national soil survey database at the 10–100 m scale. Current crop rotation practices are identified by processing land cover data available from the USDA National Agricultural Statistics Service Cropland Data Layer database. Land management and residue removal scenarios are identified for each unique crop rotation and crop management zone. Estimates of county averages and state totals of sustainably available agricultural residues are provided. The results of the assessment show that in 2011 over 150 million metric tons of agricultural residues could have been sustainably removed across the United States. Projecting crop yields and land management practices to 2030, the assessment determines that over 207 million metric tons of agricultural residues will be able to be sustainably removed for bioenergy production at that time. This biomass resource has the potential for producing over 68 billion liters of cellulosic biofuels.

1. Introduction

Biomass is being investigated and developed around the world as a potential low carbon, renewable energy source. National and continental renewable energy strategies are being investigated to utilize the range of biomass resources available [1–5], establish the energy conversion technologies that are most appropriate for the available biomass resources [6–8], and understand how global bioenergy markets may impact local food, feed, and fiber production [9]. As a part of this worldwide effort the US federal government has established goals for biofuel production through the Energy Independence and Security Act of 2007 [10]. The law specifically calls for US biofuel production of liquid transportation fuels to increase to more than 136 billion liters annually by 2022, with approximately 56 billion liters coming from non-cornstarch feedstocks. Assuming a conversion rate of 330 l of biofuel per metric ton for cellulosic feedstock [11,12], meeting this target will require at least 240 million metric tons of biomass resources. A number of research efforts have examined cellulosic bioenergy feedstocks such as switchgrass, miscanthus, energycane, energy sorghum,

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willow, hybrid poplar, forest residues, and agricultural residues, and the conversion technologies that can utilize these feedstocks [13–17]. Of these feedstocks, the resource with the greatest near term potential (1–5 years) for achieving national targets is agricultural residues [18].

Identifying a sustainable and reliable agricultural residue resource base has been a significant challenge for the emerging cellulosic biofuels industry [19]. Agricultural residue removal must be managed carefully to be sustainable, and spatial and temporal variability (soil, climate, and management practices) impact the reliability of the supply. Residues play a number of critical roles within an agronomic system including direct and indirect impacts on physical, chemical, and biological processes within the soil [19–22]. Excessive residue removal can degrade the long term productive capacity of soil resources [23,24]. The large capital investments required for cellulosic biorefineries (>$100 M) require knowledge of the agricultural residue resource base that is locally available to support a facility. This includes not only regional and national scale perspectives, but also local, subfield scale spatial and temporal impacts on potential residue removal. Furthermore, the analyses must lead to residue removal rates that will be certified as sustainable by the Natural Resource Conservation Service (NRCS) of the US Department of Agriculture (USDA) conservation management planning process.

To address this need for a robust national assessment of sustainably available agricultural residues built upon local soil, climate, and land management data, this study utilizes an integrated modeling strategy to perform a multi-factor assessment of sustainably available agricultural residues across the United States. This integrated assessment utilizes the models and data currently used by the NRCS to administer agricultural land management policy. This novel approach integrates the environmental process models and associated databases required to determine the impact of residue removal. Specifically, this study is performed at the Soil Survey Geographic (SSURGO) Database [25] soil type scale and is then aggregated to county-level projections using USDA Cropland Data Layer data [26]. This integration of models and data results in three new contributions to the discussion of large spatial scale sustainable agricultural residue removal for the United States. These are a complete national scale assessment that (1) considers soil organic matter impacts of residue removal, (2) incorporates remotely sensed crop rotation data, and (3) connects NRCS conservation management planning methods with national scale residue availability projections. The data produced through this study is consistent with the guidance of sustainable agricultural land management practices as administered by the farm bill and the NRCS. Based on this, the results of this integrated assessment are data and analyses that can support cellulosic biorefinery decisions utilizing agricultural residues as the primary sources.

The paper is structured to first review the earlier regional and national scale sustainable agricultural residue removal studies. This review focuses on the limiting environmental factors considered, the spatial and temporal scale assumptions, and the modeling methodologies. The integrated modeling methodology used for this study is then presented, focusing on the key data sources, scenarios, and assumptions used for the assessment. Lastly, the results of the study are provided showing the projected sustainably available residue at the county, state, and national scales. Key conclusions from the results are discussed.

1.1. Background

One of the key challenges associated with identifying the availability of agricultural residues is accounting for the many important roles that residues play in the agronomic system. Wilhelm et al. [19] performed an extensive review of sustainability indicators for agricultural residue removal. The result of this review was the identification of six environmental factors that potentially limit agricultural residue removal—soil erosion from wind and water; soil organic carbon; plant nutrient balances; soil, water, and temperature dynamics; soil compaction; and off-site environmental impacts. From their review Wilhelm et al. also determined that no model or methods were available that could comprehensively consider the range of factors that potentially limit agricultural residue removal.

Several previous efforts have considered a subset of Wilhelm et al.'s six limiting factors (Table 1) in projecting regional or national sustainable residue availability. The first large spatial scale study of agricultural residue availability was published by Larson [27]. He estimated that approximately 49 million metric tons of crop residues could be sustainably harvested at that time in the Corn Belt, Great Plains, and Southeast regions of the United States. The focus of this study was on limiting erosion below tolerable soil loss limits, and the calculations were performed utilizing the Universal Soil Loss Equation (USLE) [28]. The study investigated the effect of tillage practices on the potential of residue removal and considered the impacts of nutrient removal. At that time using the USLE required significant spatial aggregation of soil characteristics, land management practices, and crop yields to reduce the number of calculations. Because of this requirement, this study provided regional scale projections of residue availability, but could not provide local sustainable removal projections. In addition, Larson's study did not consider the relationship between residue removal and soil organic carbon.

As a result of low oil prices and generally decreased interest in bioenergy development in the United States, the next large-scale assessment of agricultural residue availability was presented more than two decades later by Nelson [29]. This was the first of a series of assessments focused on residue removal within the context of residue retention requirements. The approach for these assessments was to assemble a limited set of representative crops, rotations, and field management scenarios; apply them to selected soils; and then utilize the Revised Universal Soil Loss Equation (RUSLE) [30] and the Wind Erosion Equation (WEQ) [31] to generate residue retention requirements to limit rainfall and wind erosion below tolerable loss limits. The yield needed at the time of harvest was then correlated to an average county-level yield to determine the possible quantity of available residues at the county scale. This methodology was applied to 37 states from the Great Plains to the East Coast for the period of 1995–1997. This study determined that over 50 million metric tons of corn stover and wheat straw were potentially available annually for removal over this time span. Soil organic carbon was not considered in this study. The ability to determine residue availability at the county scale provided a significant step forward in generating data that could support bioenergy industry decisions. However, this study was computationally limited in the number of scenarios that could be investigated, and consequently, it was not able to consider the variability in soil characteristics and management practices that are typically found within a single county. These local (10–100 m) considerations are important for certifying sustainable removal practices within NRCS conservation management planning guidelines, thus ensuring reliable biomass supplies for biorefiners.

Sheehan et al. [23] applied the methodology developed by Nelson [29] to a life cycle assessment of corn stover to produce ethanol. This study focused on providing a stover-to-ethanol system level analysis including collection, transport, and conversion for the state of Iowa. Nelson's methodology [29] was extended by including the CENTURY agro-ecosystem model [32,33] to quantitatively assess the impact on soil carbon from residue removal. The scale of the calculations was at the county level, consistent with

Table 1
Environmental limiting factors and primary characteristics and assumptions for large geographic scale crop residue sustainability studies.

Reference year limiting factors	Previous studies								Current study
	[27]	[29]	[23]	[34]	[36]	[37]	[38]	[40]	
	1979	2002	2003	2004	2005	2007	2010	2012	
Soil erosion	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Soil organic carbon	No	No	Yes	No	No	No	Yes	Yes	Yes
Plant nutrient balances	No	No	No	No	Yes	Yes	No	No	No
Soil water and temperature	No	No	No	No	No	Yes	Yes	Yes	Yes
Soil compaction	No	No	No	No	No	No	No	No	No
Off-site environmental impacts	No	No	No	No	No	No	No	No	No
Spatial extent	Corn Belt, Great Plains, Southeast	37 States	Iowa	10 States	US	US	16 Counties	Iowa	US
Analysis year	1975	1997	1997	2001	2005–2040	2000	2010–2110	2010	2011 and 2030
Calculation scale	MLRA	County	County	Soil Type	County	Soil Type	Soil Type	Soil Type	Soil Type
Number of crop rotations included	N/A	3	1	6	6	2	4	5	915
Residue crops included	Corn, Wheat	Corn, Wheat	Corn	Corn, Wheat	Corn, Wheat, Barley, Sorghum	Corn	Corn, Wheat, Cotton	Corn, Wheat	Corn, Wheat, Barley, Sorghum, Rice

Nelson's methodology [29], and it was assumed that all land would shift to continuous corn crop rotation and no-till management practices. These assumptions, along with implementation at the county scale, were due to the computational limitations on the number of scenarios that could be investigated with the analysis tools being used. Residue removal was established using Nelson's erosion methodology [29], and the 0, 5, 10, 15, 20, and 90 year soil carbon values at the county-level removal rates were calculated. From this Sheehan et al. [23] found that for the scenarios investigated, limiting soil erosion to less than the tolerable limits maintained soil organic matter. This study provided a life cycle perspective on producing ethanol using corn stover in Iowa. However, the county-level spatial fidelity and the limited number of production scenarios investigated do not provide sufficient detail for decision makers in the cellulosic bioenergy industry.

In 2004, Nelson et al. [34] introduced an updated methodology that calculated the requirements for residue retention at the SSURGO soil type scale (10–100 m). The updated methodology was applied to the top 10 corn producing states in the United States based on total production from 1997 to 2001. SSURGO soils with land capability classes from 1 to 8 [35] were investigated. The RUSLE and WEQ computational approach from Nelson's [29] study was applied at the soil type scale rather than using county-level aggregation. Nelson [34] used the updated methodology to investigate a broader set of crop rotations and tillage scenarios. For each soil type–crop rotation–tillage combination, the residue retention requirement for limiting water and wind erosion losses to below tolerable limits was identified. Following this, additional residues above the retention requirement were identified as available for removal based on actual crop yields. Soil organic carbon and general soil tilth were not considered. This study concluded that if continuous corn, reduced tillage management practices were adopted for all cropland acres in each of the ten states that more than 430 million dry metric tons of corn stover would be sustainably available from 1997 to 2001. The study also determined that if all cropland acres in each of the ten states were managed with a corn–winter wheat rotation using reduced tillage practices that more than 241 million dry metric tons of wheat straw would be sustainably available from 1997 to 2001. Nelson et al.'s methodology [34] advanced the analysis of sustainable residue availability by investigating scenarios at the SSURGO soil map unit scale. Calculations at the soil map unit scale provide useful insight for decisions about residue removal in individual fields and can be directly applicable within the NRCS conservation management planning process. However, the study investigated a limited set of environmental factors, land management scenarios, and areas in the United States.

Perlack et al. [36] implemented Nelson et al.'s methodology [34] within a broader economic analysis framework for a study outlining the path to a billion-ton annual biomass supply in the United States. The methodology was applied across the United States for a limited set of crop rotation and tillage scenarios. This approach only considered erosion constraints. This study concluded that nearly 176 million metric tons of agricultural residues were available annually. The study projected that within 35–40 years over 400 million metric tons of agricultural residues could potentially be available annually under specific tillage and yield increase assumptions. The results of Perlack et al.'s study [36] were challenged within the soil science and agronomy communities for

Table 2
The key data sources and models used here are identified with the method for public access to the data or model.

Data input	Database	Access
Soils	SSURGO	NRCS NASIS Server (http://soils.usda.gov/technical/nasis/)
RUSLE2 climate	RUSLE2 native.gdb format	http://fargo.nserl.purdue.edu/rusle2_dataweb/RUSLE2_Index.htm
WEPS climate	CLIGEN	http://www.ars.usda.gov/Research/docs.htm?docid=18094
Wind	WINDGEN	http://www.weru.ksu.edu/
Land management	NRCS native.gdb format	http://fargo.nserl.purdue.edu/rusle2_dataweb/RUSLE2_Index.htm
Crop yields	NASS	http://www.nass.usda.gov/
Modeling function	Model	Access
Water erosion/SCI	RUSLE2	http://fargo.nserl.purdue.edu/rusle2_dataweb/RUSLE2_Index.htm
Wind erosion/SCI	WEPS	http://www.weru.ksu.edu/weps/wepshome.html
Integration framework	VE-Suite	http://www.vesuite.org

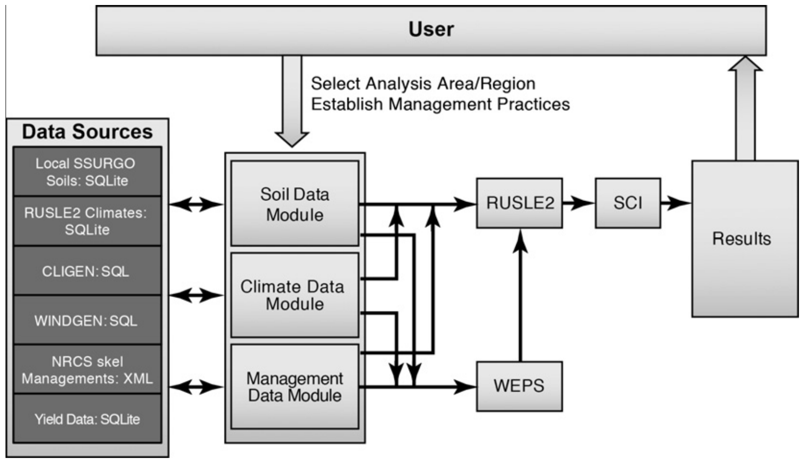


Fig. 1. The integrated model utilized for this assessment (Muth and Bryden [40]).

not considering a broader set of limiting factors, specifically soil organic carbon [19,22]. The argument was made that when soil organic carbon constraints are considered, there would be less residue sustainably available than the quantities identified by Perlack et al. [36]. In spite of these objections, by establishing a roadmap to biomass resource production at levels that could support large-scale cellulosic biofuels production, Perlack et al. provided a key dataset for an emerging biorefining industry.

A study by Graham et al. [37] examined corn stover availability and built upon Nelson et al.'s methodology [34] by disqualifying non-irrigated corn production in arid climates on the basis that stover would be required on the soil surface to conserve soil moisture. Considering soil erosion and the assumed soil moisture constraint, this study estimated that 58.3 million metric tons of stover could be sustainably removed annually. The study noted the importance of considering soil organic carbon, but identified the computational limitations of the available tools. Specifically, Graham et al. stated that "in its current form with manual input, the Soil Conditioning Index is not practical to run for the thousands of corn production situations that occur in the USA" [37].

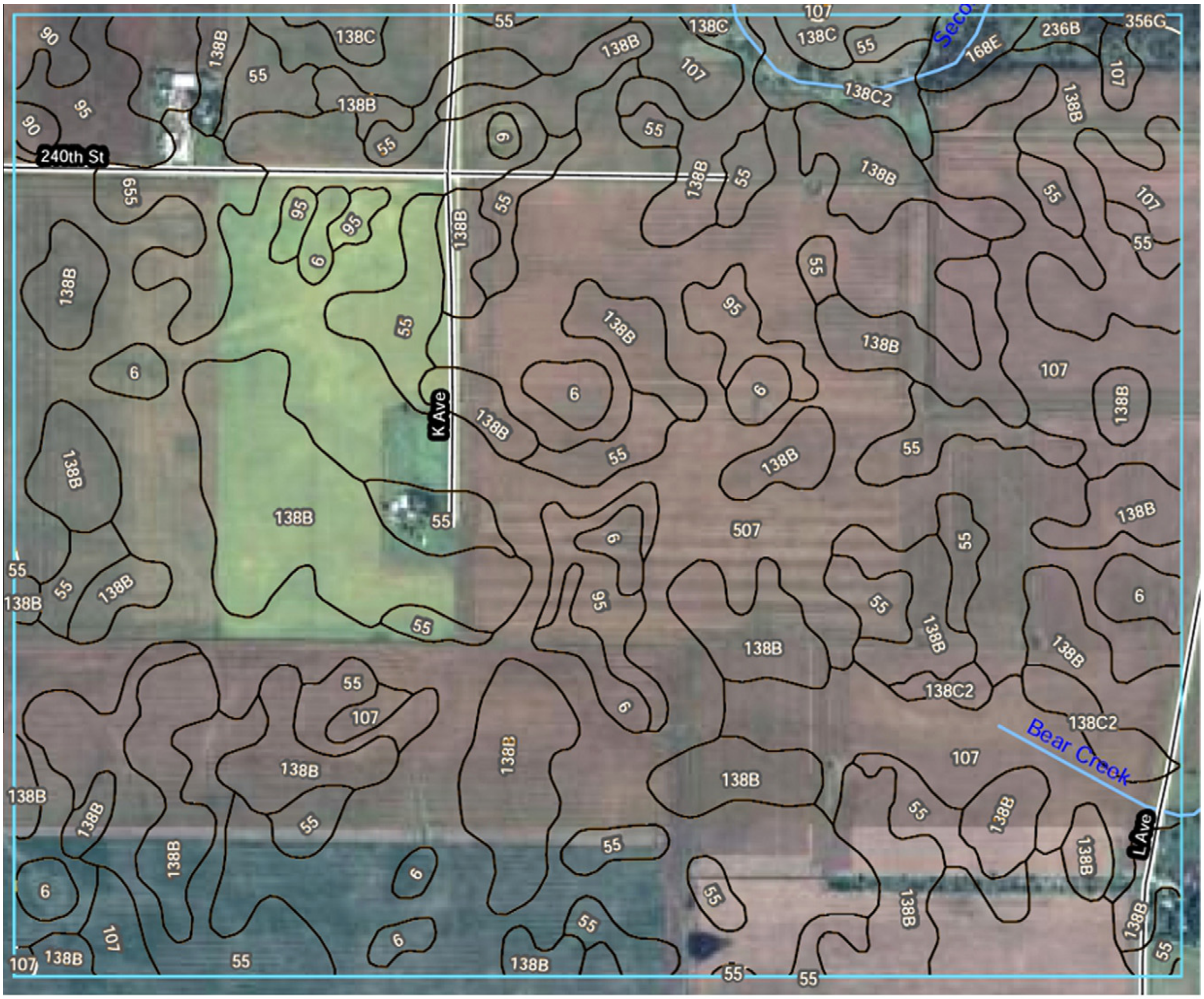
Gregg and Izaurralde [38] designed a factorial modeling study to investigate soil erosion, crop yield, soil carbon, and nitrogen balance impacts of residue harvest. The Erosion Productivity Impact Calculator/Interactive Environment Policy Integrated Climate (EPIC) model [39] was employed for this study. This analysis addressed the computational limitations of the existing modeling tools in a similar way to the studies discussed previously, that is, by selecting a subset of representative scenarios to determine a broadly applicable sustainable removal rate. Gregg and Izaurralde [38] investigated a greater number of limiting factors than previous studies, but were only able to look at four crop rotations in sixteen counties across the entire country. The conclusions of Gregg and Izaurralde [38] were that a 30% residue removal assumption will typically be sustainable; and for flat, highly productive land, removal rates could be higher. This provided a useful perspective on a broad set of factors that potentially limit agricultural residue removal and provided the research community with an analysis toolset differing from previous studies. However, the results from this study were of limited value to cellulosic bioenergy decision makers in terms of identifying a spatially explicit, sustainable, and reliable resource base, and in providing confidence to growers that NRCS conservation management planning certification would be attained.

Muth and Bryden [40] developed an integrated modeling approach that addressed a number of the challenges from previous studies. A model and data integration framework [41] was used to build an integrated model that enables the investigation of the full range of soil characteristics, climate conditions, crop rotations, and land management practices. This approach enabled large numbers of scenarios to be investigated computationally, thus enabling analyses across a full range of spatial scales from field scale to a national assessment. Integrating NRCS models and data to calculate soil erosion from wind and water, and the impact of residue removal decisions on soil organic carbon, this study evaluated potential residue removal scenarios across the state of Iowa. The study was performed with SSURGO soil map units as the base spatial units and included representative crop rotations, tillage management practices, and crop yields at the county level for the state of Iowa. Five commercially available residue removal configurations were modeled to provide a range of potential removal rates. Over five million scenarios were calculated in the study to represent residue removal in the state of Iowa. The conclusion was that for yield and management practices at that time, the state could sustainably provide nearly 26.5 million metric tons of residues annually.

2. Materials and methods

This paper presents an assessment of sustainably removable agricultural residues across the conterminous United States for bioenergy production. Soil erosion from wind and water, and soil organic carbon sustainability factors were considered in the assessment through the implementation of the integrated multi-model computation framework presented in Muth and Bryden [40]. The assessment includes two yield scenarios, 2011 projected yields, and 2030 projected yields. The integrated model is built around the computational methodologies used for NRCS conservation management planning, which is the mechanism used by the USDA to ensure sustainable agricultural land management. There are several advantages for utilizing this approach. The models and datasets, presented in Table 2, are well defined, tested, and validated. The validated models are used directly without alteration. Substantial investment has been made developing and validating these models. Using these models without revision, seamlessly preserves and leverages that investment. Another key advantage of adopting this approach is that the data produced in the analysis can be used to make decisions about residue removal with confidence that the USDA will deem the removal rates to be sustainable.

The models used in the integrated model are the Revised Universal Soil Loss Equation 2 (RUSLE2) [42], the Wind Erosion Prediction System (WEPS) [43], and the Soil Conditioning Index (SCI)



Boone County, Iowa (IA015)			
Map Unit Symbol	Map Unit Name	Hectares In Area of Interest	Percent of Area of Interest
6	Okoboji silty clay loam, 0 to 1 percent slopes	10.2	3.1%
55	Nicollet loam, 1 to 3 percent slopes	44.1	13.4%
90	Okoboji mucky silt loam, 0 to 1 percent slopes	1.8	0.5%
95	Harps loam, 0 to 2 percent slopes	10.2	3.1%
107	Webster silty clay loam, 0 to 2 percent slopes	28.0	8.5%
138B	Clarion loam, 2 to 5 percent slopes	93.8	28.4%
138C	Clarion loam, 5 to 9 percent slopes	2.1	0.6%
138C2	Clarion loam, 5 to 9 percent slopes, moderately eroded	5.9	1.8%
168E	Hayden loam, 14 to 18 percent slopes	1.7	0.5%
236B	Lester loam, 2 to 5 percent slopes	0.7	0.2%
356G	Hayden-Storden loams, 25 to 50 percent slopes	0.3	0.1%
507	Canisteo silty clay loam, 0 to 2 percent slopes	126.6	38.3%
655	Crippin loam, 1 to 3 percent slopes	4.7	1.4%
Totals for Area of Interest		330.3	100%

Fig. 2. SSURGO map units in an approximately 330 hectare area in Boone County, IA. The width and height of the figure is slightly greater than 1.8 km [25].

[44]. RUSLE2 simulates daily changes in conditions including water and temperature dynamics within the soil to quantify the impacts of water erosion processes. It has been applied to a wide range of land management scenarios including cropland, pastureland, rangeland, and disturbed forestland [45–48]. WEPS is a process-based daily time-step model that simulates how field conditions including soil water and temperature interact with wind forces including direction and magnitude. WEPS models a three-dimensional region to resolve mass balance equations and projects wind erosion impacts. WEPS has been used for cropland scenarios [49], including previous studies for evaluating the impacts of corn stover removal [22]. The SCI utilizes parameters contributed by RUSLE2

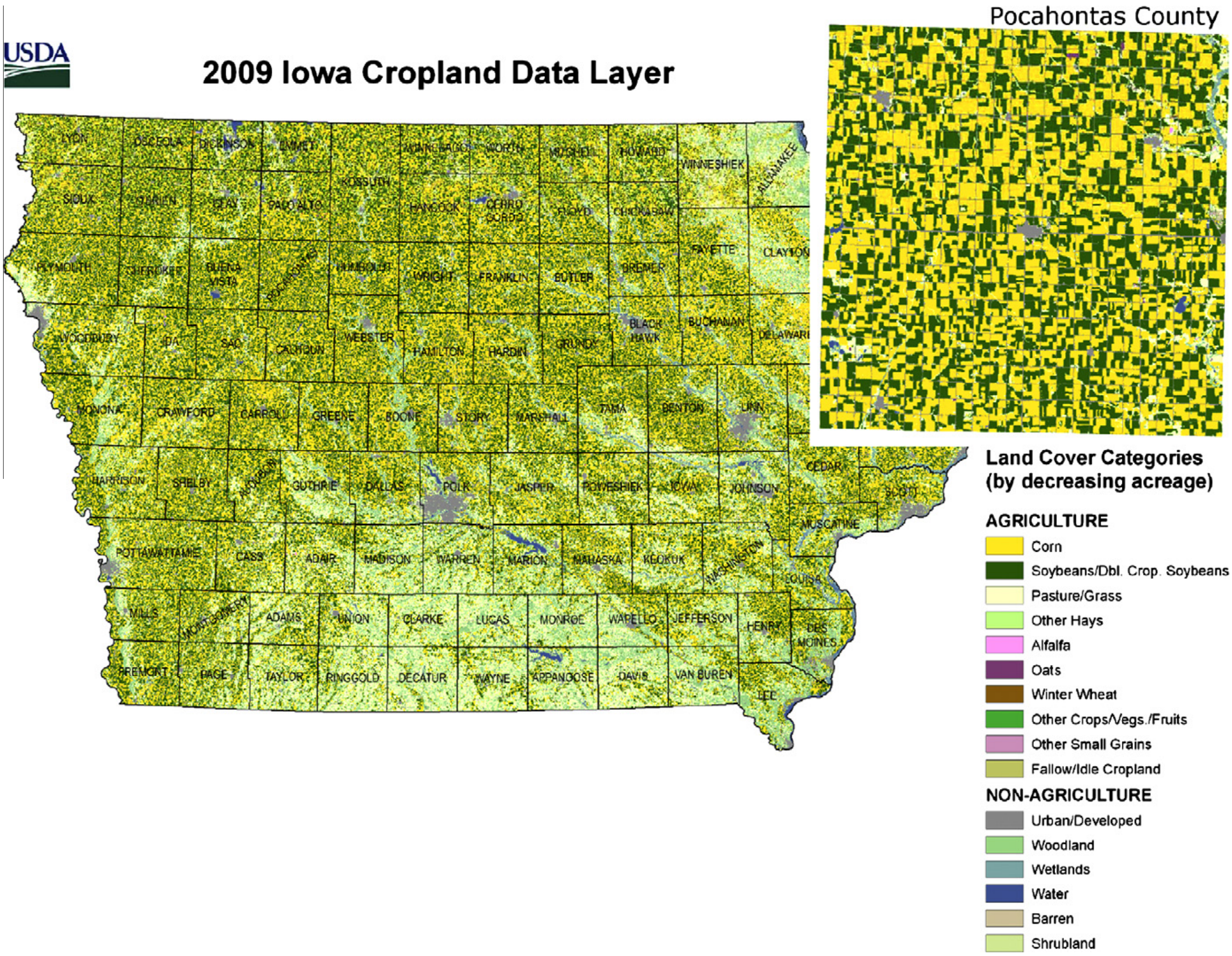


Fig. 3. CDL data representing land use in Iowa and in Pocahontas County for 2009.

and WEPS to provide qualitative predictions of the impact of land management practices on soil organic carbon. The SCI has been used for a broad range of soil quality assessments [50–52]. Fig. 1 provides a flow diagram of the computational methodology used to make each of the three models run within an integrated framework. By using a model integration framework, this methodology enables these models to be run over the large number of scenarios required to represent agricultural residue production in the US. Muth and Bryden [40] provides the technical details of the integrated methodology. The integrated model in Fig. 1 is executed for all scenarios where residue-producing crops are grown in the conterminous United States. The following sections describe these scenarios.

2.1. Soil data

The SSURGO soil survey database provides the soil data used in the assessment. The SSURGO soil map units typically represent spatial discretization in the 10–100 m scale and are the base spatial elements for this assessment. Fig. 2 shows SSURGO map unit spatial data from a 330 ha area in central Boone County, Iowa. The SSURGO data used in this study is a snapshot of the USDA managed server from April 8th, 2011. The SSURGO snapshot is used in a locally managed SQLite database. This choice was made because network or server interruptions would have represented a significant challenge considering the total number of SSURGO queries required for the analysis (nearly 600,000). Muth and Bryden [40] describe in detail the data flow from the SSURGO database into the integrated model. This includes a description of the specific queries, data tables, and soil characteristics used for each individual model. The SSURGO soil database includes soils covering agricultural and non-agricultural land. Land capability class ratings range from 1 to 8. The soils considered in this study have SSURGO land capability class ratings of 1 through 4, which are the classes considered most suitable for agricultural production. In addition, SSURGO soils with less than 405 ha in each county were not considered. Within the area in Fig. 2, four of the thirteen soils account for nearly 90% of the area. This relationship is common for entire counties. The choice to only consider soils that represent areas greater than 405 ha within a county reduces the computational time required for this national scale study by over 70%, but still accounts for more than 90% of the agricultural lands.

2.2. Climate data

Three data sources are used to provide the required climate data for this assessment: the NRCS managed RUSLE2 climate databases, the CLIGEN daily climate generator, and the WINDGEN daily wind speed and direction generator. The integrated model identifies the county location of the SSURGO map unit for a model scenario and loads the required RUSLE2 climate data from the NRCS assembled dataset. The WEPS model requires input from

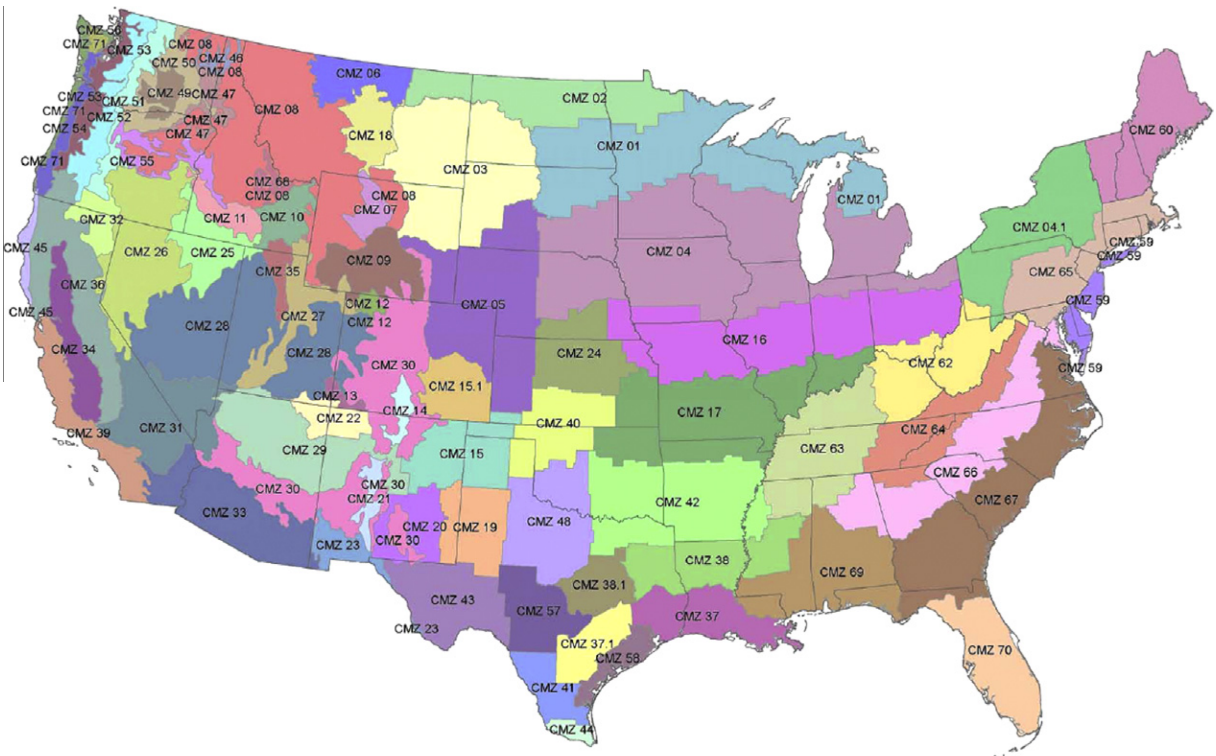


Fig. 4. NRCS designated crop management zones [18].

the two climate generator models CLIGEN and WINDGEN. Both generators are stochastic models utilizing historic data, and they provide daily weather inventories for specified time periods. CLIGEN generates precipitation, minimum and maximum temperatures, solar radiation, dew point, wind speed, and wind direction as daily inventories for a specific geographic location. WINDGEN generates hourly wind speed and direction inventories that provide the WEPS model with the wind event intensity data required to calculate erosion. The CLIGEN and WINDGEN generators used for this study are given the location of the model scenario at the county level based on the SSURGO soil map unit location. The generators are used to create the datasets required to drive the model scenario.

2.3. Establishing crop rotations

A new methodology for determining representative crop rotation scenarios and establishing the county-level distribution of crop rotations is used in this study. In the past, establishing representative crop rotations for large-scale assessments has been challenging because of the computational limitation of the number of crop rotation scenarios that could be examined and because the spatial distribution of crop rotations has not been readily available. The integrated model approach used for this study addresses the first challenge by facilitating the investigation of significantly more crop rotation scenarios than previous approaches. This is possible because the automation of data formatting and information flow through the integrated models shown in Fig. 1 allows a large number of crop rotations to be executed without direct user interaction for each unique scenario. The second challenge is addressed by the use of USDA National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL) information [53]. The CDL provides spatially explicit descriptions of where different crops are grown by executing a ''census by satellite'' [26] that delivers in-season, spatially explicit remote sensing estimates of acreages in a range of crop and land use categories. Prior to 2009, CDL data were delivered at 56 m resolution with incomplete coverage of the conterminous states. In 2009 and 2010 coverage for all lower 48 states was delivered at 30 m resolution. Fig. 3 shows the 30 m resolution data produced for Iowa in 2009 with an expanded view of Pocahontas County in northwest Iowa.

The methodology developed for this assessment utilizes CDL data to establish 3-year crop rotations by overlaying the CDL data for each state for 2008, 2009, and 2010. The 2008 CDL was not published for six states: California, Florida, Idaho, Montana, Oregon, and Washington. For these six states, the same approach was applied to establish 2-year crop rotations. It should also be noted that because the 2008 CDL was delivered at 56 m resolution, the 2009 and 2010 CDLs were scaled from 30 m to 56 m to perform the data layer intersection.

Data for all 3 years were spatially joined and intersected for every county in the conterminous United States. The land cover category in each year for each 56 m grid cell was written to a database. All ''like'' grid cells were then aggregated. The next step in processing the CDL was selecting the crop rotations of interest for this assessment. Those areas that do not include at least 1 year of a residue-producing crop were removed. The crops assumed to produce removable residues are barley, corn, rice, sorghum, durum wheat, spring wheat, and winter wheat. All wheat crops are reported together in this analysis. It was found that 13.9% of the land across the United States had a residue-producing crop for at least 1 year from 2008 to 2010.

The next step was to remove those areas that had land cover category shifts between agricultural and non-agricultural uses. Using the example in Fig. 3, if any of the years in a rotation included one of the following land cover categories, it was removed from the dataset: urban/developed, woodland, wetlands, water, barren, and shrubland. This is reasonable because shifts from agricultural categories to non-agricultural categories will typically represent a long-term move that makes that land unavailable for residue removal, and land that is shifting from non-agricultural uses to agricultural uses will typically experience a number of agronomic challenges, making residue removal practices unlikely to be adopted. In addition, those areas that have transitions between agricultural and non-agricultural land uses can represent error in the spatial processing.

The multi-year data generated was then mapped to the set of crop rotations to be modeled in the assessment. For example, corn–soybean–corn grid cells and soybean–corn–soybean grid cells were both mapped to a corn–soybean rotation for the model scenarios, and corn–corn–soybean grid cells and soybean–corn–corn grid cells were both mapped to corn–corn–soybeans for the model scenarios.

2.4. Land management scenarios

A land management scenario includes comprehensive descriptions of all interactions with the land. These interactions include the crop(s) grown, fertilizer treatments, tillage managements, and crop yields. In this study the timing and equipment for planting crops, tillage operations, harvesting grain, and residue removal are established based on crop rotation and geographic location. The timing and order of field operations is based on the NRCS crop management zones (CMZs) [54], shown in Fig. 4. NRCS has established the 72 CMZs as regions where field operations and their associated timing are generally consistent. Furthermore, NRCS has built an extensive database of management operations and scenarios using the CMZ methodology. To use the CMZ data, all of the unique crop rotations within a CMZ are identified. Based on this, land management scenarios including operational timing, tillage, and removal rate scenarios are built. Two criteria were applied to limit the number of management scenarios for each CMZ. First, the largest crop rotations in a CMZ needed to include 90% of the area in the CMZ were selected, and all rotations beyond the 90% cut off point were discarded. The second criteria eliminated any rotations that did not comprise at least 405 ha in the CMZ. These assumptions significantly reduced the number of computations required while still providing an accurate representation of the land management practices for 90% of the area. Table 3 lists the number of crop rotations for each CMZ.

2.5. Tillage management practices

Tillage practices can impact sustainable residue removal [19]. One of the primary reasons tillage operations are performed is to incorporate residues into the soil, thus creating more manageable soil surface conditions for planting the next crop. Because of this, sustainable residue removal can potentially reduce the need for tillage operations. To investigate the impacts and opportunities associated with tillage management practices, three tillage regimes were modeled for each crop rotation–residue removal scenario in the assessment. The tillage regimes used in this study are categorized as conventional, reduced, or no-till. These tillage regimes are consistent with the tillage definitions provided by the Conservation Technology Information Center (CTIC) [55]. The three regimes represent standard practices determined by CMZ and crop rotation as defined by NRCS. The standard practices were collected from the NRCS standard management database specified in Table 2. For each CMZ, the specific tillage equipment, the dates that operations were performed, and the number of passes were established for each crop and tillage regime. This data is used to create CMZ and crop specific rules, and populate the specific set of tillage operations for each CMZ–crop rotation–tillage regime combination. Conventional tillage is the most invasive tillage regime and includes at least one full-width complete soil inversion tillage operation, resulting in less than 15% residue on the soil surface after planting.

Table 3
Number of crop rotations required for each CMZ to account for 90% of the CMZ area.

CMZ	No. Rots.	CMZ	No. Rots.	CMZ	No. Rots.	CMZ	No. Rots.	CMZ	No. Rots.	CMZ	No. Rots.
01	15	12	1	23	2	36	1	46	5	59	14
02	72	13	5	24	15	37	27	47	6	60	6
03	36	14	11	25	8	37.1	27	48	6	62	5
04	5	15	13	26	2	38	35	49	7	63	10
4.1	5	15.1	13	27	7	38.1	35	50	8	64	15
05	15	16	6	28	10	39	22	51	8	65	10
06	7	17	12	29	7	40	21	52	6	66	22
07	15	18	6	30	30	41	14	53	7	67	25
08	7	19	19	32	10	42	24	54	6	68	5
09	4	20	5	33	26	43	2	55	12	69	18
10	11	21	1	34	20	44	6	57	22	70	6
11	17	22	9	35	8	45	1	58	15	71	1

Table 4
Description and approximate residue removal rates for the five residue harvest methods used in this study.

Residue harvest method	Residue collection equipment and process	Approximate residue collection rate (%)
No residue harvest (NRH)	Combine harvester functions as normal	0
Harvest grain and cobs (HGC)	Combine harvester internal mechanisms are set to break apart cobs and collect them with the grain	22
Moderate residue harvest (MRH)	Combine harvester residue chopper and spreader are disengaged, leaving a windrow behind the machine. In a second pass a baler picks up the windrow, making $3' \times 4' \times 8'$ square bales	35
Moderately high residue harvest (MHH)	Combine harvester residue chopper and spreader are disengaged, leaving a windrow behind the machine. A rake is used to collect additional surface residue into a single windrow. In a third pass a baler picks up the windrow, making $3' \times 4' \times 8'$ square bales	52
High residue harvest (HRH)	Combine harvester residue chopper and spreader are disengaged, leaving a windrow behind the machine. A flail shredder is used to cut standing stubble and to collect surface residue into a single windrow. In a third pass a baler picks up the windrow, making $3' \times 4' \times 8'$ square bales	83

Conventional tillage typically involves multiple tillage passes. Reduced tillage includes at least one full-width tillage pass, but leaves up to 30% residue on the soil surface after planting. No-till is defined as the minimum soil disturbance required for input of the following crop. The specific set of operations for each tillage regime is based on the CMZ and crop rotation using the NRCS rule set described above. The assumptions for tillage management practices at the county level match those used for the *US Billion Ton Update* [18].

2.6. Residue removal practices

The agricultural residue removal rate scenarios used in this study follow the schema developed by Muth and Bryden [40]. They included five standard residue removal methods for each crop rotation–tillage combination. Each of these residue removal methods utilizes existing equipment and methods to remove residues from the field. Table 4 lists and describes each of these five removal methods. These five residue removal equipment configurations represent the current state of technology for commercially available residue removal equipment. There are two advantages to selecting existing harvest methods: (1) the models are provided with an accurate representation of residue quantity and orientation after harvest and (2) the results of the assessment represent the current state of technology by implementing commercially available removal operations. The decision to use existing equipment configurations is an important distinction between the assumptions used in this assessment and those used in past regional and national scale analyses. In the past only the quantity of material left on the soil was considered when investigating sustainable residue removal limits. The environmental process models need an accurate representation of the orientation of the material left on the field. In many scenarios the orientation of the remaining material is as or more important than the quantity. For example, water erosion is best controlled with residue covering as much of the soil surface as possible, while wind erosion is best controlled by leaving taller standing stubble in the field to reduce the kinetic energy of the wind prior to interaction with the soil surface.

2.7. Yield scenarios

County average crop yields are used for all crops in this study. Yield assumptions at the county level for residue-producing crops match those used for the *US Billion Ton Update* [18], which utilized the USDA Economic Research Service (ERS) Agricultural Baseline Projections [56]. The ERS Baseline Projections provide projections for 10 years. The 2030 yield assumptions were linearly extrapolated from the 10-year projection to 2030. Table 5 shows the national average grain yield for the 2011 and 2030 yield scenarios for each of the residue producing crops considered in this study. The national average yield is calculated using the county average yields weighted against the total grain produced in each county. For crops that were not considered in the *US Billion Ton Update*, county-level average yields were acquired from NASS using 2008–2010 reported averages, and it was assumed that there would be no yield increases between 2011 and 2030. This assumption is reasonable because these crops typically have less historical data to support yield increase projections, and these are not residue-producing crops, but are crops that are in rotation with residue-producing crops. A key assumption for the 2030 yield scenario is that crop rotations remain the same as the 2011 scenario. The grain yield scenarios are critical to the results of the study because the grain-to-residue ratio for each crop is assumed to be constant for all yields (Table 5). Based on this, any increases in yield will result in a matching increase in biomass potentially available for sustainable removal.

The integrated modeling framework can facilitate biophysical modeling to simulate crop yields under various crop rotation, soil, and tillage management practices. However, currently there are no biophysically based models that are validated across the wide range of conditions used in this study. Based on this, county level average yields were used to provide consistency of results with the *US Billion Ton Update* scenarios which the data from this analysis supports. In addition, it is not clear that biophysical simulation tools will be more effective than using county yields in establishing accurate yield projections across the extensive range of crop rotations, tillage managements, soils, and climate conditions used in this analysis.

2.8. Determining sustainable removal rates

A residue removal rate is considered sustainable in this analysis if the combined soil loss from wind and water erosion is less than or equal to the tolerable soil loss (T-value) reported in SSURGO, and soil organic matter is not being depleted. Specifically, for each removal rate scenario the wind and water erosion outputs from the models were combined to a total erosion value and then compared with the soil T-value from SSURGO. Following this, the integrated model output for the SCI was tested to be greater than or equal to zero. The SCI is currently used by NRCS as an indicator that soil organic carbon is not decreasing and that the future productive capacity of the soil will be maintained, or increased under the agronomic scenario in question. This second consideration is important for reconciling sustainable removal practices with the 2030 yield projections from USDA ERS data discussed previously. Achieving the projected yields from ERS requires the current productivity capacity of the soil to be at least maintained. An SCI greater than or equal to zero meets that requirement and provides confidence the residue removal scenario will not decrease future yields. If the combined soil loss was less than the soil T-value, and the SCI was greater than or equal to zero, then a removal rate scenario was considered sustainable.

2.9. County and state level residue quantities

Establishing the available sustainable agricultural residues at a county level requires aggregating the soil–crop rotation–tillage–yield scenarios to the county level. To do this, the maximum sustainable removal rate for each soil-rotation-tillage-yield scenario

Table 5
National average grain yields and assumed residue-to-grain ratios for the residue producing crops investigated in this study.

Crop	2011 National average grain yield (Mg ha^{-1})	2030 National average grain yield (Mg ha^{-1})	Assumed residue-to-grain ratio
Corn	10.1	12.6	1:1
Spring wheat	2.9	3.3	1.3:1
Winter wheat	2.9	3.3	1.7:1
Barley	3.6	4.2	1.5:1
Sorghum	4.0	4.6	1:1
Rice	8.5	9.5	1.2:1

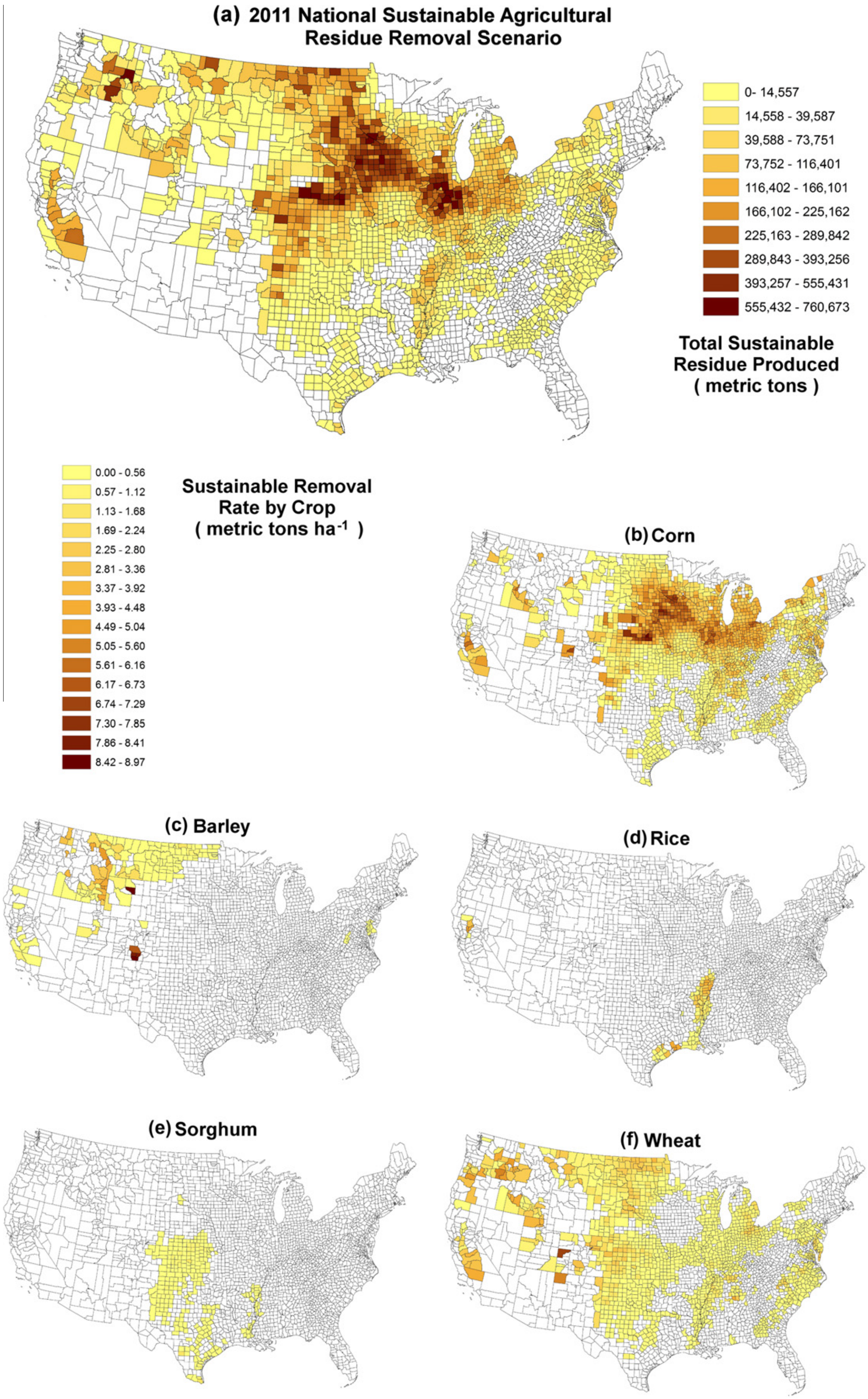


Fig. 5. 2011 Sustainable residue scenario results.

Table 6
State and US total sustainable residue available in 2011 and 2030 scenarios. Also included is a projection assuming that 100% of acres adopt no-tillage practices.

State	2011 Sustainable residue (1000 metric tons)	2030 Sustainable residue (1000 metric tons)	Percentage increase from 2011 to 2030 (%)	2030 Sustainable residue – all no-till assumption (1000 metric tons)
IA	25,916	37,321	44	49,761
IL	20,935	29,995	43	44,071
NE	18,609	25,147	35	31,542
MN	16,006	21,252	33	27,925
IN	8615	12,457	45	18,218
SD	9215	11,437	24	12,890
ND	7333	8614	17	10,953
OH	5687	8225	45	10,620
KS	6491	8170	26	13,156
WI	4262	6392	50	11,590
MI	3200	4375	37	7220
TX	2282	3342	46	7296
MO	2252	3303	47	6456
AR	1792	2934	64	6405
CO	2674	2926	9	3474
KY	1516	2413	59	3273
WA	1863	2240	20	2711
MT	2104	2036	−3	2208
CA	1575	1903	21	2121
ID	1586	1813	14	2184
NY	938	1257	34	2799
PA	764	1246	63	3525
NC	458	1120	144	1701
OR	961	1070	11	1439
MD	597	1022	71	1445
TN	589	1012	72	1443
OK	362	787	117	2821
LA	448	767	71	2654
MS	401	749	87	1762
VA	296	615	108	815
SC	186	448	141	618
AL	221	350	59	404
DE	203	336	65	600
GA	105	239	128	405
NM	169	230	36	285
UT	133	148	12	178
WY	85	103	21	251
NJ	46	71	54	210
WV	21	37	75	63
FL	3	3	21	7
US total	150,897	207,905	38	297,499

was determined using the sustainability metrics discussed earlier. Each SSURGO soil is given a relative area percentage for the county based on the SSURGO database. This assumes that all crop rotations and tillage management practices for a county are evenly distributed across each soil in that county. The county average sustainable residue removal rate, CR_i, for each crop i is

$$CR_i = \sum_j \left(\alpha_j \sum_k \left(\beta_{k,i} \sum_l (\gamma_l cr_{i,j,k,l}) \right) \right) \tag{1}$$

where α_j is the fraction of the area of each j soil, $\beta_{k,i}$ is the fraction of the area for crop i that is in k rotation, γ_l is the fraction of the area in l tillage regime, and $cr_{i,j,k,l}$ is the sustainable residue removal rate for crop i in j soil in k rotation and l tillage regime. The CR_i are then summed over the county to determine the total sustainable residue available in each county, TR,

$$TR = \sum_i CR_i A_i \tag{2}$$

where A_i is the area of the county producing crop i. State level sustainably removable residue totals are determined by summing the sustainable residue available in each of the state's counties. Total sustainably removable residue quantities at the national level are established by summing the sustainable residue for each of the conterminous states. All residue quantities are reported in dry metric tons.

3. Results and discussion

Using the assessment procedure discussed above, nearly 100 million unique scenarios creating a spatially comprehensive representation of the conterminous United States were examined. The complete set of runs for this study was distributed on a 48-node computing cluster comprised of 3.0 GHz Intel Xeon Quad-Core rack-mounted machines running Microsoft Server 2008™ with no other computational duties. The wall clock run time for the assessment was nearly 10 weeks. Fig. 5a shows the annual sustainable residue availability at the county level in terms of metric tons. As shown, large sections of the Corn Belt, Great Plains, and Pacific Northwest have the potential to contribute significant quantities of agricultural residues sustainably for bioenergy production. Specifically, 503 counties combined in the 2011 scenario sustainably provide over 100,000 metric tons of residues on an annual basis. Fig. 5b–f shows the county-level sustainable residue removal rates, in metric tons per hectare, for each of the five residue-producing crops. Higher sustainable removal rates generally support better economic viability for residue removal operations, and removal rates of 2.25 metric tons per hectare will often provide the best opportunity for economically viable operations [57,58]. For all five

Table 7
Results split out by crop.

Crop	2011 Sustainable residue (1000 metric tons)	Percentage of total 2011 residue provided by each crop (%)	2030 Sustainable residue (1000 metric tons)	Percentage of total 2030 residue provided by each crop (%)	2030 Sustainable residue – all no-till assumption (1000 metric tons)
Barley	1220	0.8	1382	0.7	1721
Corn	123,515	81.9	174,625	84.0	244,628
Rice	2602	1.7	3939	1.9	9123
Sorghum	636	0.4	682	0.3	2113
Wheat	22,924	15.2	27,277	13.1	39,914
Total	150,897	100.0	207,905	100.0	297,499

residue-producing crops, the majority of counties have a sustainable removal rate of less than 2.25 metric tons per hectare for the 2011 yield and land management scenario. Corn stover residue shows the greatest potential for higher sustainable removal rates primarily because corn produces more total biomass than the other residue-producing crops. Barley and wheat have potential for sustainable removal rates above 2.25 metric tons per hectare under irrigated production in the Great Plains and Pacific Northwest. Sustainable rice residue production is limited to the South Central United States and areas in California, and removal rates above 2.25 metric tons per hectare are found in these regions. Sorghum residue is available across a large region of the South Central United States and Great Plains, but sustainable removal rates for sorghum do not exceed 1.14 metric tons per hectare for any county in the country. Table 6 shows the sustainable residue removal potential by state for the 2011 and 2030 scenarios, as well as providing a hypothetical scenario for 2030 that assumes all acres adopt no-tillage practices. The Corn Belt states of Iowa, Illinois, Nebraska, Minnesota, and Indiana provide 60% of the sustainably available residue nationally for the 2011 scenario. This result is consistent with the by crop residue totals shown in Table 7. Corn stover residue accounts for 81.9% of the sustainably available residue nationally in the 2011 scenario.

The results for the 2030 scenario are shown in Fig. 6. The county-level sustainable residue quantities are significantly higher across the country due to higher grain crop yields in the 2030 scenario. In this scenario, 605 counties nationally produce 100,000 metric tons or greater of sustainable residue. As shown in Fig. 6, areas in the Corn Belt show significant increases in sustainable residue removal potential as compared to 2011. This occurs because increasing corn grain yields have the greatest potential impact on sustainable residue availability. As shown in Table 7, corn stover residue grows to 84% of the total residue available in the 2030 scenario. The sustainable removal rate maps for each crop in 2030 (Fig. 6b–f) show nearly the same spatial distribution of residue as the removal rate maps for each crop in 2011 (Fig. 5b–f). The primary change from 2011 to 2030 is that increased yields provide higher sustainable removal rates for each crop. In 2030 corn stover residue removal rates approach 11 metric tons per hectare for high yielding counties under irrigated production. Sorghum residue removal rates remain low with all county averages at less than 1.3 metric tons per hectare. As shown in Table 6, the sustainable residue for the 2030 scenario increases between 30% and 50% for the highest producing states with a national increase in sustainable residue of 38%. An interesting note is the slight decrease in residue available from Montana. This is a result of the tillage assumptions associated with higher crop yields.

Tables 6 and 7 also provide the sustainably removable residue quantities for a 2030 scenario that assumes all acres use no-tillage management practices. This scenario provides a hypothetical upper bound for sustainable residue removal potential that accounts for the management practices considered in this study. The total sustainable residue potential under these assumptions increases 43% from the standard 2030 management assumptions to nearly 300 million metric tons of residues. Considering the individual crop results shown in Table 7, no-tillage management practices provide the largest increases in sustainably removable residues for sorghum and rice at 210% and 132% increases, respectively. The sustainable corn stover residue removal potential increases 40% nationally with the assumption of the all no-tillage management practice.

Table 8 compares the results from this study and previous regional and national scale sustainable agricultural residue removal assessments. These studies cannot be directly compared because of the wide range in the spatial scales, timeframes represented, environmental factors considered, crop management practices considered, and modeling methodologies utilized. However it is informative to identify commonalities across the different studies and compare the results for those common elements. Nearly all of the studies evaluate sustainable corn stover removal potential in the state of Iowa. Larson [27] identified nearly 49 million metric tons of agricultural residues as being sustainably removable across the Corn Belt in the mid 1970s. With grain yield increases through the mid 1990s and improved erosion modeling methodologies Nelson in 2002 [29] identified nearly 10.1 million metric tons of corn stover sustainably available in Iowa. Nelson [29] also concluded that 47.6 million metric tons of residues were available across a 37 state region in the Midwestern and Eastern US. Nelson [29] and Larson [27] found similar sustainably accessible residue quantities, but over different spatial extents. Using Nelson's methodology with simplified management assumptions, Sheehan et al. [23] identified 40 million metric tons of residue that were sustainably available in Iowa using 1995–1997 crop yields. This significant increase in sustainable residue removal potential was primarily because of assumptions that all land was managed under continuous corn rotations and no-tillage management practices. Nelson et al. [34] refined the analysis methodology to consider additional tillage and crop rotation scenarios. Nelson et al. [34] identified 59.5 million metric tons of residue sustainably available in Iowa using 1997–2001 crop yields when assuming continuous corn and no-tillage management practices. Adding an additional soil moisture constraint to Nelson et al.'s [34] methodology in conjunction with updated land management assumptions Graham et al. [37] found that only 13.7 million metric tons of corn stover was sustainably available in Iowa using similar grain yield assumptions. Graham et al. [37] improved the crop rotation and tillage management practices assumptions by including a range of management practices scenarios and aggregating the estimates based on projections of how much land was being managed under the different rotations and tillages. Muth and Bryden [40] presented a comprehensive model in terms of the spatial extent, management practices, and environmental limiting factors considered. From this it was identified that 26.5 million metric tons of corn stover were sustainably available in Iowa using 2008–2010 yield scenarios. After

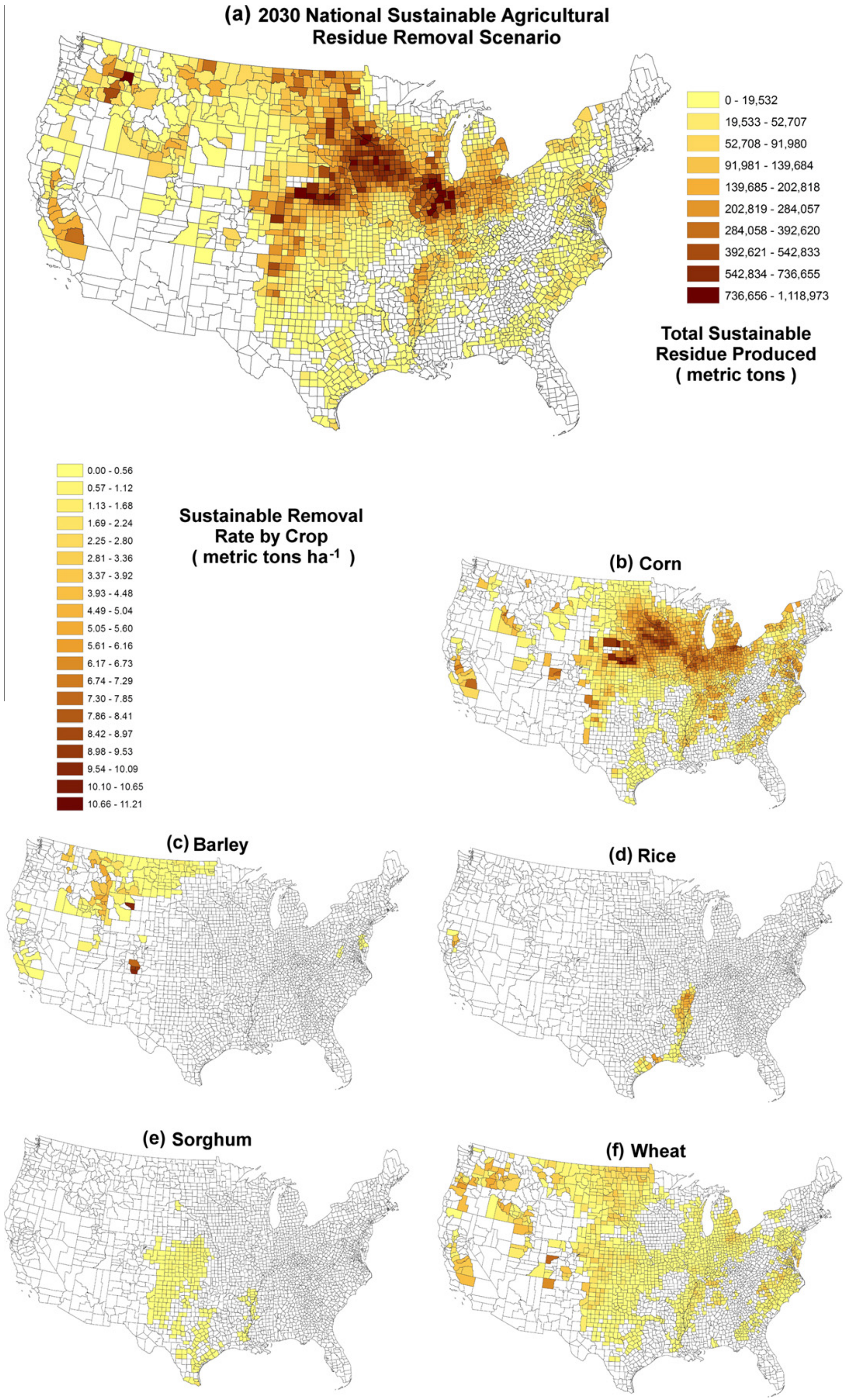


Fig. 6. 2030 Sustainable residue scenario results.

Table 8
Summary of primary findings for large geographic scale residue removal studies.

Study[1]	Year	Spatial extent	Crop residues included	Timeframe	Annual total residue sustainably available (million metric tons)		
					US	Iowa	Regional[2]
[27]	1979	Corn Belt, Great Plains, and Southeast	Corn, Wheat	1975	–	–	49.0
[29]	2002	37 states from the Great Plains to the East Coast	Corn, Wheat	1997	–	10.1	47.6
[23]	2003	Iowa	Corn	1997	–	40	–
[34]	2004	10 Corn Belt and Great Plains States	Corn, Wheat	2001	–	59.5[3]	430.3[3]
[36]	2005	Entire Continental US	Corn, Wheat, Barley, Sorghum	2005	176	14.5	176
[37]	2007	Entire Continental US	Corn	2000	58.3	13.7	58.3
[40]	2012	Iowa	Corn, Wheat	2010	–	26.5	–
Current		Entire Continental US	Corn, Wheat, Barley, Sorghum, Rice	2011	150.9	25.9	150.9
				2030	207.9	37.3	207.9

[1] Study [38] did not project a total quantity of residue, simply an assumption of 30% removal as sustainable.
[2] The regional column represents the full spatial extent of each analysis and is comprised of different total area and regions for the different studies.
[3] These values represent corn stover only and an assumption that all cropland acres are continuous corn, reduced tillage management practices.

seeing a number of methodologies applied to this problem in which each have continued to make advances in the analysis approach, the Muth and Bryden 2012 study falls near the middle of the range of sustainable corn stover removal potential for the state of Iowa. This current study extends the Muth and Bryden 2012 study by incorporating additional data processing to enable more accurate crop rotation scenarios and acreage representations, as well as using updated grain yield and tillage management practice numbers. Based on this, this study identifies that 25.9 million metric tons of corn stover are sustainably available in Iowa.

When analyzing these results it is important to consider current markets for agricultural residues that may compete with energy production for the biomass quantities reported in this study. There are currently four primary uses of agricultural residues other than energy production in the United States. These are animal feed, animal bedding, mushroom production, and composite products such as fiberboard [59]. Significant quantities of cereal straws from wheat and barley are currently collected in the Pacific Northwest for animal feed and bedding [60]. In the Midwest Corn Belt, Nebraska in particular, grazing of cattle through corn stover residue left in the fields is a common practice [61]. Another niche use of agricultural residues includes corn stover for mushroom production in Pennsylvania [62]. Perlack and Stokes [18] concluded that as much as 30% of the currently available agriculture residue resources at $60 per dry ton farm gate cost are being used in existing markets. Their projection for 2030 states that approximately 15% of the available material at $60 per dry ton farm gate cost is likely to be used for non-energy markets.

4. Conclusions

This study utilized an integrated environmental process modeling strategy to investigate sustainable agricultural residue removal potential in the conterminous United States. The modeling strategy utilized NRCS conservation management planning principles to perform multi-factor sustainability analysis for the residue removal scenarios. Soil erosion from wind and water forces, and soil organic carbon constraints were considered to determine the sustainability of residue removal. Scenarios were developed for sustainable residue removal for 2011 and 2030 crop yield projections. The yield scenarios are based on USDA Economic Research Service data and projections for current and future yields. Using the NRCS national soil survey database, SSURGO, individual soil map units represent the base spatial unit for the assessment and provided the soils data across the country for each of the models in the integrated framework. Crop rotations for each county were established by processing the CDL land use data from NASS. A geoprocessing technique and spatial aggregation algorithm was developed and utilized to overlay 3 years of CDL data at a 56 m grid scale and determine the relevant crop rotations, and the spatial extent of those rotations, at the county scale. Land management scenarios were built using NRCS–CMZ rules for determining operational timing and equipment systems. Three tillage regimes were included in the land management scenarios for each crop rotation. Residue removal equipment configurations utilized NRCS standard assumptions and included five residue removal rates. The integrated modeling framework was iteratively executed, resulting in nearly 100 million residue removal scenarios that provided a spatially comprehensive assessment of sustainable residue removal potential across the United States. The assessment found that over 150 million metric tons of agricultural residues could be sustainably removed in 2011 with 82% of that material coming from corn stover. The assessment also found that yield increases and changing tillage management practices will enable nearly 208 million metric tons of residue to be sustainably removed in 2030. Corn stover residue will account for 84% of the available sustainable residues in 2030.

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