Quantification of Biomass Feedstock Availability to a Biorefinery Based on Multi-Crop Rotation Cropping Systems Using a GIS-Based Method

A. Martinez, D. E. Maier

ABSTRACT. *The feasibility of utilizing cellulosic biomass as an energy feedstock is dominated by factors such as facility location, feedstock availability, and transportation cost. Our previous case study showed improvements in quantification of feedstock availability for a biorefinery by introducing the effect of field-level yield variance and variable residue removal rates as improvement parameters into the GIS-based analysis. Even though the improved GIS-based method enhanced quantification of feedstock availability with the addition of the improvement parameters, a biorefinery would most likely procure more than one feedstock type. In this case study, quantification of feedstock availability based on multi-crop rotation cropping systems was done using the previously improved GIS-based variable residue removal (VRR) method. We observed on average a 3,793 ±5,733 DT per service area difference when increasing the number of crops used to estimate feedstock quantification. The supplementary use of crop-specific VRR rates affected residue availability, given that a crop's residue removal rate is influenced by crop yield, crop rotation, soil characteristics, as well as field location and management. It was also observed that the amount of available hectares of the three main crops analyzed in this case study affected residue availability. Corn represented 26.2% (440,636 ha; 1,101,591 acres), sorghum represented 12.9% (217,432 ha; 543,579 acres), and wheat represented 60.9% (1,024,607 ha; 2,561,518 acres) of the hectares in the study area. The validation study showed the importance of taking into account the seasonal availability of crop residue when estimating procurement service areas, given that in some cases feedstock requirements were not met.*

Keywords. *Biomass, Feedstock availability, GIS, Transportation logistics, Wind Erosion Prediction System (WEPS).*

Extensive research is ongoing to evaluate the potential of various feedstocks for efficient conversion into biofuel. One challenge lies in strategically locating biomass conversion facilities in order to supply them with feedstock in an economically feasible manner. The logistics challenge is dominated by factors such as facility location and accessibility, feedstock quantity and seasonal availability, as well as transportation costs.

A feedstock's dispersed spatial and seasonal availabilities are among the challenges

Submitted for review in August 2013 as manuscript number BET 10354; approved for publication by the Biological Engineering Division of ASABE in April 2014.

Contribution No. 14-378-J from the Kansas Agricultural Experimental Station.

The authors are **Adrian Martinez,** Graduate Student, and **Dirk E. Maier, ASABE Member,** Professor and Head, Department of Grain Science and Industry, Kansas State University, Manhattan, Kansas. **Corresponding author:** Dirk E. Maier, 201 Shellenberger Hall, Kansas State University, Manhattan, KS 66506; phone: 785-532-4052; e-mail: dmaier@ksu.edu.

associated with the quantification of feedstock availability. Thus, this influences optimized selection of a facility's location and transportation costs, as reported in the Biomass Road Map (USDOE, 2003) and several other studies (De Mol et al., 1997; Sokhansanj et al., 2002; Ravula et al., 2008; Krishnakumar and Ileleji, 2010; Cundiff and Grisso, 2012). Ultimately, correct selection of the facility location will result in more precise quantification of feedstock availability and prediction of transportation costs.

Martinez and Maier (2011) proposed a geographical information system (GIS) based approach for quantifying feedstock availability that utilized a real road network and georeferenced, crop-specific satellite imagery. This GIS-based approach was subsequently improved by Martinez and Maier (2014) by taking into account the effect of field-level yield variance based on soil characteristics and variable residue removal rates based on erosion, soil characteristics, yield, and conservation management practices. The researchers concluded that the variable residue removal (VRR) method using conservation tillage was a more sustainable approach for the quantification of feedstock availability compared to the constant residue removal (CRR) method. While the deployment of these improvement parameters in the GIS-based feedstock sourcing method proved feasible, the next logical step was to improve the method's capability of quantifying feedstock by estimating multi-crop residue availability based on crop rotation using the VRR method.

The main goal of this case study was to further improve the previously developed GIS-based feedstock sourcing method and to use the improved approach to predict multi-crop feedstock availability for a Kansas-based biomass conversion facility.

Benefits of Rotation Cropping Systems

The agricultural practice of growing a single crop in the same field in consecutive years is known as monoculture, whereas polyculture or crop rotation is the practice of growing multiple crops in the same field in alternating years. Crop rotation is often more costly and requires more labor than monoculture, yet its advantages outweigh its disadvantages. The advantages include increased yield, improved soil fertility as a result of nutrient cycling, and reduced economic risk by having more than one crop as a potential income source. Ultimately, a farmer's goal is to increase yield potential and prolong farm productivity and sustainability, which can be achieved by using rotation cropping systems.

Crop type and sequence are typically dictated by location, soil characteristics, duration of the production cycle, pest pressure, pathogen resistance, and water availability. Sequencing different types of crops is advisable, given that growing the same crop in the same field year after year may deplete the soil of a specific nutrient and make the crop more vulnerable to diseases. Therefore, by incorporating different types of crops in a rotation, nutrient depletion can be counterbalanced. A common example of a crop rotation is a cereal crop (e.g., corn, wheat) followed by a leguminous crop (e.g., soybean, alfalfa). Using a corn-soybean rotation as an example, corn requires additional nitrogen for development, so by subsequently planting soybeans, which have nitrogen-fixing bacteria nodules on their roots, nitrogen is returned to the soil, extending its productivity (Vanotti and Bundy, 1995; USDA, 1998). Crookston et al. (1991) observed an increase in crop productivity when they evaluated the impact of various corn and soybean cropping patterns on yields in a nine-year field study. They observed a yield increase in corn (10%) and sorghum (8%) when rotated annually, as well as a yield increase in first-year corn (15%) and sorghum (17%) when compared to multi-year monoculture. They also observed that yield did not differ between a monoculture of either crop when alternating two different cultivars annually and with continuous cropping of just one cultivar.

Crop rotations can also have an effect on the amount of soil loss due to erosion. In highly susceptible areas, management practices such as reduced or conservation tillage can be supplemented with specific crop rotations to reduce soil loss caused by wind and/or water erosion. Crop residue left on the field after harvest protects the soil by minimizing detachment and transport of sediment caused by high wind speeds and water droplet impact. Crop rotations together with a reduction or elimination of tillage can also help condition the soil by increasing the soil organic matter content, which helps improve the soil's structure and capability to retain water and nutrients, as well as reduce the severity of drought, flood, or diseases (USDA, 2006). Havlin et al. (1990) evaluated the effects of tillage, crop rotation, and nitrogen fertilizer on soil organic carbon and nitrogen in eastern Kansas with continuous sorghum, continuous soybean, and sorghum-soybean rotations. They concluded that crop management systems that included rotations with high-residue crops and maintenance of surface residue cover with reduced tillage resulted in greater soil organic carbon and nitrogen, which improved soil productivity.

Effect of Residue Management in Rotation Cropping Systems

It is important to consider how much of the available residue will be harvested from a field. Removing 100% of the residue is not the best practice because that will lead to erosion problems and loss of soil productivity due to the lack of nutrient cycling. Wilhelm et al. (1986) evaluated corn and soybean yield response to crop residue management under no-tillage production systems by returning 0%, 50%, 100%, and 150% of the previous crop residue. They found a positive linear response between grain and stover yield and the amount of residue on the soil surface. They estimated that each Mg ha^{-1} of residue removed resulted in about a 10% (0.10 Mg ha^{-1}) reduction in grain yield and a 30% (0.30 Mg ha^{-1}) reduction in residue yield. They also estimated that the quantity of residue on the field accounted for 81% and 84% of the variation in grain yield of corn and soybean, respectively, and 88% and 92% of the variation in residue yield. In a follow-up case study, Power et al. (1998) evaluated the residual effects of crop residues on grain production and soil properties. They observed that residual effects of the 150% residue treatment increased grain production by 16% compared with the 0% residue treatment. Therefore, they concluded that returning crop residues improved water conservation and storage, nutrient availability, and crop yields.

Modeling Crop Residue Removal Rates in Rotation Cropping Systems

Agricultural residue removable rates are highly variable and depend on factors such as crop type, yield, location, climate, soil characteristics, and field management. Despite their high variability, constant residue removable rates are typically used in case studies where feedstock availability is being estimated based on hectare availability. Perlack and Turhollow (2003) evaluated the costs for collecting, handling, and hauling corn stover to an ethanol conversion facility using a corn stover yield that was estimated by multiplying the average corn yield of 8.27 MT ha^{-1} (130 bu ac^{-1}; 6.36 to 10.18 MT ha^{-1}; 100 to 160 bu ac^{-1}), corn grain dry matter content (0.85), and stover to grain ratio (1:1), this equated to a constant removal rate of 7.7 DT ha^{-1} (3.1 DT ac^{-1}). Mukunda et al. (2006) used a similar constant removal rate of 7.4 DT ha^{-1} (3 DT ac^{-1}) to quantify feedstock availability in a given service area, which was fed into their developed discrete event simulation to model the transportation logistics of a corn stover feedstock-based supply system. Therefore, to more accurately estimate agricultural crop residue removal, variable residue removal (VRR) rates are needed. Martinez and Maier (2014) developed a methodology that estimates VRR rates with respect to erosion, soil characteristics, field-level crop yield, and field management. They observed that the procurement area was considered practically the same for the VRR method using conservation tillage as for the constant residue removal (CRR) method using intensive tillage with 100% residue removal. Consequently, the VRR method was a more sustainable approach for the quantification of biomass feedstock availability.

Most studies examine residue removal based on the weight of residue removed at harvest, while management practices and conservation programs often concentrate on the percentage of soil covered by residue after planting the next crop. While these measurements are related, a 30% residue removal rate is not the same as 70% soil cover, regardless of when the soil cover is measured (USDA, 1998). Several tillage practices exist, with the three main practices being intensive, reduced, and conservation tillage. These practices differ by the percent of soil coverage that the first-year crop residue provides at the time the second-year crop is planted. Intensive tillage provides less than 15% cover, reduced tillage provides between 15% and 30%, and conservation tillage provides a minimum of 30%.

Materials and Methods

The reference location for this case study was the Abengoa Bioenergy Hybrid of Kansas facility near Hugoton, Kansas. This is the same location that Martinez and Maier (2014) used to quantify the accuracy gained as a result of using field-level yield variance and variable residue removal rates as improvement parameters.

Cropland Data Layers and Service Areas

Cropland data layers (CDL) were acquired from the USDA-NASS CropScape geospatial data web service application (USDA, 2013). A shape file of the study area was first created in ArcGIS (ArcGIS, 2012) and then imported into CropScape using the “import area of interest” feature. Subsequently, the CDLs for the years 2008 to 2012 were downloaded based on available data, given our area of interest. Case study service areas were then created the same way Martinez and Maier (2014) did using the Network Analyst tool in ArcGIS, in 16 km (10 mi) increments up to 160 km (100 mi), starting from the selected facility location (Hugoton, Kans.) as the reference point.

Crop Rotation Identification and Sequencing

To simplify crop identification and sequencing, ArcGIS crop attribute values for the five acquired CDL years were first reclassified. Corn was given a reclassification value of 1, sorghum 2, wheat 3, and fallow 4. The Combine tool in ArcGIS was then used to sequence the crop values using the reclassified CDLs. The output layer, which contained all possible crop sequences within the study area from 2008 to 2012, was then exported to a spreadsheet to be identified and manually re-labeled. Crop rotations were re-labeled according to their numerical crop value sequence. For example, a five-year crop value sequence of 3-1-3-1-3 was identified as a corn-wheat crop rotation and re-labeled as 1-3-1. If the crop value sequence could not be clearly identified, it was re-labeled RndRot. Representative crop rotations were then identified within the study area by adding the total acres of each crop value sequence. The spreadsheet containing the re-labeled crop value sequences was subsequently imported back to ArcGIS to update the crop sequence layer created using the Combine tool. Continuous corn (i.e., 1-1-1 rotation), corn-wheat (i.e., 1-3-1 rotation), and sorghum-wheat-fallow (i.e., 2-3-4 rotation) were the representative rotations in the study area. Cells with 1-1-1, 1-3-1, or 2-3-4 crop rotation values were then separately extracted and converted into polygons with their corresponding crop rotation sequence value assigned in the new layer. The layer with polygons in a 1-1-1 rotation was labeled CrpRot_CCC, the layer with polygons in a 1-3-1 rotation was labeled CrpRot_CWC, and the layer with polygons in a 2-3-4 rotation was labeled CrpRot_SWF.

Residue Removal Rates Based on Crop Rotation

Variable residue removal rates for each crop in each of the three representative crop rotations in the study area were obtained using Martinez and Maier's (2014) VRR methodology. In brief, VRR rates were estimated using the USDA Agricultural Research Service (ARS) Wind Erosion Prediction System (WEPS), which can be used to estimate long-term soil productivity as well as plant damage (WEPS, 2010). Factors such as weather, soil characteristics, crop yield, and field management were taken into account when running wind erosion simulations for each county in the study area for soils that the USDA Natural Resources Conservation Service (NRCS) classified as land capability class (LCC) 1, 2, 3, or 4. The soil with the highest hectare extent in each LCC was chosen to represent that LCC. The LCC classification is based on the quality of soil resources for agricultural use. Soils are grouped according to their limitations, among other factors, and are designated by one of eight categories, with LCC 1 being the best soils and LCC 8 being the poorest. Hectare-weighted yields (HWYlds) were then calculated, and a field management was chosen (table 1).

Table 1. Field management used to simulate residue removal rates using conservation tillage.

Crop Rotation	Date	WEPS Operation	Crop
Continuous corn (1-1-1)	1 Apr. 2001	Sprayer, killing crop	-
	20 Apr. 2001	Fertilizer application, anhydrous w/ knife, 30 in.	-
	20 Apr. 2001	Planter, double disk opener, fluted coulter	Corn
	20 June 2001	Sprayer, post-emergence	-
	20 July 2001	Sprayer, insecticide, post-emergence	-
	1 Oct. 2001	Harvest, killing crop, 20% standing stubble	-
	2 Oct. 2001	Rake or windrower	-
	5 Oct. 2001	Bale straw or residue	-
Corn-wheat (1-3-1)	25 Apr. 2001	Planter, double disk opener w/ coulter	Corn
	1 July 2001	Sprayer, post-emergence	-
	15 July 2001	Sprayer, insecticide, post-emergence	-
	1 Oct. 2001	Harvest, killing crop, 30% standing stubble	-
	2 Oct. 2001	Rake or windrower	-
	3 Oct. 2001	Bale straw or residue	-
	15 Oct. 2001	Drill or air seeder, double disk, fluted coulters	Wheat
	15 Apr. 2002	Sprayer, post-emergence	-
	10 July 2002	Harvest, killing crop, 30% standing stubble	-
	11 July 2002	Rake or windrower	-
	12 July 2002	Bale straw or residue	-
Sorghum-wheat-fallow (2-3-4)	1 May 2001	Sprayer, post-emergence	-
	16 June 2001	Planter, double disk opener, fluted coulter	Sorghum
	15 July 2001	Sprayer, post-emergence	-
	1 Oct. 2001	Harvest, killing crop, 30% standing stubble	-
	2 Oct. 2001	Rake or windrower	-
	3 Oct. 2001	Bale straw or residue	-
	4 Oct. 2001	Sprayer, post-emergence	-
	15 Oct. 2001	Drill or air seeder, double disk, fluted coulters	Wheat
	15 Apr. 2002	Sprayer, insecticide, post-emergence	-
	15 June 2002	Harvest, killing crop, 30% standing stubble	-
	16 June 2002	Rake or windrower	-
	17 June 2002	Bale straw or residue	-

Other WEPS parameters of importance were region, location, and simulation run. The region was set to 64 ha (160 acres), which is a quarter section of a typical square-mile Kansas field, for WEPS simulation in 1-3-1 and 2-3-4 crop rotations and set to 52 ha (130 acres) for WEPS simulations in a 1-1-1 crop rotation to simulate the use of center-pivots in southwestern Kansas. The location parameter varied depending on which county was being simulated. The simulation run parameter specified the WEPS simulation length. The NRCS mode, which specifies a fixed number of rotation cycles or years to be simulated (50 for this study), was chosen for all simulations. Simulations were run for all possible combinations of crop rotation, crop type, soil type, and LCC HWYld. They were then joined to the main soil thematic map, from which four crop- and rotation-based residue removal maps were created.

Estimating Feedstock Availability Based on Crop Rotation

Identifying Field Crop Rotation

Corn, sorghum, and wheat fields were first extracted from each CDL year, which created three layers: one with only corn fields (labeled CDL_Corn), another with only sorghum fields (labeled CDL_Sorghum), and a third layer with only wheat fields (labeled CDL_Wheat). For scenario 1 (Sc1), all corn fields were assumed to have a 1-1-1 crop rotation sequence, so a copy of the CDL_Corn layer was created and then renamed Sc1_C_CCC. The same procedure was done for sorghum and wheat fields, resulting in two additional layers: one that contained sorghum fields in a 2-3-4 rotation (Sc1_S_SWF) and a second layer that contained wheat fields in a 2-3-4 rotation (Sc1_W_SWF). For scenario 2 (Sc2), the previously created layer that contained only cells in a 1-3-1 crop rotation sequence (i.e., CrpRot_CWC) was clipped from the CDL_Corn layer, outputting a layer with only corn fields in a 1-3-1 rotation (Sc2_C_CWC). This newly created layer was then subtracted from the CDL_Corn layer to output a layer with only corn fields in a 1-1-1 crop rotation sequence (Sc2_C_CCC), which included corn fields that were re-labeled RndRot during the crop rotation identification and sequencing. The same procedure was done for the wheat fields, resulting in two additional layers: one that only contained wheat fields in a 1-3-1 rotation (Sc2_W_CWC) and a second layer that only contained wheat fields in a 2-3-4 rotation (Sc2_W_SWF). All sorghum fields were assumed to have a 2-3-4 crop rotation sequence, so a copy of the CDL_Sorghum layer was created and then re-named Sc2_S_SWF.

Estimating Feedstock Availability

The corn, sorghum, and wheat fields with specific crop rotations were then overlayed with corresponding residue removal maps to create crop- and rotation-specific maps with a specific residue removal rate. The output layer was subsequently intersected with the previously created service area polygons to generate maps of the fields and their corresponding residue removal rates according to service area. This allowed for the quantification of residue in each 16 km (10 mi) service area. To calculate the percent of feedstock per service area, the total dry tonnage required to meet the annual feedstock requirement of a given facility was first calculated on an average crop acreage basis using the following feedstock-specific theoretical ethanol yields: 491.4 L DT^{-1} (130 gal DT^{-1}) for corn stover, 428.3 L DT^{-1} (113 gal DT^{-1}) for sorghum stalk, and 483.8 L DT^{-1} (128 gal DT^{-1}) for wheat straw. The theoretical ethanol yields were calculated with the NREL web-based calculator (USDOE, 2013) using feedstock composition analysis data obtained from work done by Guragain et al. (2013). The residue available per service area was then divided by the estimated annual feedstock requirement, resulting in the percent of feedstock per service area for five facility capacities ranging from 151 to 757 million liters per year (MLY; 40 to 200 MGY).

Results and Discussion

Determining Representative Crop Rotations

A total of 3,118 possible crop value sequences were identified by the ArcGIS Combine tool within the study area for the five-year period from 2008 to 2012. The study area consists of 31 counties with a total area of 8,442,951 ha (21,107,377 acres). The majority of the hectares (58.1%; 4,908,659 ha; 12,271,648 acres) comprised developed land, rangeland, or pasture where no crops were grown in the specified five-year period. The remaining 41.9% (3,533,950 ha; 8,834,874 acres) of hectares had at least one crop planted in the specified five-year period, i.e., 9.6% (339,718 ha; 849,296 acres) of hectares had a 1-1-1 rotation, 14.3% (504,369 ha; 1,260,923 acres) had a 1-3-1 rotation, 27.5% (973,173 ha; 2,432,932 acres) had a 2-3-4 rotation, and the remaining 48.6% (1,716,690 ha; 4,291,724 acres) had less typical rotations for that specific study area. Therefore, the 1-1-1, 1-3-1, and 2-3-4 rotations were chosen to be representative crop rotations, given that they represented more than half of the cropland hectares in the study area.

Estimating Feedstock Availability Based on Crop Rotation

Table 2 shows estimated residue availability per 16 km (10 mi) service area from the plant location (Hugoton, Kans.) for five plant capacities (151, 227, 378, 567, and 757 MLY; 40, 60, 100, 150, and 200 MGY) using the multi-crop VRR (MC-VRR) GIS-based method as well as estimated annual feedstock requirements using crop hectare-weighted theoretical ethanol yields for corn, sorghum, and wheat. The first part of table 2 shows residue availability per 16 km (10 mi) service area using three different VRR rates (i.e., scenario 1). The VRR rate for corn was obtained using the 1-1-1 rotation WEPS simulation; the VRR rates for sorghum and wheat were obtained using the 2-3-4 rotation WEPS simulation. In the case of a plant with a 151 MLY (40 MGY) capacity in scenario 1, the first service area (0 to 16 km; 0 to 10 mi) was estimated to provide 37.8% of the annual feedstock requirement, while the second (16 to 32 km; 10 to 20 mi) provided the remaining 62.2%. Accordingly, a plant with a 151 MLY (40 MGY) capacity would meet its annual feedstock requirements within the second service area (16 to 32 km; 10 to 20 mi). For plants with other capacities, the total annual feedstock requirement would be met in the second service area (16 to 32 km; 10 to 20 mi) for the 227 MLY (60 MGY) capacity plant and in the third service area for plant capacities of 378, 567 and 757 MLY (100, 150, and 200 MGY).

The second part of table 2 shows the residue availability per 16 km (10 mi) service area using five VRR rates (i.e., scenario 2). The VRR rates for corn were obtained using the 1-1-1 and 1-3-1 rotation WEPS simulations, the wheat VRR rates were obtained with the 1-3-1 and 2-3-4 rotations, and the sorghum VRR rate was obtained with the 2-3-4 rotation. When comparing residue availability per service area from scenario 1 with scenario 2, an overall difference of 3,793 ±5,733 DT between service areas was observed. It was also observed that the first three service areas had decreases in residue availability (of 2.39%, 2.41%, and 0.04%, respectively), while the fourth and fifth service areas had

Table 2. Estimated hectare and residue availability (± standard deviations) per 16 km (10 mi) service area from the plant location (Hugoton, Kans.) for five plant capacities using the GIS-based multi-crop variable residue removal (MC-VRR) method and estimated annual feedstock requirements using crop hectare-weighted theoretical ethanol yields for two scenarios.[a]

		Service Area in km (mi)					
		0 to 16 (0 to 10)	16 to 32 (10 to 20)	32 to 48 (20 to 30)	48 to 64 (30 to 40)	64 to 80 (40 to 50)	
		Hectares (acres) Available per Service Area					
	Annual	10,268	33,821	31,572	44,298	46,290	
Plant	Feedstock	(25,372)	(83,574)	(78,017)	(109,462)	(114,385)	Total
Capacity	Required	Residue Available per Service Area (dry tons)[b]					(%)
MC-VRR Scenario 1		119,554 ±7,475	397,248 ±24,910	487,483 ±54,700	821,006 ±77,163	943,507 ±70,274	
151 (40)	315,994	37.8 ±2.4	62.2 ±7.9	-	-	-	100
227 (60)	473,992	25.2 ±1.6	74.8 ±5.3	-	-	-	100
378 (100)	789,986	15.1 ±0.9	50.3 ±3.2	34.6 ±6.9	-	-	100
567 (150)	1,184,979	10.1 ±0.6	33.5 ±2.1	56.4 ±4.6	-	-	100
757 (200)	1,579,972	7.6 ±0.5	25.1 ±1.6	67.3 ±3.5	-	-	100
MC-VRR Scenario 2		116,691 ±6,570	387,668 ±23,396	487,271 ±54,987	823,616 ±74,767	947,209 ±65,780	
151 (40)	315,992	36.9 ±2.1	63.1 ±7.4	-	-	-	100
227 (60)	473,988	24.6 ±1.4	75.4 ±4.9	-	-	-	100
378 (100)	789,980	14.8 ±0.8	49.1 ±3.0	36.2 ±7.0	-	-	100
567 (150)	1,184,970	9.8 ±0.6	32.7 ±2.0	57.4 ±4.6	-	-	100
757 (200)	1,579,960	7.4 ±0.4	24.5 ±1.5	68.1 ±3.5	-	-	100

[a] Plant capacity is in million liters per year (million gal per year), theoretical ethanol yield is in liters per dry ton (gal per dry ton), and annual feedstock required is in dry tons per year. Crop hectare-weighted theoretical ethanol yields are 491.4 L DT^{-1} (130 gal DT^{-1}) for corn stover, 428.3 L DT^{-1} (113 gal DT^{-1}) for sorghum stalk, and 483.8 L DT^{-1} (128 gal DT^{-1}) for wheat straw.

[b] Using conservation tillage practices conserving at least 30% soil coverage at second year planting.

increases (of 0.32% and 0.39%, respectively). Residue availability decreased by 2,863 DT for the first service area (0 to 16 km; 0 to 10 mi), by 9,580 DT for the second service area (16 to 32 km; 10 to 20 mi), and by 212 DT for the third service area (32 to 48 km; 20 to 30 mi), while residue availability increased by 2,610 DT for the fourth service area (48 to 64 km; 30 to 40 mi) and by 3,702 DT for the fifth service area (64 to 80 km; 40 to 50 mi). The differences in residue availability were attributed to the use of supplementary VRR rates in scenario 2, which created a shift in residue availability, given that crop rotations affect a crop's residue removal rate.

Table 3 shows the estimated annual hectare and residue availability per 16 km (10 mi) service area from the plant location (Hugoton, Kans.) for the crop rotations used in scenarios 1 and 2 using the GIS-based multi-crop variable residue removal (MC-VRR) method. It can be observed that the percent residue availability per service area differs within scenarios due to the amount of residue that each crop provides and between scenarios due to rotations used in the analysis. The five-year average for scenario 1 indicates that the majority of the residue in the first and second service areas is corn stover (64.9% and 65.5%) from a 1-1-1 rotation, with sorghum stalk (8.1% and 8.3%) and wheat straw (27.1% and 26.2%) from a 2-3-4 rotation making up the remainder. A 28.9% decrease in corn stover availability is observed between the second service area (16 to 32 km; 10 to 20 mi) and the fifth service area (64 to 80 km; 40 to 50 mi), which is counterbalanced by an increase in sorghum stalk (4.0%) and wheat straw (24.9%). Scenario 2 follows the same pattern, but the VRR rates for corn and wheat were obtained from more than one

Table 3. Estimated annual hectare and residue availability per 16 km (10 mi) service area from the plant location (Hugoton, Kans.) for the crop rotations used in scenario 1 and 2 using the GIS-based multi-crop variable residue removal (MC-VRR) method.

			Service Area in km (mi)									
			0 to 16 (0 to 10)		16 to 32 (10 to 20)		32 to 48 (20 to 30)		48 to 64 (30 to 40)		64 to 80 (40 to 50)	
			Hectares (acres) Available per Service Area									
			10,268 (25,372)		33,821 (83,574)		31,572 (78,017)		44,298 (109,462)		46,290 (114,385)	
Year	Crop	Rotation	Residue Available per Service Area[a]									
			Sc 1	Sc 2	Sc 1	Sc 2	Sc 1	Sc 2	Sc 1	Sc 2	Sc 1	Sc 2
2008	Corn	1-1-1	70.0	55.8	67.9	53.1	47.4	40.5	44.2	30.6	38.0	25.1
		1-3-1	-	12.7	-	13.2	-	14.8	-	11.5	-	10.8
	Sorghum	2-3-4	8.0	8.3	8.4	8.6	10.7	13.0	12.0	11.8	15.8	15.7
	Wheat	2-3-4	22.0	18.2	23.7	19.5	41.9	24.1	43.8	30.6	46.2	29.8
		1-3-1	-	5.0	-	5.6	-	7.6	-	15.5	-	18.6
	Total		100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
2009	Corn	1-1-1	61.4	48.0	62.6	47.6	44.6	31.2	40.0	28.0	34.4	22.6
		1-3-1	-	11.4	-	13.0	-	11.2	-	10.2	-	9.6
	Sorghum	2-3-4	7.7	7.9	8.1	8.2	7.5	7.5	9.5	9.5	8.9	8.9
	Wheat	2-3-4	30.9	22.7	29.3	21.8	47.9	37.9	50.5	42.5	56.7	48.5
		1-3-1	-	10.0	-	9.4	-	12.2	-	9.8	-	10.4
	Total		100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
2010	Corn	1-1-1	69.1	48.2	67.6	48.6	53.6	33.2	47.4	29.4	39.7	21.9
		1-3-1	-	18.7	-	16.8	-	18.0	-	16.0	-	15.6
	Sorghum	2-3-4	7.9	8.2	9.6	9.9	10.5	10.7	13.1	13.2	14.2	14.4
	Wheat	2-3-4	23.0	18.1	22.8	16.3	35.9	29.6	39.5	33.3	46.1	39.9
		1-3-1	-	6.8	-	8.4	-	8.5	-	8.1	-	8.2
	Total		100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
2011	Corn	1-1-1	64.4	52.1	68.2	52.9	52.0	37.3	46.7	33.0	38.2	24.7
		1-3-1	-	10.4	-	13.1	-	12.4	-	11.7	-	12.1
	Sorghum	2-3-4	8.0	8.2	6.0	6.1	8.2	8.1	8.5	8.4	10.0	9.9
	Wheat	2-3-4	27.6	18.4	25.8	16.4	39.8	29.3	44.8	35.2	51.8	41.4
		1-3-1	-	10.9	-	11.5	-	12.9	-	11.7	-	11.9
	Total		100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
2012	Corn	1-1-1	59.5	46.6	61.6	46.7	45.1	31.6	41.2	28.6	33.3	21.6
		1-3-1	-	10.6	-	12.7	-	11.1	-	10.8	-	9.6
	Sorghum	2-3-4	8.6	8.7	9.3	9.4	8.8	8.7	11.0	11.0	12.9	12.8
	Wheat	2-3-4	31.9	20.8	29.1	18.4	46.1	35.0	47.8	38.2	53.8	44.0
		1-3-1	-	13.3	-	12.8	-	13.6	-	11.4	-	12.0
	Total		100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Average	Corn	1-1-1	64.9	50.0	65.5	49.7	48.6	34.2	43.9	29.9	36.6	23.1
		1-3-1	-	12.9	-	13.8	-	13.4	-	12.1	-	11.5
	Sorghum	2-3-4	8.0	8.3	8.3	8.5	9.1	9.4	10.8	10.7	12.3	12.3
	Wheat	2-3-4	27.1	19.6	26.2	18.5	42.3	31.8	45.3	36.1	51.1	41.1
		1-3-1	-	9.2	-	9.5	-	11.2	-	11.2	-	12.0
	Total		100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

[a] Using conservation tillage practices conserving at least 30% soil coverage at second-year planting for scenarios 1 and 2.

rotation. The five-year average for the first service area (0 to 16 km; 0 to 10 mi) in scenario 2 indicates that 50.0% of the corn stover came from a 1-1-1 rotation and 12.9% came from a 1-3-1 rotation. In the case of wheat straw, 19.6% came from a 2-3-4 rotation and 9.2% came from a 1-3-1 rotation. Note that the percent total corn stover (62.9%) and wheat straw (28.8%) in scenario 2 differs from scenario 1 (64.9% and 27.1%, respectively). This is due to a difference in residue availability from disproportionally fewer corn hectares between scenario 1 (119,554 ±7,475) and scenario 2 (116,691 ±6,570).

Even though supplementary use of VRR rates in scenario 2 shifted how much each crop residue provides to each service area, the main driver for the difference in residue availability between scenarios was that a crop would have different VRR rates depending on which rotation it was in. The overall residue removal rates in scenario 1 averaged 5.8 ±2.0 DT ha^{-1} (2.3 ±0.8 DT ac^{-1}) for corn stover, 3.8 ±1.5 DT ha^{-1} (1.5 ±0.6 DT ac^{-1}) for sorghum stalk, and 3.8 ±1.0 DT ha^{-1} (1.5 ±0.4 DT ac^{-1}) for wheat straw. In scenario 2, supplementary VRR rates for corn and wheat were used, with average residue removal rates of 5.0 ±1.5 DT ha^{-1} (2.0 ±0.6 DT ac^{-1}) for corn stover in a 1-3-1 rotation and 4.5 ±1.3 DT ha^{-1} (1.8 ±0.5 DT ac^{-1}) for wheat in a 1-3-1 rotation. The supplementary use of VRR rates affected the overall residue removal rates in scenario 2 by decreasing corn stover to 5.5 ±2.0 DT ha^{-1} (2.2 ±0.8 DT ac^{-1}) and increasing wheat straw to 4.0 ±1.0 DT ha^{-1} (1.6 ±0.4 DT ac^{-1}). Sorghum stalk residue removal rates remained the same (3.8 ±1.3 DT ha^{-1}; 1.5 ±0.5 DT ac^{-1}), given that sorghum VRR rates for only the 2-3-4 rotation were used.

The difference between crop residue removal rates in different rotations was further investigated by analyzing the effect of soil characteristics (i.e., LCC), crop yield, and rotation on estimated residue removal rates within the study area. The study area average corn stover residue removal difference between 1-1-1 and 1-3-1 rotations was 10.7% ±3.8% for LCC 1, 32.7% ±3.6% for LCC 2, 6.7% ±3.8% for LCC 3, and 9.9% ±6.3% for LCC 4. The average wheat straw residue removal difference between 1-3-1 and 2-3-4 rotations was 10.6% ±2.4% for LCC 1, 10.2% ±7.3% for LCC 2, 13.0% ±6.0% for LCC 3, and 12.4% ±8.3% for LCC 4. When looking at the overall study area data for wheat straw, a larger percent difference was observed as the soil quality improved. Although this was not as obvious for corn stover, it became more apparent when looking at individual county data. Table 4 shows the effects of soil characteristics, crop yield, and crop rotation on estimated residue removal rates for corn and wheat in Stevens County. Given that yield and soil quality remained the same, the difference in residue removal rates was assumed to be affected by soil conditioning, which differs by rotation. For example, corn in a 1-1-1 rotation is typically supplemented with nitrogen, given that corn is a nitrogen-demanding crop. In contrast, corn in a 1-3-1 rotation might not necessarily be supplemented with as much nitrogen, given that wheat is expected to counterbalance some of the corn's demand for nitrogen. Hence, corn in a 1-1-1 rotation would have a higher grain yield potential, and consequently more residue would be available for harvest.

Table 4. Effect of soil characteristics, crop yield, and crop rotation on estimated residue removal rates using conservation practices for corn in 1-1-1 and 1-3-1 rotations and wheat in 1-3-1 and 2-3-4 rotations in Stevens County, Kansas.[a]

	Corn				Wheat			
LCC	Yield	VRR 1-1-1	VRR 1-3-1	% Diff.	Yield	VRR 1-3-1	VRR 2-3-4	% Diff.
1	12.28 (193)	9,643 (8,486)	8,638 (7,601)	10.4	4.45 (70)	6,560 (5,773)	5,920 (5,210)	9.8
2	10.44 (164)	7,376 (6,491)	5,000 (4,400)	32.2	3.50 (55)	4,474 (3,937)	3,817 (3,359)	14.7
3	8.59 (135)	4,442 (3,909)	4,173 (3,672)	6.1	2.23 (35)	3,477 (3,060)	2,784 (2,450)	19.9
4	5.09 (80)	2,383 (2,097)	2,245 (1,976)	5.8	2.55 (40)	2,570 (2,262)	2,433 (2,141)	5.3

[a] Yield is in metric tons per hectare (bushels per acre), and estimated variable residue removal (VRR) rate is in kg per hectare (lbs per acre).

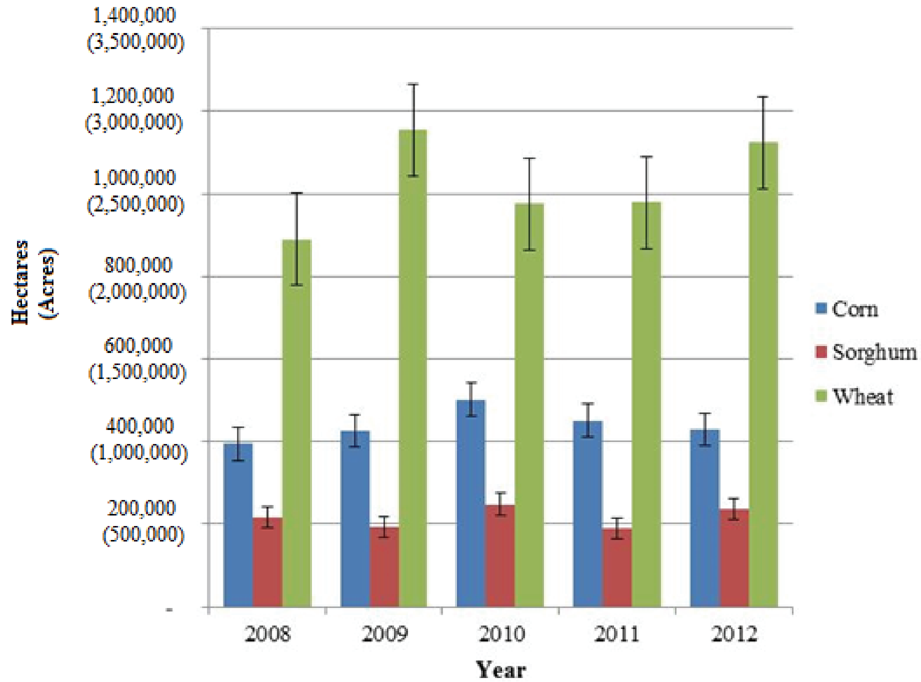

Figure 1. Five-year estimate of hectares planted to corn, sorghum, and wheat in the 100-mile service area.

The amount of residue available for harvest is a function of the amount of crop-specific hectares available in the study area. The higher the number of hectares, the more crop residue would be available, assuming that the soil quality remains constant. It was estimated, on average for the years 2008 to 2012, that the 100-mile service area had 1,682,675 ha (4,206,687 acres) planted to corn, sorghum, or wheat. Corn represented 26.2% (440,636 ha; 1,101,591 acres) of the total, sorghum represented 12.9% (217,432 ha; 543,579 acres), and wheat represented 60.9% (1,024,607 ha; 2,561,518 acres). Figure 1 shows the estimated hectares in the 100-mile service area per calendar year planted to corn, sorghum, and wheat. It can be observed that corn and sorghum hectares remained relatively constant throughout the five-year period, while wheat hectares had a drastic increase in 2009 and then leveled off and rose again in 2012. This surge was attributed to farmers planting more wheat hectares in response to the crop's higher market value due to global demand.

Validation of Estimated Procurement Area for Different Plant Capacities

Given that crop residue has seasonal availability, the procurement area previously estimated with the MC-VRR method using scenario 2 (table 2) was validated to ensure that the monthly feedstock requirement was met for the five plant capacities. First, the monthly feedstock requirement was calculated for each plant capacity by dividing the previously calculated annual feedstock requirement by twelve. The monthly feedstock requirements were 26,332.7 DT for a 151 MLY (40 MGY) plant, 39,499.0 DT for a 227 MLY (60 MGY) plant, 65,831.7 DT for a 378 MLY (100 MGY) plant, 98,747.5 DT for a

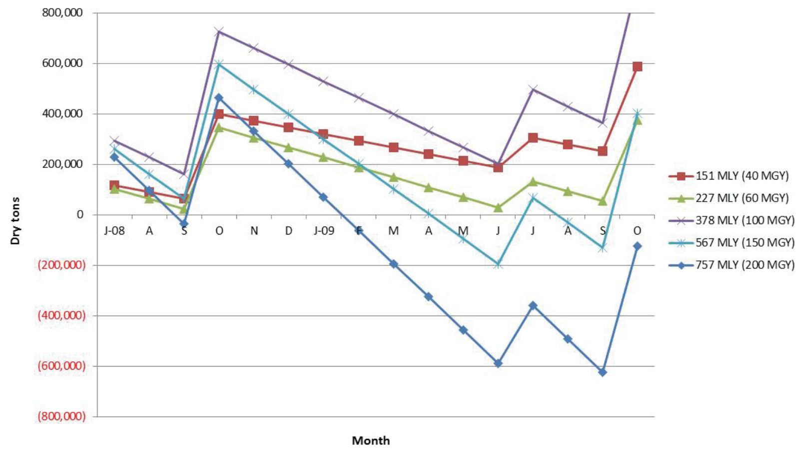

Figure 2. Monthly feedstock balance (in dry tons) for five plant capacities with plant operations starting in July 2008 and continuing through October 2009.

567 MLY (150 MGY) plant, and 131,663.3 DT for a 757 MLY (200 MGY) plant. The residue harvest month for each crop was obtained from the field management used to estimate the VRR rates (table 1). Therefore, wheat straw was harvested in July, and corn stover and sorghum stalk were harvested in October. Five-year average crop-specific residue availability at harvest time was obtained by calculating the amount of residue available in the number of service areas previously estimated.

Figure 2 shows the monthly feedstock balance (in dry tons) for the five plant capacities. It can be observed that plant capacities of 151 MLY (40 MGY), 227 MLY (60 MGY), and 378 MLY (100 MGY) would have enough raw material to produce the indicated amount of cellulosic ethanol every month, given that they procured feedstock from two service areas for plant capacities of 151 and 227 MLY (40 and 60 MGY) and from three service areas for a plant capacity of 378 MLY (100 MGY). In the case of higher-capacity plants (567 and 757 MLY; 150 and 200 MGY), this would not be the case, given that their monthly feedstock requirements are more than what the previously estimated service areas could provide. Therefore, an additional service area would be required for these plant capacities to meet their annual demands.

Given that residue availability varies by year, an annual assessment was done to see when higher-capacity plants (567 and 757 MLY; 150 and 200 MGY) would run out of feedstock if the plants started operations in July of the following years (2009 to 2012). It was estimated that a 567 MLY (150 MGY) capacity plant would run out of feedstock in 10, 10, 8, and 10 months, respectively. In the case of the 757 MLY (200 MGY) capacity plant, it would run out of feedstock in 7, 2, 2, and 8 months, respectively. Therefore, an additional service area would be required for both plant capacities if they started operations sometime between 2008 and 2012.

Conclusions

The results of this case study emphasize the importance of using multi-crop rotation cropping systems to better quantify feedstock availability to supply a biorefinery. Residue removal was maximized based on crop yield and rotation, soil characteristics, and field location and management, without causing soil erosion and while maintaining soil productivity. The following are specific conclusions reached in this study:

A difference of 3,793 ±5,733 DT was observed in estimated residue availability using conservation tillage practices, which ensures that at least 30% of the soil surface is covered with the first-year crop at the time the second-year crop is planted, between scenarios 1 and 2. This difference in residue availability was attributed to the supplementary use of VRR rates in scenario 2, which created a shift in residue availability, given that crop rotations affect a crop's residue removal rate.

The 1-1-1, 1-3-1, and 2-3-4 rotations were considered representative rotations for the study area because the total 3,533,950 ha (8,834,874 acres) of cropland were comprised of 9.6% (339,718 ha; 849,296 acres) with a 1-1-1 rotation, 14.3% (504,369 ha; 1,260,923 acres) with a 1-3-1 rotation, 27.5% (973,173 ha; 2,432,932 acres) with a 2-3-4 rotation, and the remaining 48.6% (1,716,690 ha; 4,291,724 acres) with less typical rotations.

The supplementary VRR rates in the analysis caused a decrease in average residue removal of corn from 5.8 ±2.0 DT ha^{-1} (2.3 ±0.8 DT ac^{-1}) in scenario 1 to 5.5 ±2.0 DT ha^{-1} (2.2 ±0.8 DT ac^{-1}) in scenario 2 (-5.2%). In the case of wheat, an increase in average residue removal was observed from 3.8 ±1.0 DT ha^{-1} (1.5 ±0.4 DT ac^{-1}) in scenario 1 to 4.0 ±1.0 DT ha^{-1} (1.6 ±0.4 DT ac^{-1}) in scenario 2 (+5.3%). Average residue removal for sorghum remained the same, given that sorghum VRR rates from only the 2-3-4 rotation simulation were used.

Crop-specific residue availability per service area affects residue availability. It was observed in scenarios 1 (SA1) and 2 (SA2) that the majority of the residue in the first (0 to 16 km; 0 to 10 mi) and second (16 to 32 km; 10 to 20 mi) service areas was corn stover (64.9% for SA1Sc1, 62.9% for SA1Sc2, 65.5% for SA2Sc1, and 63.5% for SA2Sc2), with sorghum stalk (8.1% for SA1Sc1, 8.3% for SA1Sc2, 8.3% for SA2Sc1, and 8.5% for SA2Sc2) and wheat straw (27.1% for SA1Sc1, 28.8% for SA1Sc2, 26.2% for SA2Sc1, and 28.1% for SA2Sc2) making up the rest of the residue available in those service areas. A decrease in corn stover availability was then observed between the second service area (16 to 32 km; 10 to 20 mi) and the fifth service area (64 to 80 km; 40 to 50 mi), which was counterbalanced by an increase in some sorghum stalk and mostly wheat straw.

Crop-specific hectare availability per service area also affected residue availability, given that the crops were not evenly distributed throughout the service areas. Corn represented 26.2% (440,636 ha; 1,101,591 acres), sorghum represented 12.9% (217,432 ha; 543,579 acres), and wheat represented 60.9% (1,024,607 ha; 2,561,518 acres) of the total hectares in the study area.

Crop-specific residue seasonal availability had an effect on procurement area, given that not all available feedstock was harvested at the same time. A validation of the previously estimated service areas indicated that plant capacities of 151 MLY (40 MGY), 227 MLY (60 MGY), and 378 MLY (100 MGY) would have enough feedstock every month to produce the indicated amount of cellulosic ethanol. For higher-capacity plants (567 and 757 MLY; 150 and 200 MGY), their monthly feedstock requirement was more than what the service areas could provide. Therefore, an additional service area would be needed to supply these larger plant capacities.

References

ArcGIS. (2012). ArcMap. Ver. 10. Redlands, Cal.: ESRI, Inc.

Crookston, R. K., Kurle, J. E., Copeland, P. J., Ford, J. H., & Lueschen, W. E. (1991). Rotational

cropping sequence affects yield of corn and soybean. *Agron. J., 83*(1), 108-113. http://dx.doi.org/10.2134/agronj1991.00021962008300010026x.
Cundiff, J. S., & Grisso, R. D. (2012). In-field operations to deliver biomass to a biorefinery. *Agric. Eng. Intl.: CIGR J., 14*(4), 115-122.
De Mol, R. M., Jogems, M. A., Beek, P. V., & Giglet, J. K. (1997). Simulation and optimization of the logistics of biomass fuel collection. *Netherlands J. Agric. Sci., 45*(1), 219-228.
Guragain, Y. N., Wilson, J., Staggenborg, S., McKinney, L., Wang, D., & Vadlani, P. (2013). Evaluation of pelleting as a pre-processing step for effective biomass deconstruction and fermentation. *Biochem. Eng. J., 77*(15), 198-207. http://dx.doi.org/10.1016/j.bej.2013.05.014.
Havlin, J. L., Kissel, D. E., Maddux, L. D., Claassen, M. M., & Long, J. H. (1990). Crop rotation and tillage effects on soil organic carbon and nitrogen. *SSSA J., 54*(2), 448-452. http://dx.doi.org/10.2136/sssaj1990.03615995005400020026x.
Krishnakumar, P., & Ileleji, K. E. (2010). A comparative analysis of the economics and logistical requirements of different biomass feedstock types and forms for ethanol production. *Appl. Eng. Agric., 26*(5), 899-907. http://dx.doi.org/10.13031/2013.41332.
Martinez, A., & Maier, D. E. (2011). Quantifying feedstock availability using a geographical information system. *Biol. Eng. Trans., 4*(3), 133-146. http://dx.doi.org/10.13031/2013.39814.
Martinez, A., & Maier, D. E. (2014). Improvements in quantification of biomass feedstock availability to a biorefinery using GIS-based method. *Trans. ASABE, 57*(2), 533-542.
Mukunda, A., Ileleji, K. E., & Wan, H. (2006). Simulation of corn stover logistics from on-farm storage to an ethanol plant. ASABE Paper No. 066177. St. Joseph, Mich.: ASABE.
Perlack, R. D., & Turhollow, A. F. (2003). Feedstock cost analysis of corn stover residues for further processing. *Energy, 28*(14), 1395-1403. http://dx.doi.org/10.1016/S0360-5442(03)00123-3.
Power, J. F., Koerner, P. T., Doran, J. W., & Wilhelm, W. W. (1998). Residual effects of crop residues on grain production and selected soil properties. *SSSA J., 62*(5), 1393-1397. http://dx.doi.org/10.2136/sssaj1998.03615995006200050035x.
Ravula, P. R., Grisso, R. D., & Cundiff, J. S. (2008). Cotton logistics as a model for a biomass transportation system. *Biomass Bioenergy, 32*(4), 314-325. http://dx.doi.org/10.1016/j.biombioe.2007.10.016.
Sokhansanj, S., Turhollow, A., & Perlack, R. (2002). Stochastic modeling of costs of corn stover costs delivered to an intermediate storage facility. ASAE Paper No. 024190. St. Joseph, Mich.: ASAE.
USDA. (1998). Legumes and soil quality. Soil Quality - Agronomy. Technical Note 6. Washington, D.C.: USDA Natural Resources Conservation Service. Retrieved from www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_053276.pdf.
USDA. (2006). Crop residue removal for biomass energy production: Effects on soils and recommendations. Soil Quality - Agronomy Technical Note 19. Washington, D.C.: USDA Natural Resources Conservation Service. Retrieved from www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_053253.pdf.
USDA. (2013). CropScape: Cropland data layer. Washington, D.C.: USDA Natural Resources Conservation Service. Retrieved from http://nassgeodata.gmu.edu/CropScape.
USDOE. (2003). Roadmap for agricultural biomass feedstock supply in the United States: Energy efficiency and renewable energy. Washington, D.C.: U.S. Department of Energy. Retrieved from http://feedstockreview.ornl.gov/pdf/hess/roadmap_for_ag_biomass_feedstock_supply_in_us.pdf.
USDOE. (2013). Theoretical ethanol yield calculator. Washington, D.C.: U.S. Department of Energy. Retrieved from www1.eere.energy.gov/biomass/ethanol_yield_calculator.html.
Vanotti, M. B., & Bundy, L. G. (1995). Soybean effects on soil nitrogen availability in crop rotations. *Agron. J., 87*(4), 676-680. http://dx.doi.org/10.2134/agronj1995.00021962008700040012x.
WEPS. (2010). WEPS ver. 1.0. Manhattan, Kans.: USDA-ARS Wind Erosion Research Unit.
Wilhelm, W. W., Doran, J. W., & Power, J. F. (1986). Corn and soybean yield response to crop residue management under no-tillage production systems. *Agron. J., 78*(1), 184-189. http://dx.doi.org/10.2134/agronj1986.00021962007800010036x.