A FEASIBILITY STUDY OF POSTHARVEST HANDLING, STORAGE AND LOGISTICS OF BIOENERGY CROPS

by

ADRIAN MARTINEZ-KAWAS

B.S., Universidad Autónoma de Nuevo León, 2006
M.S., Kansas State University, 2008

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Grain Science & Industry
College of Agriculture

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Abstract

The feasibility of utilizing cellulosic biomass as an energy feedstock is dominated by factors such as facility location, feedstock availability, and transportation cost. The main goal of this research was to develop a GIS-based method that will generate more accurate biomass residue availability data as input data to biomass supply chain logistics models. This research was carried out in four objectives to ensure that, as improvement parameters were implemented, the methodology remained valid and became more accurate. The first objective compared an existing method to a proposed method to quantify feedstock availability given a facility's location using a geographical information system. The proposed method proved to be more robust (by a factor of 1.45) than the existing method because it calculates the distance from the facility to farm fields using a real road network, and the acreage of crop-specific fields in a given service area based on crop season specific satellite images. The second objective implemented two improvement parameters to the previously proposed constant removal rate (CRR) method. It examined the effect of field-level yield variance and variable removal rates (VRR) on quantification of the feedstock availability supply for a biorefinery. The new VRR method predicted on average 113,384 ± 38,770 dry tons (DT) of additional residue per service area compared to the CRR method. The third objective further improved the VRR method by utilizing multiple crops as biomass sources and estimating VRR based on crop rotation. On average a 3,793 ± 5,733 DT per service area difference resulted when increasing the number of crop-specific VRR rates used to estimate feedstock quantification. The supplementary use of crop-specific VRR rates affected residue availability given a crop's residue removal rate is influenced by crop yield, crop rotation, soil characteristics, as well as field location and management. The fourth objective assessed the suitability of potential feedstock storage locations (FSL) to store multi-crop biomass remotely based on a spatial and location-allocation analysis. The sensitivity analysis showed that scenario 2 (16-km; 10-mile service area) appeared to be the more cost-effective option given fewer FSLs (35) were needed and more demand points could be serviced (98.1%) compared to scenario 1 (8-km; 5-mile service area; 62.1% demand points; 50 FSLs), despite presumably higher transportation costs.

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Dedication

This dissertation is dedicated to my mom Aida – a true example of a mother's devotion and love to her children.

Chapter 1 - Introduction

Renewable energy sources are critical for guaranteeing the energy future of the United States. Starch-based ethanol has been considered a significant renewable energy source, yet our increased dependence on this source has had negative effects on food and feed prices. Additionally, starch-based ethanol conversion has become a mature technology and is not expected to gain further significant conversion optimization or production cost reduction. Consequently, new alternative sources need to be explored in the quest for energy independence.

Cellulosic-based ethanol from lignocellulosic feedstock has become increasingly popular and is regarded as a sustainable and promising alternative renewable energy source (DiPardo, 2005; Farell et al., 2006). Lower greenhouse gas emissions, improved energy balance of the cellulosic-based ethanol conversion, advancement in fermentation technology, reduction in enzymes costs are just a few reasons why the use of renewable feedstock for fuel ethanol production has become more attractive. Despite these advancements, this technology has not yet reached its optimization point and many challenges remain.

Among the challenges are a feedstock's dispersed spatial and seasonal availability which are associated with the quantification of feedstock availability and the optimized selection of a biorefinery's location. These challenges are also known to make the collection, storage, and transportation of feedstock increasingly difficult and costly, as reported in the Biomass Road Map (USDA, 2003) and several recent studies (De Mol et al., 1997; Sokhansanj and Turhollow, 2002; Caputo et al., 2005; Ravula et al., 2008; Cundiff et al., 2004; Krishnakumar and Ileleji, 2010). Ultimately, correct selection of the facility location will result in more precise quantification of feedstock availability and prediction of transportation costs.

The use of simulation models provides researchers a quick and cost-effective method for determining the impact, value, cost of changes, as well as validating proposed enhancements. Recent studies have used simulation modeling to better understand the challenges and seek solutions to optimize the biomass supply chain and make cellulosic-based ethanol a cost competitive and sustainable renewable energy source for the coming years (Sokahansanj et al., 2003; Ravula et al., 2003; Atchinson and Hettenhaus, 2004; Cundiff et al., 2004). This study aims to further advance the research on the front-end of the biomass supply chain through the development of a new method which will more precisely quantify feedstock availability for a biorefinery using a Geographic Information System (GIS).

Chapter 2 - Research Objectives

The main goal of this research was to develop a GIS-based method that will generate more accurate biomass residue availability data as input data to biomass supply chain logistics models. The GIS-based method developed will be more accurate by using a real road network dataset, geo-referenced cropland satellite images, field-level yields, erosion control assessments, variable residue removal rates, and satellite storage depots to provide biomass in order to estimate residue availability in a feasible and sustainable way. This research was carried out through four objectives to ensure that, as improvement parameters were implemented, the GIS-based method remained valid and became more accurate.

1. Develop a new method to quantify biomass availability using a Geographical Information System (GIS) and compare it to the method developed by Mukunda et al. (2006).
2. Improve the developed GIS-based method by estimating variable residue removal rates based on location, climate, erosive force, soil characteristics, field-level yield, and field management.
3. Refine the developed GIS-based method by utilizing multiple crops as biomass sources and estimating variable residue removal rates based on crop rotation.
4. Assess the suitability of potential storage sites to store multi-crop biomass remotely based on a spatial analysis of the study area, and utilize these satellite storage depots to reduce on-site inventory of a biomass conversion facility.

Each objective is a self-contained peer-reviewed journal publication that makes up chapters 3, 4, 5, and 6, respectively. An overall summary of conclusions is provided in chapter 7, and future research recommendations are summarized in chapter 8.

Chapter 3 - Quantifying Feedstock Availability Using a Geographical Information System[1]

A. Martinez-Kawas, and D. E. Maier

ABSTRACT. *The feasibility of utilizing cellulosic biomass such as corn stover as an energy feedstock is dominated by factors such as facility location, feedstock availability, and transportation logistics. This study compares two methods to quantify feedstock availability given a facility's location using a geographical information system (GIS). The purpose is to highlight the advantages of using the proposed method (method 2) compared to a previously developed method (method 1). Method 1 is a straightforward approach in which the distance from the facility to the farm fields is first estimated and then hectare availability per service area is calculated using USDA-NASS statistics. Method 2 determines hectare availability by using geospatial images from which a service area is created based on a detailed road network dataset and a crop data layer. This method proved to be more accurate because it calculates the distance from the facility to the farm fields using a real road network and uses hectares of crop-specific fields in a given service area based on crop season-specific satellite images. Method 1 overestimated hectare availability per service area by 14,374 ha (35,518 ac; a factor of 1.45) on average, giving the false impression that a facility's annual feedstock requirement can be met within a shorter distance and with presumably lower transportation costs. The proposed GIS-based methodology will allow more reliable prediction of a feedstock supply area for existing or planned biomass- based processing facilities.*

Keywords. *Biomass, Corn stover, Feedstock, GIS, Transportation models.*

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[1] This chapter was published under the same title by A. Martinez and D. E. Maier in Biological Engineering Transactions of ASABE in August 2011 with the following citation 4(3): 133-146.

Introduction

Extensive research has been undertaken to evaluate various renewable feed-stocks capable of being converted efficiently into biofuel. Corn stover has received much attention in the past because it is considered the largest grain crop residue potentially available for use as a bioenergy feedstock (US DOE, 2005). It has been estimated that more than 238 million tons of corn stover (dry basis) are available annually in the U.S. (Sokhansanj et al., 2002). The challenge lies in strategically locating biomass conversion facilities in order to supply them with this corn stover in an economically feasible manner. This logistics challenge is dominated by factors such as facility location, feedstock availability, and transportation costs. A feedstock's dispersed spatial and seasonal availability are among the challenges associated with the optimized selection of a facility's location and the quantification of feedstock availability. These challenges are also known to significantly contribute to feedstock transportation costs, as reported in the Biomass Road Map (USDOE, 2003) and several recent studies (De Mol et al., 1997; Sokhansanj and Turhollow, 2002; Ravula et al., 2008; Cundiff et al., 2004; Krishnakumar and Ileleji, 2010). Ultimately, correct selection of the facility location will result in more precise quantification of feedstock availability and prediction of transportation costs. The main goal of this case study was to compare two approaches for the prediction of feedstock availability when modeling biomass logistics, and to utilize the more accurate approach to predict corn stover availability for a Kansas-based biomass conversion facility.

Literature Review

Geographical Information Systems (GIS) have been used in the past by researchers to predict a feedstock supply area for existing or planned biomass-based processing facilities. Accurately predicting a feedstock supply area will help to locate and supply conversion facilities with biomass in an economically feasible manner. A review of the literature revealed four different implementations of GIS-based approaches for feedstock availability analysis in biomass logistics models. Significant differences were found between models in regard to impact of implementation in terms of data used, data preparation, and the analysis itself. The first model was developed by Graham et al. (1996) for analyzing variations in potential bioenergy feedstock supplies and optimal locations for bioenergy facilities. This model had four basic components. The first component mapped cropland availability using GIS. The model then defined expected yield and farm-gate price in the second component. The third component calculated potential farm-gate supply of feedstock and mapped marginal costs of delivery. The last component identified, ranked, and mapped suggested site locations. This model used digital mapping to map cropland availability. Cropland availability analysis was done using a cropland map with a spatial resolution of 1 km^2 (i.e., 1 km^2 pixel size). The cropland map was created by first overlaying county boundary, soil group, and land use maps. The model then defined what proportion of each pixel was cropland suitable for growing switch-grass by linking county-level data on the relative dominance of conventional crops in each county to the map. To define what proportion of the pixel was cropland, several assumptions were made. Many assumptions were made based on bioenergy market maturity. For example, in a mature bioenergy market, farmers would only dedicate as much land to energy crops as they currently dedicate to the dominant crop in their area. However, in an immature bioenergy market, farmers would only grow energy crops on that land currently dedicated to minor crops. These assumptions and the spatial resolution of the cropland map may have reduced accuracy when quantifying feedstock availability.

The second biomass transportation logistics model was developed by the University of California, Davis, as part of the Western Governors' Association's Strategic Assessment of Bioenergy Development in the West Project (WGA, 2008). This model was found to be one of the most comprehensive biomass transportation logistics models to be developed in terms of feedstocks utilized, transportation network utilized, and area covered. Twenty-two different feedstocks were derived from agricultural and forest resources, as well as the utilization of municipal solid waste. The transportation network included existing highways, rail lines, and marine transportation routes. The area covered included 17 states in the western half of the U.S. Available feedstocks, potential biorefinery locations, and transportation costs were determined using GIS. These values were then input into a mixed integer linear optimization model created in the General Algebraic Modeling System (GAMS) to determine optimal spatial distributions of biomass supply. A trade-off made in this model was the use of county-level feedstock and transportation data. This helped simplify the complexity of network analysis, given the extent of the area covered by this model, by reducing the distances and times between potential locations. However, it also reduced accuracy when quantifying feedstock availability.

The third model provided a comprehensive GIS tool for locating cellulosic ethanol plants in the southeastern region of the U.S., with switchgrass as the primary feedstock (Wilson, 2009). The goal was to find a balance between functionality (UC Davis) and run time (RIBA project; Graham et al., 2002). The UC Davis model would not capture enough spatial variability for the purposes of this study, and the RIBA model's spatial resolution of 1 km^2 would make processing time unreasonable given that this was a multi-state analysis. It was determined that the switchgrass supply would be represented using areas defined by the intersection of soil boundaries and county boundaries, since the smallest unit of geographic data available for estimating crop yields is based on soil boundary data (Wilson, 2009). County-level crop hectares and yields were acquired from the USDA-NASS database. Overlaying county boundaries and soil maps generated a new dataset of boundaries referred to as crop zones, which varied depending on the underlying soil map pattern. Feedstock analysis was performed at the crop zone level for crop zones surrounding a potential biorefinery site within an 80 km (50 mi) concentric ring buffer. This model seemed to have a good balance between functionality and run time. However, it was still dependent on county-level agricultural statistics, which reduces accuracy when quantifying feedstock availability.

The fourth biomass transportation logistics model was developed by Mukunda et al. (2006). This model used discrete event simulation and ArcGIS to model the transportation logistics of a corn stover feedstock-based supply system. The feedstock availability was estimated using a straightforward approach in which the distance from the facility to the farm fields was first estimated using 16 km (10 mi) concentric ring buffers. Hectare availability per service area (i.e., each 16 km ring buffer) was then calculated using the 2002 Census of Agriculture (USDA-NASS, 2002). Based on observations, two input variables were responsible for most of the loss of accuracy in Mukunda's feedstock availability analysis. First, distance calculations from the facility to the farm fields used straight-line roads that do not exist in the real world; thus, a tortuosity factor had to be introduced into the model calculations. The tortuosity factor helped correct the straight-line ring buffer distances by simulating a road's natural weaving pattern. However, it was still not as accurate as a real road network. Second, the agricultural statistics used were based on county-level accuracy. As a result, when calculating acreage availability per service area, the available hectares were assumed to be evenly distributed throughout the county.

Based on the published literature, an improved GIS-based approach was explored that utilizes a real road network and geo-referenced, crop-specific spatial images to increase output accuracy. The potential of GIS has further improved because the USDA-NASS has made available satellite imagery taken during the crop growing season in every U.S. state. Cropland Data Layer (CDL) satellite images are a geo-referenced, crop-specific land cover data layer with a ground resolution of 56 m. These CDL images are produced during the growing season using satellite imagery using the Lansat 5 TM sensor, Landsat 7 ETM+ sensor, and the Indian Remote Sensing RESOURCESAT-1 (IRS-P6) Advanced Wide Field Sensor (AWiFS). The purpose of these satellite images is to (1) provide acreage estimates for each state's major commodities, and (2) produce digital, crop-specific, categorized geo-referenced output data. Development of a model using GIS combined with USDA-NASS satellite images will provide a powerful new tool for improved feedstock availability quantification.

Material and Methods

The reference location for this case study was the Abengoa Bioenergy Hybrid of Kansas facility near Hugoton, Kansas, which is in a high-density corn production area.

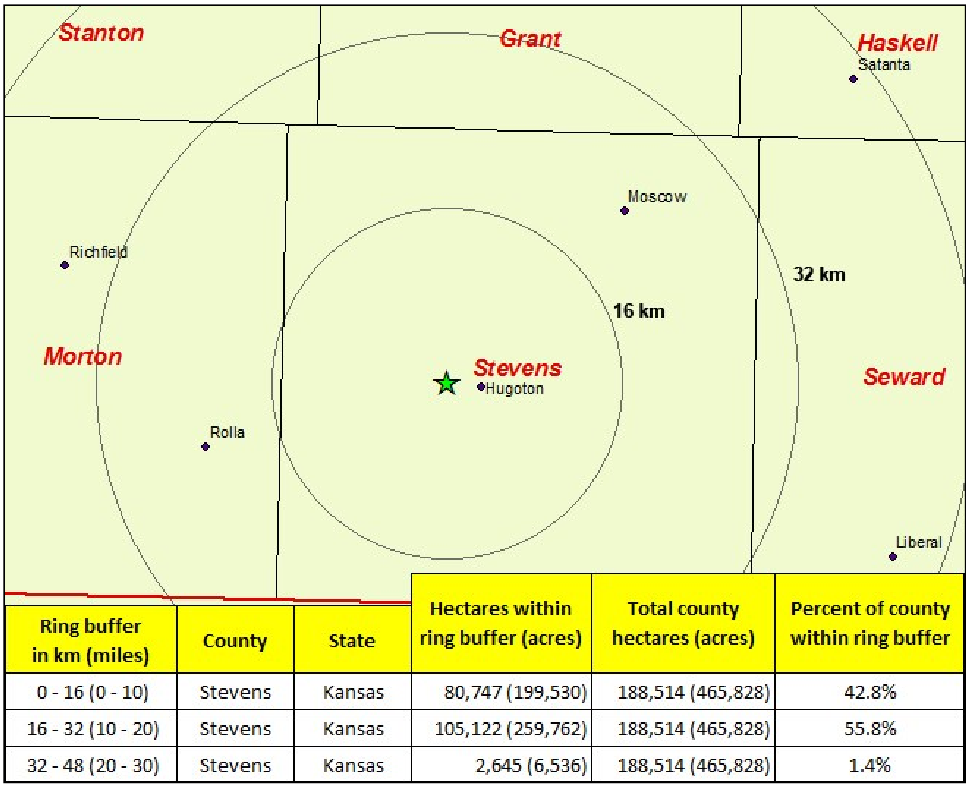
Method 1 – Using Concentric Ring Buffers

Method 1 is a straightforward approach developed by Mukunda et al. (2006) in which the distance from the facility to the farm fields is first estimated and then hectare availability per service area is calculated using agricultural statistics from the 2007 Census of Agriculture (USDA-NASS, 2007). It was assumed that a biorefinery will not procure corn stover that is more than 160 km (100 mi) from the facility, so concentric ring buffers were created in 16 km (10 mi) increments up to 160 km (100 mi) starting from the selected facility location (Hugoton, Kan.) as the reference point. Each ring buffer defined a specific service area. Once service areas were created, a summary of the counties and portions of counties falling into the respective service area was generated, as shown in figure 3.1. These percentages were later used to calculate the hectare feedstock availability per county per service area.

In order to calculate hectare feedstock availability, the harvested hectares per county during a past crop year and the number of farms that could supply corn stover to the facility per county were required. This information was found in the 2007 Census of Agriculture (USDA-NASS, 2007). The harvested hectares per county was found in "Table 26 – Field Crops 2007 and

2002" under "2007 Harvested Acres," subheading "Corn for Grain (Bushels)," and the number of farms that could supply corn stover to the facility by county was found under "Harvested Cropland by Acres Harvested," subheading "2007 Acres Harvested" in "Table 9 – Harvested Cropland by Size of Farm and Acres Harvested: 2007 and 2002." Mukunda et al. (2006) assumed that only farms with 40 ha (100 ac) or more would have the necessary resources to economically harvest and supply corn stover. Thus, the same was assumed for the purpose of this analysis. Selecting hectares harvested (USDA-NASS, 2007, table 9) from farms greater than 40 ha (100 ac) and then dividing by the total hectares harvested per county (USDA-NASS, 2007, table 9) resulted in the percent of farms presumed capable of supplying corn stover to the facility. Multiplying this by the harvested corn for grain hectares per county (USDA-NASS, 2007, table 26) yielded the value defined as "relevant corn hectares." Knowing the relevant corn hectares by county and the percent of county within each service area allows for calculation of the hectare availability per service area.

Figure 3.1 Concentric ring buffers representing three service areas from plant location 1 (located at the star). The table summarizes the hectares within each of the three ring buffers and the percent of the hectares within a specified county (i.e., Stevens) based on method 1.



Ring buffer in km (miles)	County	State	Hectares within ring buffer (acres)	Total county hectares (acres)	Percent of county within ring buffer
0 - 16 (0 - 10)	Stevens	Kansas	80,747 (199,530)	188,514 (465,828)	42.8%
16 - 32 (10 - 20)	Stevens	Kansas	105,122 (259,762)	188,514 (465,828)	55.8%
32 - 48 (20 - 30)	Stevens	Kansas	2,645 (6,536)	188,514 (465,828)	1.4%

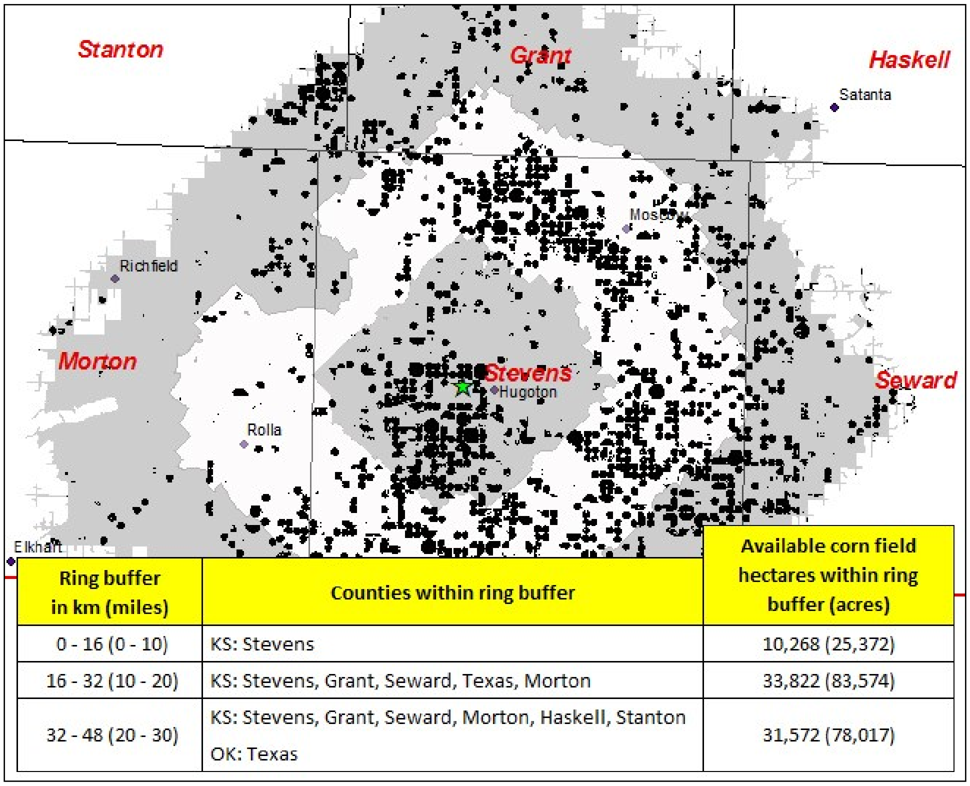
In order to determine the annual feedstock demand that would be supplied by each service area, the total hectares required to meet the annual feedstock requirement of the facility was calculated using a dry ton (DT) per hectare corn stover biomass conversion rate, and a liter per dry ton biomass yield constant. The biomass conversion factor is highly dependable on factors such as crop type, hybrid selection, till/no-till farming, and the use of irrigation. Mukunda et al. (2006) used 4.9 DT/ha (2 DT/ac) as the biomass conversion factor. Ileleji (2007) later suggested 7.4 DT/ha (3 DT/ac). These values represent 100% harvested biomass, which is not done in most cases because residue helps prevent soil erosion, as well as reduce crop water use by reducing soil water evaporation. In the case of the corn stover biomass yield, both suggest 272.5 L/DT (72 gal/DT). This value is highly dependable on the crop type and fermentation process. In this case study, the annual feedstock requirement was calculated using a corn stover biomass conversion factor of 7.4 DT/ha (3 DT/ac) and a bio-mass yield of 272.5 L/DT (72 gal/DT). The hectares available per service area was then divided by the estimated annual feedstock requirement, which resulted in the percent of feedstock per service area for five facility capacities ranging from 151 to 757 million liters per year (MLY), or 40 to 200 million gallons per year (MGY).

Method 2 – Using a GIS-Based Road Network Dataset

Method 2 estimates hectare availability using satellite images, from which a service area was created from a map-based road network dataset and an actual crop data layer for the same location in Hugoton, Kansas. Given the location, the study area boundary necessarily included the states of Colorado, Kansas, Oklahoma, Texas, and New Mexico. A CDL satellite image for each of these states was acquired from the USDA Geo-spatial Data Gateway (USDA-NRCS, 2010). The CDL satellite images were merged to reduce the computational processing time. Corn hectares were then selected from the merged image and extracted into a single-layer image containing only that biomass crop for the specific year selected. Using the Network Analyst Tool in ArcGIS, a service area based on the actual road network was created every 16 km (10 mi) from the specified facility location.

The corn production layer and service areas were then intersected to generate a layer with fields according to service area (figure 3.2). This allowed for the calculation of the corn field hectares in each 16 km (10 mi) service area. The total hectares required to meet the annual feedstock requirement of the facility was calculated using the same estimated average corn stover biomass conversion factor and estimated average biomass yield as in method 1. The hectares and percent of feedstock per service area for the same five facility capacities were then calculated.

Figure 3.2 GIS-based ring buffers representing three service areas from plant location 1 (located at the star). The table summarizes the counties by state within each of the three ring buffers and the available corn field hectares within the specified ring buffer based on method 2. The black dots indicate actual corn hectares within the three service areas as recorded by satellite image in 2009.



Ring buffer in km (miles)	Counties within ring buffer	Available corn field hectares within ring buffer (acres)
0 - 16 (0 - 10)	KS: Stevens	10,268 (25,372)
16 - 32 (10 - 20)	KS: Stevens, Grant, Seward, Texas, Morton	33,822 (83,574)
32 - 48 (20 - 30)	KS: Stevens, Grant, Seward, Morton, Haskell, Stanton OK: Texas	31,572 (78,017)

Validation of Area Calculation for Method 2

Precise area calculation is crucial for feedstock sourcing using a GIS-based method since satellite images are used to calculate field size area. Validation of area calculation was done to ensure that the area calculated by method 2 was correct. The approximate land area of all counties in Kansas was compared between the 2007 agricultural statistics from the Census of Agriculture (USDA-NASS, 2007) and the spatial values from the Tele Atlas Dynamap/2000 database obtained from the ESRI Maps and Data 2007 DVD (ESRI, 2007). The approximate land area from the Census of Agriculture was found in “Table 8 – Farms, Land in Farms, Value of Land and Buildings, and Land Use: 2007 and 2002,” subheading “Approximate Land Area,” and calculated using the “Calculate Geometry” function in ArcMap when using GIS (ArcGIS, 2005). The percent error between the 2007 Ag Census data and GIS calculated geometry was 0.78% on average (0.00% to 4.94% range) for all counties in Kansas.

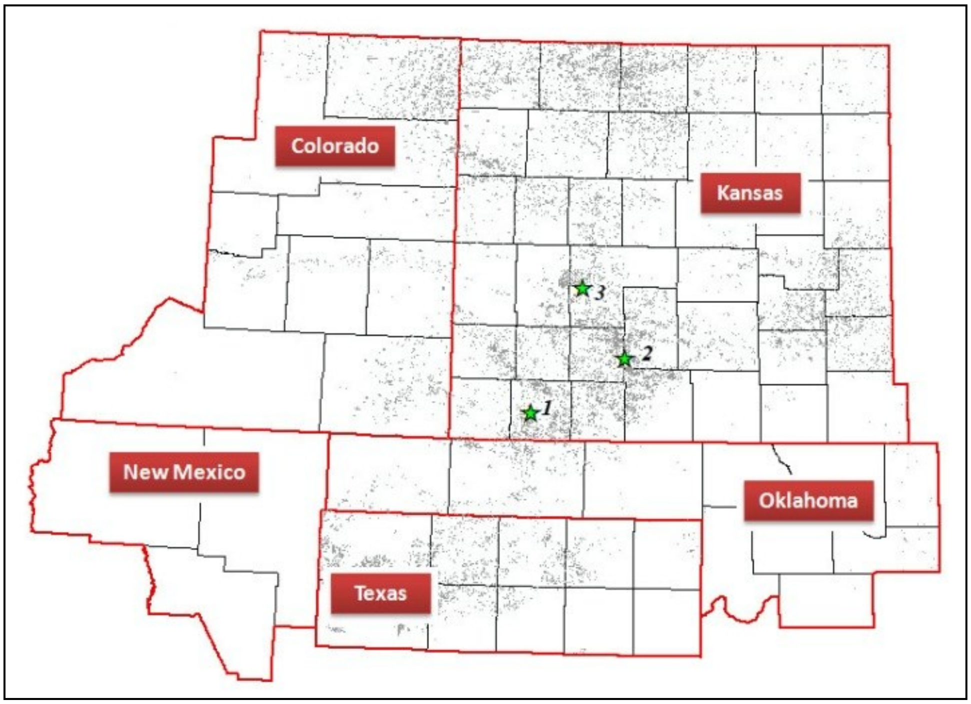
Validation of Method 2

To ensure that method 2 accurately quantified hectare availability regardless of corn hectare distribution, method 2 was validated by relocating the facility twice and observing the shift in hectare availability per service area. Figure 3.3 shows the original location (location 1) and the two alternative sites (locations 2 and 3) chosen for validation purposes. Location 2 is in Copeland, Kansas, southwest Gray County, approximately 80 km (50 mi) northeast of location 1. Location 3 is in Holcomb, Kansas, approximately 97 km (60 mi) northeast of location 1 and approximately 16 km (10 mi) west of Garden City, Kansas, in Finney County. Once the locations were set, new service areas were created for locations 2 and 3 using the same map-based road network used in method 2. The hectare availability and percent of feedstock per service area for the same five facility capacities were then calculated as in method 1.

ArcGIS Tools for Method 2

Tools were created in ArcGIS to reduce processing time as well as repetition error when processing data. Using the ArcGIS Model Builder together with existing tools from ArcToolbox, four tools were created. The first tool was used to clip the CDL satellite images to the user-specified study area boundary using extraction by mask. The second tool created a mosaic of the previously clipped CDL satellite images and output a single CDL satellite image. The new, merged image contained all the original layers. The purpose of clipping and merging the CDL images was to reduce processing time by only working with data included in the plant’s supply area. The third tool extracted a user-specified, crop-specific layer from the merged image. At this point the image was converted from a raster to polygon format for analysis purposes. The fourth tool intersected the crop-specific layer and the service area layer (created separately using the Network Analyst Tool in ArcGIS) to produce a layer with crop fields according to service area.

Figure 3.3 Location 1 of the facility near Hugoton, Kansas, and the two alternate locations (2 and 3) chosen for validation purposes. The black dots indicate actual corn hectares as recorded by satellite image within the selected study area boundary, which included the states of Colorado, Kansas, Oklahoma, Texas, and New Mexico in 2009.



Results and Discussion

Table 3.1 shows the estimated hectares and percent of hectare availability per 16 km (10 mi) service area from plant location 1 for five plant capacities (151, 227, 378, 567, and 757 MLY; 40, 60, 100, 150, and 200 MGY) and estimated annual feedstock requirements using both methods. The first part of table 1 shows the percent of hectare availability per 16 km (10 mi) service area using method 1. In the case of a plant with a 151 MLY (40 MGY) capacity, the first service area (0 to 16 km; 0 to 10 mi) was estimated to provide 32.5% of the annual feedstock requirements, while the second (16 to 32 km; 10 to 20 mi) and third (32 to 48 km; 20 to 30 mi) service areas would provide 58.9% and 8.6%, respectively. Consequently, according to method 1, a plant with a 151 MLY (40 MGY) capacity would meet its annual feedstock requirements based on the 2007 crop year in a 48 km (30 mi) ring buffer from plant location 1. In the case of plants with higher capacity (227, 378, 567, and 757 MLY; 60, 100, 150, and 200 MGY), the total annual feedstock requirements would be met in the third (32 to 48 km; 20 to 30 mi), fifth (64 to

80 km; 40 to 50 mi), sixth (80 to 96 km; 50 to 60 mi), and eighth (112 to 128 km; 70 to 80 mi) ring buffers, respectively.

The second part of table 3.1 shows the percent of hectares availability per 16 km (10 mi) service area using method 2. In the case of the 151 MLY (40 MGY) plant, annual feedstock requirement would still be met in the third service area (32 to 48 km; 20 to 30 mi), yet the percent of hectares available per service area was shifted due to a change in hectare availability per service area. The first service area (0 to 16 km; 0 to 10 mi) could now only provide 13.7% of the annual feedstock requirements because sustainably fewer hectares (10,268 ha; 25,372 ac) were predicted to be available in that service area compared to method 1 (24,392 ha; 60,275 ac). Fewer hectares were available in the second service area, too; hence, only 45.1% could be provided by the second service area (16 to 32 km; 10 to 20 mi). The rest of the annual required feed-stock (41.2%) would be supplied by the third service area (32 to 48 km; 20 to 30 mi). For the other four plant capacities (227, 378, 567, and 757 MLY; 60, 100, 150, and 200 MGY), it is important to notice that the supply area shifted by one service area (i.e., 16 km; 10 mi) in order to meet their respective annual feedstock requirements. In the case of plants of higher capacity (227, 378, 567, and 757 MLY; 60, 100, 150, and 200 MGY), the total annual feedstock requirements would be met in the fourth (48 to 64 km; 30 to 40 mi), sixth (80 to 96 km; 50 to 60 mi), seventh (96 to 112 km; 60 to 70 mi), and ninth (128 to 144 km; 80 to 90 mi) ring buffers, respectively. Differences in hectare availability per service area were observed for all service areas for the same five different plant capacities when comparing both methods. In the case of the first service area (0 to 16 km; 0 to 10 mi) for a 151 MLY (40 MGY) capacity plant, method 1 estimated that 24,392 ha (60,275 ac; 32.5%) would be available compared to the 10,268 ha (25,372 ac; 13.7%) predicted by method 2. This reduction in hectare availability per service area caused an increase in the number of total service areas needed to meet annual feedstock requirements: one additional service area for plants with 227, 378, and 567 MLY (60, 100, and 150 MGY) capacities and two additional service areas for the 757 MLY (200 MGY) capacity plant. This implies a higher prediction accuracy by method 2 compared to method 1, which repeatedly overestimated hectare availability, thus suggesting higher hectare availability per service area. This gave the false impression that a facility's annual feedstock requirement could be met within a shorter distance and presumably lower transportation costs.

Table 3.1 Estimated hectares and percent of hectare availability per 16 km (10 mi) service area from plant location 1 (Hugoton, Kansas) for five plant capacities using two methods and an estimated annual feedstock requirement.[a]

Plant Capacity	Annual Feedstock Required	Service Area, km (mi)										
		0-16 (0-10)	16-32 (10-20)	32-48 (20-30)	48-64 (30-40)	64-80 (40-50)	80-96 (50-60)	96-112 (60-70)	112-128 (70-80)	128-144 (80-90)	144-160 (90-100)	
		Hectares (acres) Available per Service Area										Total (%)
Method 1		24,392 (60,275)	44,114 (109,008)	44,051 (108,854)	60,534 (149,584)	56,980 (140,800)	55,063 (136,064)	66,523 (164,383)	68,637 (169,606)	71,269 (176,110)	69,323 (171,303)	
151 (40)	74,941 (185,185)	32.5	58.9	8.6	--	--	--	--	--	--	--	100
227 (60)	112,413 (277,778)	21.7	39.2	39.1	--	--	--	--	--	--	--	100
378 (100)	187,355 (462,963)	13.0	23.5	23.5	32.3	7.7	--	--	--	--	--	100
567 (150)	281,032 (694,444)	8.7	15.7	15.7	21.5	20.3	18.1	--	--	--	--	100
757 (200)	374,709 (925,926)	6.5	11.8	11.8	16.2	15.2	14.7	17.8	6.0	--	--	100
		Hectares (acres) Available per Service Area										
Method 2		10,268 (25,372)	33,821 (83,574)	31,572 (78,017)	44,298 (109,462)	46,290 (114,385)	62,350 (154,071)	56,696 (140,100)	50,378 (124,486)	45,548 (112,551)	37,388 (92,387)	
151 (40)	74,941 (185,185)	13.7	45.1	41.2	--	--	--	--	--	--	--	100
227 (60)	112,413 (277,778)	9.1	30.1	28.1	32.7	--	--	--	--	--	--	100
378 (100)	187,355 (462,963)	5.5	18.1	16.9	23.6	24.7	11.2	--	--	--	--	100
567 (150)	281,032 (694,444)	3.7	12.0	11.2	15.8	16.5	22.2	18.6	--	--	--	100
757 (200)	374,709 (925,926)	2.7	9.0	8.4	11.8	12.4	16.6	15.1	13.4	10.6	--	100

[a] Plant capacity is in million liters per year (million gallons per year), and annual feedstock required is in ha/year (ac/year).

Table 3.2 shows the differences in area and hectare availability per 16 km (10 mi) service area using method 1 and method 2. Estimating hectares and percent of hectare availability per 16 km (10 mi) service area is highly dependent on area calculation, and the area covered by each 16 km (10 mi) service area is different for each methodology (fig. 3.4). The first part of table 3.2 shows that on average, individual service area calculations using method 1 were 1.5 ± 0.12 times larger compared to method 2. This difference is due to how the area is calculated in each method. For method 1, the area per service area is calculated using the formula for the area of a circle, whereas method 2 uses ArcGIS to determine the shape complexity of each service area. The second part of table 3.2 shows that on average method 1 estimated 1.45 ± 0.41 times more hectare availability per service area compared to method 2. The larger standard deviation is the result of how hectare availability is estimated in each method. Using Stevens County as an example, figure 3.4 shows that most of the county's corn hectares are not evenly spread throughout the county, and most lay outside the innermost ring buffer. Method 1, which assumes that the total harvested hectares are evenly spread throughout the county, overestimated hectare availability by 14,124 ha (34,903 ac; a factor of 2.38) in the first service area (0 to 16 km; 0 to 10 mi) compared to method 2, which used map-based corn acreage locations to quantify hectare availability based on field-level data, creating the largest estimation difference between the methods. No correlation was observed between area and hectare availability estimation in either of the methods.

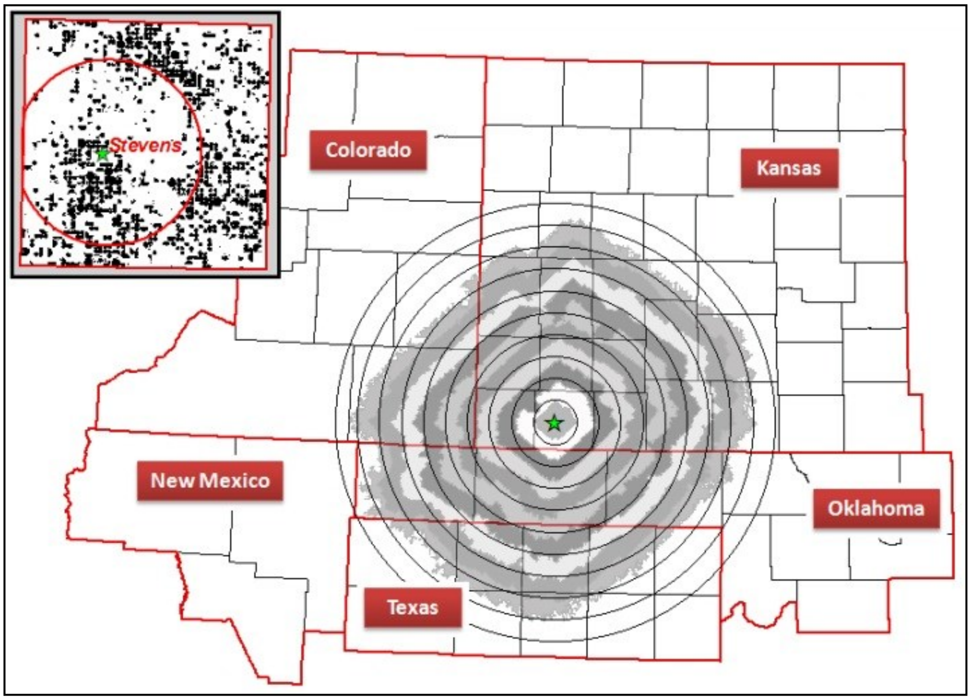
Table 3.2 Area and hectare availability per 16 km (10 mi) service area using method 1 and method 2.

	Service Area, km (mi)										
	0-16 (0-10)	16-32 (10-20)	32-48 (20-30)	48-64 (30-40)	64-80 (40-50)	80-96 (50-60)	96-112 (60-70)	112-128 (70-80)	128-144 (80-90)	144-160 (90-100)	Mean ± SD
Area per service area, km^2 (mi^2)											
Method 1	813 (314)	2,442 (943)	4,069 (1,571)	5,695 (2,199)	7,321 (2,827)	8,951 (3,456)	10,578 (4,084)	12,204 (4,712)	13,833 (5,341)	15,460 (5,969)	
Method 2	487 (188)	1,570 (606)	2,818 (1,088)	3,901 (1,506)	4,999 (1,930)	5,993 (2,314)	7,640 (2,950)	8,647 (3,339)	10,010 (3,865)	8,780 (3,390)	
Factor	1.67	1.55	1.44	1.46	1.47	1.49	1.38	1.41	1.38	1.76	1.50 ± 0.12
Hectares (acres) available per service area											
Method 1	24,392 (60,275)	44,114 (109,008)	44,052 (108,854)	60,535 (149,584)	56,980 (140,800)	55,063 (136,064)	66,523 (164,383)	68,637 (169,606)	71,269 (176,110)	69,324 (171,303)	
Method 2	10,268 (25,372)	33,821 (83,574)	31,572 (78,017)	44,298 (109,462)	46,290 (114,385)	62,350 (154,071)	56,696 (140,100)	50,378 (124,486)	45,548 (112,551)	37,388 (92,387)	
Factor	2.38	1.30	1.40	1.37	1.23	0.88	1.17	1.36	1.56	1.85	1.45 ± 0.41

Two key factors affecting the accuracy of method 1 were modified to increase the accuracy of hectare availability estimation in method 2. The first modification was to create service areas with realistic driving distances. Method 1 used the simplistic approach of straight-line driving distances from the facility to the fields within concentric ring buffers. This is less accurate than the map-based road network dataset used in method 2. The map-based road network dataset contains actual road parameters such as path, type (i.e., county road, highway), if it is a one-way street, and the speed limit. With these parameters, a true traveling distance from the facility to the fields can be precisely calculated, not just estimated. The second modification was the use of a data source with a higher level of accuracy. Method 1 used the 2007 Census of

Agriculture (USDA-NASS, 2007), which has only county-level accuracy, compared to the field-level accuracy in the CDL satellite images used in method 2. The use of CDL satellite images helped to identify each field's exact location to quantify each field's hectares.

Figure 3.4 Overlay of the respective 16 km (10 mi) service areas surrounding plant location 1 calculated using method 1 (concentric ring buffers) versus method 2 (GIS-based ring buffers). Stevens County is shown in the upper left corner, with the black dots indicating actual corn hectares as recorded by satellite image in 2009.

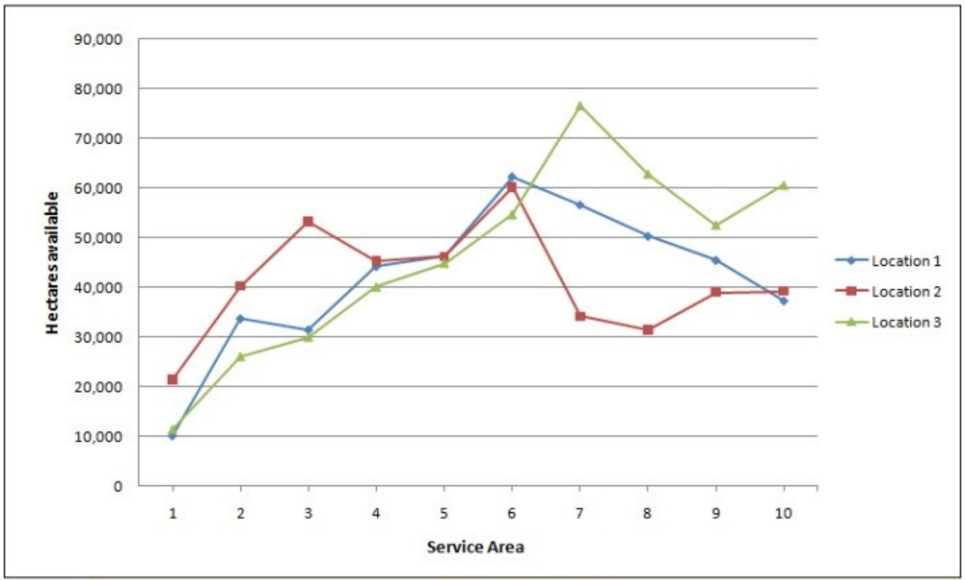


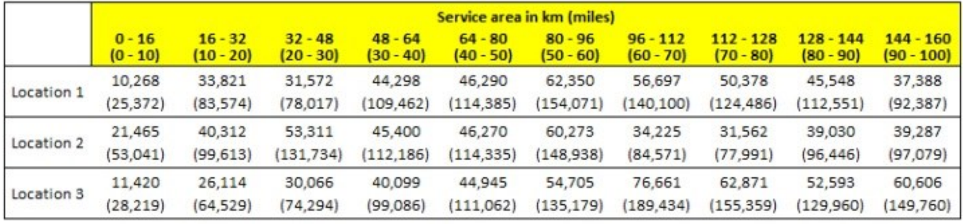
Validation Study: Method 2 – Using a GIS-Based Road Network Dataset

As expected, a shift in hectare availability per service area was observed when re-locating the plant from its original location. Figure 3.5 shows the estimated hectare availability per 16 km (10 mi) service area for the three plant locations using method 2. Location 1 showed a linear increase in hectare availability, reaching maximum availability (62,350 ha; 154,071 ac) at the sixth service area (80 to 96 km; 50 to 60 mi) and then decreasing linearly.

When the plant was moved to location 2, an increase in hectare availability toward the plant was observed, as well as two high-hectare availability areas. The first was reached at the third service area (32 to 48 km; 20 to 30 mi; 53,311 ha; 131,734 ac), followed by a decline in availability that leveled out before reaching a second maximum at the sixth service area (80 to 96 km; 50 to 60 mi; 60,273 ha; 148,938 ac). This was followed by a major drop in availability in the seventh service area (96 to 112 km; 60 to 70 mi; 34,225 ha; 84,571 ac) and a leveling off by the ninth service area (128 to 144 km; 80 to 90 mi; 39,030 ha; 96,446 ac). When the plant was moved to location 3, a steady linear increase in hectare availability was observed until maximum availability was reached at the seventh service area (96 to 112 km; 60 to 70 mi; 76,661 ha; 189,434 ac). It then decreased to 52,593 ha (129,960 ac) in the ninth service area (128 to 144 km; 80 to 90 mi) before increasing again to 60,606 ha (149,760 ac) in the tenth service area (144 to 160 km; 90 to 100 mi).

Figure 3.5 Predicted hectare availability per 16 km (10 mi) service area from three different plant locations using method 2.





	Service area in km (miles)									
	0 - 16 (0 - 10)	16 - 32 (10 - 20)	32 - 48 (20 - 30)	48 - 64 (30 - 40)	64 - 80 (40 - 50)	80 - 96 (50 - 60)	96 - 112 (60 - 70)	112 - 128 (70 - 80)	128 - 144 (80 - 90)	144 - 160 (90 - 100)
Location 1	10,268 (25,372)	33,821 (83,574)	31,572 (78,017)	44,298 (109,462)	46,290 (114,385)	62,350 (154,071)	56,697 (140,100)	50,378 (124,486)	45,548 (112,551)	37,388 (92,387)
Location 2	21,465 (53,041)	40,312 (99,613)	53,311 (131,734)	45,400 (112,186)	46,270 (114,335)	60,273 (148,938)	34,225 (84,571)	31,562 (77,991)	39,030 (96,446)	39,287 (97,079)
Location 3	11,420 (28,219)	26,114 (64,529)	30,066 (74,294)	40,099 (99,086)	44,945 (111,062)	54,705 (135,179)	76,661 (189,434)	62,871 (155,359)	52,593 (129,960)	60,606 (149,760)

These pattern variations affected the percent of hectare availability per service area. Table 3.3 shows the estimated hectares and percent of hectare availability per 16 km (10 mi) service area from the two alternate plant locations (location 2 and 3) for the same five plant capacities (151, 227, 378, 567, and 757 MLY; 40, 60, 100, 150, and 200 MGY) and estimated annual feedstock requirement using method 2. As previously discussed, location 2 hectare availability shifted toward the facility and had two high hectare availability areas. For the 227 and 378 MLY (60 and 100 MGY) capacity plants, the respective feedstock supply area was reduced by one service area. The second high hectare availability area (sixth service area; 80 to 96 km; 50 to 60 mi) did not seem to affect the percent of hectare availability for the 567 and 757 MLY (150 and 200 MGY) capacity plants much. In the case of the 757 MLY (200 MGY) capacity plant, the required service areas increased from nine to ten in order to meet the plant's annual feedstock requirements.

For location 3, a steady linear increase in hectare availability to maximum availability in the seventh service area (96 to 112 km; 60 to 70 mi) was observed. This hectare availability pattern was similar to the pattern observed for location 1. Given the steady increase, less area was available in the second service area (16 to 32 km; 10 to 20 mi), which affected the 151 and 227 MLY (40 and 60 MGY) capacity plants by requiring an extra service area to meet their annual feedstock requirements. Service area requirements remained the same for the 378, 567, and 757 MLY (100, 150, and 200 MGY) plant capacities. The maximum hectare availability area observed in the seventh service area (96 to 112 km; 60 to 70 mi) did not increase the needed service areas for plant capacities of 567 and 757 MLY (150 and 200 MGY).

ArcGIS Tools for Method 2

Not only did method 2 prove to be more accurate, but a reduction in overall processing time compared to method 1 was also observed. This reduction in processing time was achieved with the use of the tools created in ArcGIS. Processing time included image format check, loading the CDL satellite images, clipping images to the study area boundary, merging images, extracting crop-specific layers, creating service networks, intersecting layers, and finally summarizing hectare availability data. On average, a 15 min reduction (50%) in overall processing time was observed when using method 2. The limitation to using the ArcGIS tools is that the user has to have knowledge of the correct image format to be used, and how to create a service network. Method 1 can be done with a simple spreadsheet.

Table 3.3 Estimated hectares and percent of hectare availability per 16 km (10 mi) service area from two additional plant locations for five plant capacities using method 2 and an estimated annual feedstock requirement.[a]

Plant Capacity	Annual Feedstock Required	Service Area, km (mi)										Total (%)
		0-16 (0-10)	16-32 (10-20)	32-48 (20-30)	48-64 (30-40)	64-80 (40-50)	80-96 (50-60)	96-112 (60-70)	112-128 (70-80)	128-144 (80-90)	144-160 (90-100)	
		Hectares (acres) Available per Service Area										
Location 2		21,465 (53,041)	40,312 (99,613)	53,311 (131,734)	45,400 (112,186)	46,270 (114,186)	60,273 (148,938)	34,225 (84,571)	31,562 (77,991)	39,030 (96,446)	39,287 (97,079)	
151 (40)	74,941 (185,185)	28.6	53.8	17.6	--	--	--	--	--	--	--	100
227 (60)	112,413 (277,778)	19.1	35.9	45.0	--	--	--	--	--	--	--	100
378 (100)	187,355 (462,963)	11.5	21.5	28.5	24.2	14.3	--	--	--	--	--	100
567 (150)	281,032 (694,444)	7.6	14.3	19.0	16.2	16.5	21.4	5.0	--	--	--	100
757 (200)	374,709 (925,926)	5.7	10.8	14.2	12.1	12.3	16.1	9.1	8.4	10.4	0.9	100
		Hectares (acres) Available per Service Area										
Location 3		11,420 (28,219)	26,114 (64,529)	30,066 (74,294)	40,099 (99,086)	44,945 (111,062)	54,705 (135,179)	76,661 (189,434)	62,871 (155,359)	52,593 (129,960)	60,606 (149,760)	
151 (40)	74,941 (185,185)	15.2	34.8	40.1	9.9	--	--	--	--	--	--	100
227 (60)	112,413 (277,778)	10.2	23.2	26.7	35.7	4.2	--	--	--	--	--	100
378 (100)	187,355 (462,963)	6.1	13.9	16.0	21.4	24.0	18.6	--	--	--	--	100
567 (150)	281,032 (694,444)	4.1	9.3	10.7	14.3	16.0	19.5	26.1	--	--	--	100
757 (200)	374,709 (925,926)	3.0	7.0	8.0	10.7	12.0	14.6	20.5	16.8	7.4	--	100

[a] Plant capacity is in million liters per year (million gallons per year), and annual feedstock required is in ha year^{-1} (ac year^{-1}).

Conclusions

The results of this case study emphasized the importance of using an improved method to quantify the feedstock availability supply for a biorefinery. Data collected showed that quantification of feedstock availability using the GIS-based method 2 was possible, and was more accurate than the method used by Mukunda et al. (2006). Consequently, using the proposed method to predict the feedstock supply area for existing or planned biomass-based processing facilities will be faster and more reliable.

The following are specific conclusions reached from this study:

- Area calculation using method 2 was 1.5 times more accurate compared to method 1 because a map-based road network was used to calculate service areas instead of concentric circles.
- The estimation accuracy of hectare availability increased by a factor of 1.45 because the CDL satellite images used in method 2 were field-level accurate instead of being based on county-level statistics as in method 1.
- The use of GIS tools reduced human calculation error and processing time by 50% when using method 2.
- The use of a map-based road network dataset eliminated the use of a tortuosity factor, used later in method 1, to calculate driving distances in a discrete logistics model.
- Method 2 allows for calculating biomass sourcing costs based on more accurate transportation distances and times.

Chapter 4 - Improvements in Quantification of Biomass Feedstock Availability to a Biorefinery Using a GIS-Based Method[1]

A. Martinez-Kawas, and D. E. Maier

ABSTRACT. *The feasibility of utilizing cellulosic biomass such as corn stover as an energy feedstock is dominated by factors such as facility location, feedstock availability, and transportation cost. Previous research showed the advantages of using a GIS-based method compared to a previously used concentric ring buffer method. Even though the GIS-based method proved to be more accurate because it precisely calculates the distance from the facility to the farms using a real road network and hectares of crop-specific fields in a given service area, opportunities to further improve accuracy exist. In this case study two improvement parameters were implemented to the previously proposed GIS-based method to examine the effect of field-level yield spatial variance and variable residue removal rates on quantification of the feedstock availability supply for a biorefinery. The new variable residue removal (VRR) method predicted on average 113,384 ± 38,770 DT of additional residue per service area compared to the previous constant residue removal (CRR) method. The use of a constant removal rate of 3 DT/ac in the CRR method clearly underestimated feedstock availability given that residue removal rates are highly variable and subject to location, erosive forces, soil characteristics, crop type, yield, and field management. However, to prevent soil erosion and maintain soil productivity, conservation tillage practices require at least 30% of the soil surface must be covered with residue after planting the next crop. Even with a reduction in total feedstock availability, the VRR method estimated comparable residue availability per service area to the CRR method, with only a 4 ± 6% decrease per service area on average. Consequently, the VRR method turned out to be the preferred approach in the quantification of biomass feedstock availability.*

Keywords. *Biomass, Feedstock availability, Transportation logistics, GIS*

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[1] This chapter was submitted on March 8, 2013 under the same title by A. Martinez and D. E. Maier to Biological Engineering Transactions of ASABE and is still under review.

Introduction

Extensive research is ongoing to evaluate the potential of various renewable 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, feedstock availability, and transportation cost.

A feedstock's dispersed spatial and seasonal availability are amongst the challenges associated with the optimized selection of a facility's location and the quantification of feedstock availability. These challenges are also known to significantly contribute to feedstock transportation costs as reported in the Biomass Road Map (USDA, 2003) and several recent studies (De Mol et al., 1997; Sokhansanj and Turhollow, 2002; Ravula et al., 2003; Cundiff et al., 2004; Krishnakumar and Ileleji, 2010). Ultimately, correct facility location selection will result in more precisely quantifying feedstock availability and predicting 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 geo-reference, crop-specific satellite images. The intent was to compare this new approach to a previous approach proposed by Mukunda et al. (2006), which quantified hectare availability using concentric ring buffers together with the National Agricultural Statistics Service (NASS) Census of Agriculture data (USDA, 2002). Martinez and Maier's (2011) proposed GIS-based method estimated hectare availability using satellite images from which a service area was created based on a map-based road network dataset. It was concluded that the GIS-based method was more reliable compared to Mukunda et al. (2006) due to a more precise service area calculation and better estimation of hectare availability per service area. While the proposed GIS-based method proved feasible, the next logical step was to improve its capability of quantifying feedstock availability.

The main goal of this case study was to improve a previously proposed GIS-based feedstock sourcing method, and to utilize the improved approach to predict corn stover availability for a Kansas-based biomass conversion facility.

Improvement Parameters

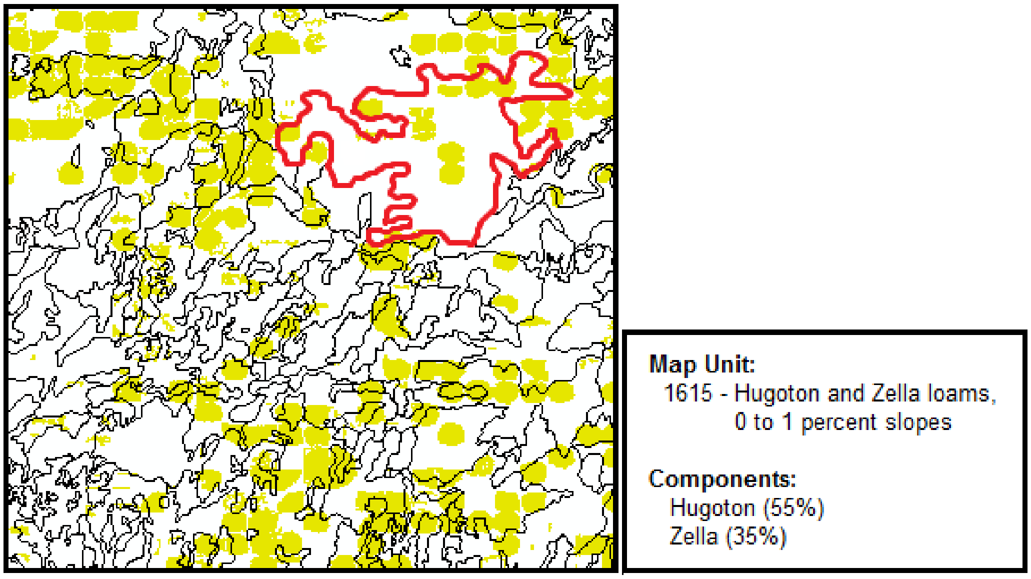
Estimating variable residue removal rates rather than having a constant removal rate was needed to improve quantification of feedstock availability. To be able to estimate variable residue removal rates, field-level yield estimations were needed. Consequently, the effect of field-level yield spatial variance based on soil characteristics, and variable residue removal rates based on erosion, soil characteristics, yield, and field management were examined as improvement parameters.

Field-level Yield Spatial Variance

The first improvement parameter examined was the effect of field-level yield spatial variance based on soil characteristics. Crop fields are generally composed of different soil map units (i.e., soil types) as observed in figure 4.1. Soil map unit delineation on a soil map represents an area dominated by one or more major types of soils. Soil map units are identified and named according to the taxonomic classification of the dominant soils. Areas of soil of a single taxonomic class rarely can be mapped without including areas of other taxonomic classes. Consequently, every map unit is made up of the soils for which it is named and some minor components that belong to taxonomic classes other than those of the major soils. Most minor soils have properties similar to those of the dominant soils or soils in the map unit, and thus they are assumed to not affect use or management.

Soil maps are available from the USDA National Resource Conservation Service (NRCS). The two most used databases are the State Soil Geographic (STATSGO) and the Soil Survey Geographic (SSURGO). The SSURGO database provides the most detailed level of information and serves as an excellent source for determining erodible areas and developing erosion control practices. Among the information available in the SSURGO database are soil-based parameters such as yield, hectare extent, erodibility factors, tolerable soil loss, and percent slope. The NRCS makes these data available both in tabular and spatial form.

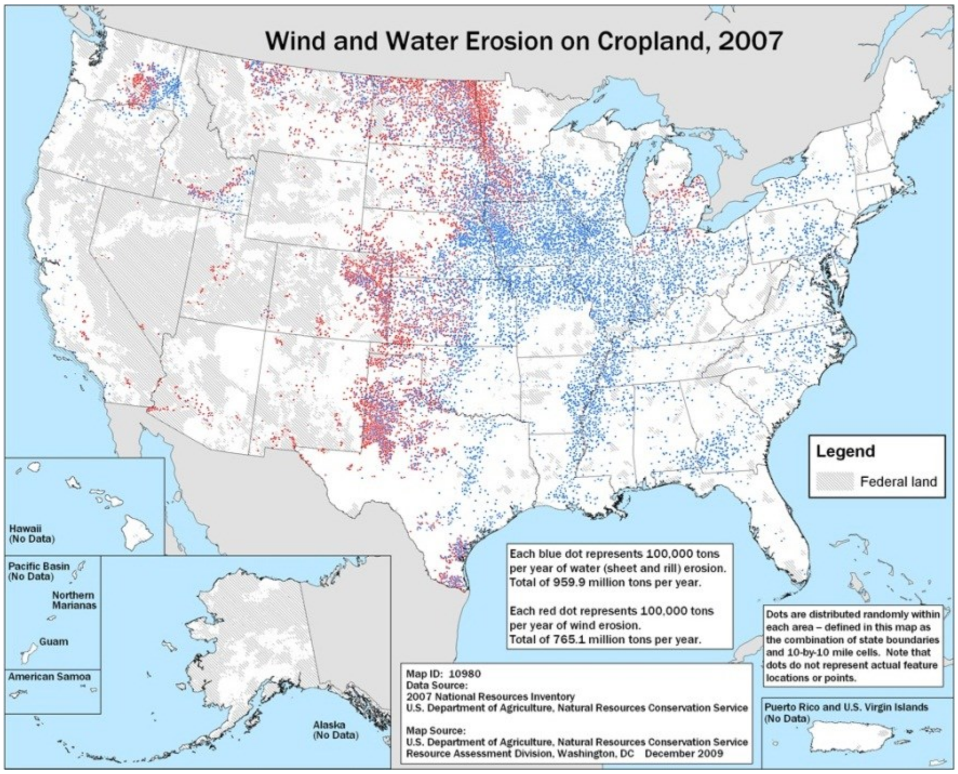
Figure 4.1 Overlay of the corn data layer showing the corn fields (yellow) and the soil layer showing the different soil map units (polygons) available in the northeastern part of Stevens County, Kansas. The insert shows the soil map unit, taxonomic classification, and percent composition of the highlighted polygon.



Variable Residue Removal Rates

The second improvement parameter examined was variable residue removal rates. The key factors affecting residue removal rates are erosion, soil characteristics, yield, and field management. In the previously proposed GIS-based method, 100% of the corn stover residue was removed at a constant removal rate of 7.4 DT/ha (3 DT/ac) throughout the study area. This is not common practice given that removing all the residue from a field will lead to erosion problems and loss in soil productivity due to the lack of nutrient cycling among other factors. Therefore, to be able to more accurately estimate agricultural crop residue removal, variable residue removal rates were examined in detail with respect to erosion, soil characteristics, field-level crop yield, and field management using the USDA Agricultural Research Service (ARS) Wind Erosion Prediction System (WEPS; USDA, 2012a). This simulation software was chosen because according to NRCS National Resource Inventory (NRI), in a typical year wind erosion predominates over water erosion in our selected study area (figure 4.2).

Figure 4.2 Twenty-five year estimate (1982-2007) of wind (red dots) and water (blue dots) erosion on cropland from the National Resource Inventory (NRI) Soil Erosion on Cropland 2007 Survey (USDA, 2007).



Each blue dot represents 100,000 tons per year of water (sheet and rill) erosion. Total of 959.9 million tons per year.

Each red dot represents 100,000 tons per year of wind erosion. Total of 765.1 million tons per year.

Dots are distributed randomly within each area – defined in this map as the combination of state boundaries and 10-by-10 mile cells. Note that dots do not represent actual feature locations or points.

Map ID: 10980
Data Source:
2007 National Resources Inventory
U.S. Department of Agriculture, Natural Resources Conservation Service

Map Source:
U.S. Department of Agriculture, Natural Resources Conservation Service
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Sensitivity Analysis of SSURGO Data

A sensitivity analysis was performed on the SSURGO data to collect preliminary data, given that not all soil yields were present in the data acquired from the NRCS. This analysis was deemed necessary given that if the soil yield was not present, the hectares the soil(s) accounts for would not be taken into account when calculating hectare weighted yields (HWYlds). HWYlds are the product of dividing total crop production, which is calculated by multiplying yield and soil hectares, by total soil hectares and are used to estimate field-level yields and variable residue removal rates. Consequently, the purpose of this sensitivity analysis was to quantify the effect of replacing “no data” yield values with an average yield.

Literature Review

GIS software has been shown by researchers to predict a feedstock supply area for existing or planned biomass-based processing facilities. Accurately predicting a feedstock supply area will help to locate and supply conversion facilities with biomass in an economically feasible manner. A review of literature published regarding factors that affect field-level yields as well as residue removable rates was done given that this case study focuses on these improvement parameters.

Agricultural residue removable rates are highly variable and depend on factors such as crop type, yield, location, climate, soil characteristics, and field management among other factors. Despite their high variability, constant residue removable rates are typically used in case studies where feedstock availability is being estimated based on hectare availability. A constant residue removal rate of 7.4 DT/ha (3 DT/ac) has been used to calculate corn stover availability (Perlack and Turhollow, 2003; Mukunda et al., 2006).

Perlack and Turhollow (2003) evaluated the costs for collecting, handling, and hauling corn stover to an ethanol conversion facility. To be able to calculate these costs, several assumptions were made regarding corn stover yield, erosion control, nutrient cycling, corn density, farmers' willingness to sell stover, and location/weather inhibiting factors. Corn stover yield was estimated by multiplying corn yield (bu/ac), corn grain dry matter content, and stover to grain ratio. Researchers estimated for their control scenario a constant removal rate of 7.7 DT/ha (3.1 DT/ac) based on an average corn yield of 8.27 MT/ha (130 bu/ac; 6.36-10.18 MT/ha; 100-160 bu/ac), corn grain dry matter of 0.85, and a grain to stover ratio of 1:1. It was assumed only 35% on average (20-50%) of this stover yield could be collected to control erosion and maintain soil nutrients. As a result, stover yield was reduced to 2.7 DT/ha (1.1 DT/ac) from initial estimates. Corn density, farmers' willingness to sell stover, and location/weather inhibiting factors were assumed to be 30, 50, and 10%, respectively. Collection area was then calculated by assuming a plant capacity (million gallons per year; MGY), a biomass yield of 272.5 L/DT (72 gal/DT), and the previously estimated corn stover yield. The hauling distance was computed as the radius of the average collection area. Given that straight-line distances were measured, a tortuosity factor had to be used to simulate a road's natural weaving pattern.

Mukunda et al. (2006) developed a discrete event simulation to model the transportation logistics of a corn stover feedstock-based supply system. Feedstock availability input data, which was fed into the transportation logistics model, was estimated using ArcGIS and agricultural statistics. Their approach was a straight forward one in which the distance from the facility to farm fields was estimated using 16-km (10-mile) concentric ring buffers in ArcGIS. Feedstock availability per service area (i.e., each 16-km ring buffer) was then calculated by multiplying hectare availability, which was estimated from the 2002 Census of Agriculture (USDA, 2002), by a constant removal rate of 7.4 DT/ha (3 DT/ac). Based on observations, two input variables were responsible for most of the loss in accuracy when estimating feedstock availability. First, straight-line distance calculations from the facility to the farm fields were used, requiring a tortuosity factor later on in the transportation logistics model similar to that of Perlack and Turhollow (2003). Nonetheless, it was still not as accurate as a real road. Second, agricultural statistics used are county-level based. As a result, when calculating hectare availability per service area it was assumed that the available hectares were distributed evenly throughout the county which is rarely seen.

Martinez and Maier (2011) proposed a GIS-based approach that utilized a real road network and geo-referenced, crop-specific satellite images to quantify feedstock availability. The intent of Martinez and Maier's (2011) proposed new GIS-based method was to compare it to the one used by Mukunda et al. (2006) as well as to explore its practical application. The proposed method estimated hectare availability using satellite images from which a service area was created based on a map-based road network dataset. Service areas, based on the actual road network, were created every 16 km (10 miles) from the specified facility location. The cropland data layer (CDL) and service areas were then intersected to generate a layer with corn fields according to service area. This allowed for the calculation of the corn field hectares in each 16-km (10-mile) service area. Subsequently, feedstock was quantified using a constant removal rate of 7.4 DT/ha (3 DT/ac). The authors concluded that their proposed method was more reliable compared to Mukunda et al. (2006) in service area calculation and estimation of hectare availability. The more precise service area calculation (on average by a factor of 1.5 ± 0.12) was the result of using a road network dataset instead of concentric circles. The better estimation of hectare availability per service area (on average by a factor of 1.45 ± 0.41) was a result of using field-level satellite images instead of county-level statistics. The one drawback was the use of a constant removal rate of 7.4 DT/ha (3 DT/ac) to estimate feedstock availability. Removal rates are highly variable due to location, erosive forces, soil characteristics, crop type, yield, and field management, thus vary from field to field.

Nelson (2002) developed a methodology to estimate "hectare-weighted" county-level, corn stover and wheat straw removable quantities subject to rainfall and wind-induced soil erosion. He chose both rainfall and wind erosion because these erosion forces predominate in his selected study area, which consisted of 37 States. Nelson concluded that of the 37 States analyzed North Dakota, Nebraska, Kansas, Oklahoma, Texas, and portions of south central Minnesota and north central Iowa were predominantly subject to wind erosion. In all other States, rainfall was the dominant erosive force. To estimate the amount of crop residue that could be removed from the field without exceeding tolerable soil loss limits, the amount of corn stover and/or wheat straw residue produced on an annual basis was subtracted from the amount of residue required for rainfall or wind erosion control, whichever was greater. The amount of residue required for erosion control was estimated using the wind erosion equation (WEQ) and the revised universal soil loss equation (RUSLE). With these equations, the minimum crop yields required to ensure that the average annual soil loss did not exceed the tolerable soil loss limit were calculated.

Another study (Larson et al., 1979) was found to use WEQ in past analysis to evaluate whether agricultural crop residues could be removed for alternative purposes such as bioenergy feedstock. The WEQ was the precursor of the WEPS. Nowadays, the WEPS is used to estimate average annual soil erosion on a site-specific field characterized by a particular soil type, slope and runoff length, field length, cropping and management practice, and localized climate.

Material and Methods

The reference location for this case study was the Abengoa Bioenergy Hybrid of Kansas facility near Hugoton, Kansas. Choosing the same location as Martinez and Maier (2011) helped us quantify accuracy gained as a result of utilizing field-level yield spatial variance and variable residue removal rates as improvement parameters.

Sensitivity Analysis of SSURGO Data

To quantify the effect of replacing “no data” yield values with an average yield on field-level yields and variable residue removal rates, county HWYlds were first calculated for all Counties in the study area. Individual county soil data (i.e., land capability class, hectare extent, and yield) was first obtained through the NRCS Soil Data Mart (USDA, 2012b). Land capability class (LCC), hectare extent, and yield were then matched using soil map units - a unique soil identifier. County soil data was then sorted by LCC, and then hectare extent within LCC. The county HWYld was calculated using only existing SSURGO yields by dividing the total crop production by total hectares of soils classified LCC 1, 2, 3 and 4, which was then labeled original county HWYld. A modified county HWYld was then calculated in the same manner with "no data" soil yield values, if any, replaced with the corresponding soil average LCC yield. This average LCC yield was calculated for each county LCC using only existing SSURGO yields. The counties with the minimum and maximum percent difference between original and modified county HWYlds were selected, as well as eight others that fell within that range, to be further analyzed.

Improvements to GIS-Based Method

Corn hectare availability and service areas were obtained using Martinez and Maier's (2011) GIS-based methodology. In brief, CDL satellite images for crop years 2008 and 2009 were first acquired from the USDA Geospatial Data Gateway (USDA, 2010). The CDL images were then merged, from which corn hectares were extracted. Using the Network Analyst Tool in ArcGIS, service areas were created in 16-km (10-mile) increments up to 160 km (100 miles) starting from the selected facility location (Hugoton, KS) as the reference point. The methodology was then modified to take into account the two improvement parameters.

The first improvement parameter, field-level yield spatial variance, was estimated using soil data from the SSURGO database. This data was acquired and sorted in the same manner as in the sensitivity analysis. County HWYlds were then calculated with "no data" soil yield values, if any, being replaced with the corresponding soil average LCC yield. These county HWYLds were subsequently validated against a 10-year National Agricultural Statistics Service (NASS) county yield average. Once yields were validated, a LCC HWYld was calculated in the same manner using only soils in each LCC. All LCC HWYlds were then joined to a soil LCC thematic map of the study area, which was created in ArcGIS using the NRCS Soil Data Viewer extension (USDA, 2011a).

The second improvement parameter, variable residue removal rates, was estimated using the USDA ARS WEPS. Factors such as weather, soil characteristics, yield, and field management were taken into account when running wind erosion simulation for soils NRCS classified as LCC 1, 2, 3, or 4 for each county. The soil with the highest hectare extent in each LCC was chosen to represent that LCC. Yields (i.e., LCC HWYlds) were obtained from the first improvement parameter estimates, and field management chosen was one representative for that region (table 4.1). Other WEPS parameters of importance were "region", "location", and "simulation run". The "region" describes the field geometry for WEPS. Field size was set to 53 hectares (130 acres) for all wind erosions given that center-pivots in southwestern Kansas are typically installed in 160-acre quarter sections of a square mile field. The "location" parameter defines the physical location of the field to be simulated and assists in selecting weather stations. Location 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 (50 for this study case) to be simulated, was chosen for all simulations. Simulations were run for all possible soil types and LLC HWYld combination scenarios and then joined to the soil thematic map created in ArcGIS.

Table 4.1 Field management used to simulate wind soil erosion.

Date, m/d/y	WEPS Operation	Vegetation
Apr 01, 01	Sprayer, kill crop	
Apr 20, 01	Fertilizer application – anhydrous w/ knife 30 in	
Apr 20, 01	Planter, double disk opener, fluted coulter	Corn
Jun 20, 01	Sprayer, post emergence	
Jul 20, 01	Sprayer, insecticide post emergence	
Oct 01, 01	Harvest, killing crop 20pct standing stubble	
Oct 02, 01	Rake or windrower	
Oct 05, 01	Bale straw or residue	

Once both improvement parameters were joined to the soil thematic map, this map was intersected with the corn hectare availability map. The output map was subsequently intersected with the service area polygons to generate ten maps with fields and their corresponding residue removal rate according to service area. This allowed for the quantification of residue in each 16-km (10-mile) service area. To calculate percent of feedstock per service area, the total dry tonnage required to meet the annual feedstock requirement of a given facility was first calculated using a biomass yield of 272.5 L/DT (72 gal/DT) as in the previous constant residue removal rate GIS-based method. The residue available per service area was then divided by the estimated annual feedstock requirement resulting in percent of feedstock per service area for five facility capacities ranging from 151 to 757 million liters per year (MLY; 40 to 200 MGY).

Validation of Hectare Weighted Yields

Before LCC HWYlds were used to estimate variable residue removal rates, the county HWYlds were validated against 10-year NASS irrigated corn yield averages, which were initially cross-checked for accuracy against 7-year Farm Service Agency (FSA) irrigated corn yield averages. First, NASS and FSA irrigated corn yields were acquired. County averages were then calculated for each set using the ten (NASS) and seven (FSA) most recent (year-wise) available county yields. A ±10% yield range was then calculated for each county using the 10-year NASS irrigated corn yield averages. The 7-year FSA yield averages were then compared against the established range to see if they were within range. The goal was not to have more than 20% of the 7-year FSA yield averages fall outside the established range. Once NASS yield averages were validated, these were compared against the county HWYlds in the same manner.

Results and Discussion

Sensitivity Analysis of SSURGO Data

The first part of table 4.2 shows estimated original and modified HWYlds and estimated residue removal rates per LCC for ten counties in the study area. Using Stevens County as an example, the original LCC 1 HWYld was calculated using only LCC 1 soils that came with a yield in the original SSURGO data. The original HWYld value for LCC 1 was 12.35 MT/ha (194 bu/ac). After the "no data" yield values were replaced with the calculated average LCC 1 yield, the HWYld for LCC 1 decreased to 12.22 MT/ha (192 bu/ac; 1.0% difference). In the case of the other LCCs, the HWYld increased for LCC 2 from 10.31 MT/ha (162 bu/ac) to 10.37 MT/ha (163 bu/ac; 0.6% difference), and remained unchanged for LCC 3 (8.59 MT/ha; 135 bu/ac) and LCC 4 (5.09 MT/ha; 80 bu/ac). The reason HWYlds remained the same for LCC 3 and 4 was because existing soil yields were all the same value, and since existing soils are used to calculate the average LCC yield, the HWYlds remained the same. Interestingly, even though there was a percent difference in LCC 1 and 2, the estimated LCC residue removal rates remained the same.

The second part of table 4.2 shows the percent difference between original and modified HWYld and percent of soil hectares without a yield per LCC. For Stevens County, it was observed that 13.7% (9,407 ha; 23,245 ac) of the total LCC 1 soil hectares had missing yields. LCC 2 had 10.1% (9,691 ha; 23,947 ac), LCC 3 99.9% (31,371 ha; 77,519 ac), and LCC 4 65.1% (5,993 ha; 14,809 ac) of the total LCC soil hectares without a yield. In total, 27.5% (56,462 ha; 139,520 ac) of the county soil hectares classified LCC 1, 2, 3 and 4 were missing a yield values.

A separate analysis was undertaken to calculate the percent soil hectares without a yield per county. It was observed that on average, 21.8 ± 20% of county hectares were missing a yield value, with the minimum being 0.0% (Greeley, KS) and the maximum 67.9% (Cimarron, OK). The State of Texas had on average the highest percent of soil hectares without a yield (37.4 ± 18.2%), followed by Oklahoma (36.3 ± 25.9%), Colorado (27.9 ± 18.1%) and Kansas (10.3 ± 11.7%). In order to determine at what level of missing yield values the modified HWYLd should be calculated, the number of counties with soil hectares missing yield values was quantified. A lower limit was set and then the number of counties was counted for which the percent of soil hectares missing yield exceeded the established limit. The lower limit of 20% was increased to 50% in 5 percent point increments. Fifteen counties out of the 31 in the study area (i.e., 48%) had 20 and 25% of its hectares missing yield values decreasing to 10 (32%), 6 (19%), 5 (16%), 3 (10%), and 3 (10%) counties having hectares missing a yield, respectively. Given that the greatest decrease in number of counties missing yield values was observed between limits of 25 and 35%, it was concluded that setting the lower limit at 35% would be best for our case study.

Given that estimation of LCC HWYlds is dependent on existing SSURGO yields, we determined that it is advisable to verify acquired SSURGO yield data before using it. If more than 20% of the study area counties have more than 35% of their soil hectares without a yield value, calculating modified HWYLd values will offer a more accurate representation of a county's LCC HWYlds, which is used to predict residue removal rates.

Table 4.2 Estimated original and modified hectare weighted yields (HWYlds) and estimated residue removal rates per land capability classification (LCC) for ten counties in the study area as well as percent difference between HWYlds and percent soil hectares without a yield. Original HWYlds were calculated using only existing soil yields whereas modified HWYlds took into account soil hectares without a yield after replacing the "no data" yield value for an average LCC yield.

	HWYlds in MT/ha (bu/ac) and Estimated Residue Removal Rates in kg/ha (lb/ac) per LCC									
	Original values									
	LCC 1		LCC 2		LCC 3		LCC 4		County	
Baca, CO	8.65	8,607	8.53	8,955	8.34	8,697	7.95	9,084	8.40	
	(136)	(7,574)	(134)	(7,880)	(131)	(7,653)	(125)	(7,994)	(132)	
Ford, KS	11.84	11,760	11.45	11,883	8.72	9,334	6.62	7,651	11.07	
	(186)	(10,349)	(180)	(10,457)	(137)	(8,214)	(104)	(6,733)	(174)	
Greeley, KS	11.39	11,159	8.40	9,090	7.45	8,130	6.05	7,213	10.37	
	(179)	(9,820)	(132)	(7,999)	(117)	(7,154)	(95)	(6,347)	(163)	
Meade, KS	11.84	12,307	10.37	10,826	9.67	10,398	--	--	11.01	
	(186)	(10,830)	(163)	(9,527)	(152)	(9,150)			(173)	
Stevens, KS	12.35	12,523	10.31	10,585	8.59	9,185	5.09	5,920	11.01	
	(194)	(11,020)	(162)	(9,315)	(135)	(8,083)	(80)	(5,210)	(173)	
Beaver, OK	9.23	9,411	8.53	8,782	6.17	6,992	7.32	8,241	7.89	
	(145)	(8,282)	(134)	(7,728)	(97)	(6,153)	(115)	(7,252)	(124)	
Cimarron, OK	--	--	11.71	11,914	11.14	12,231	6.36	7,211	10.63	
			(184)	(10,484)	(175)	(10,763)	(100)	(6,346)	(167)	
Hutchinson, TX	--	--	11.90	11,838	9.35	10,128	--	--	11.26	
			(187)	(10,417)	(147)	(8,913)			(177)	
Lipscomb, TX	--	--	11.01	10,924	10.18	10,925	7.95	8,538	10.05	
			(173)	(9,613)	(160)	(9,614)	(125)	(7,513)	(158)	
Roberts, TX	10.18	10,216	11.58	11,984	9.48	9,611	7.06	8,009	10.37	
	(160)	(8,990)	(182)	(10,546)	(149)	(8,458)	(111)	(7,048)	(163)	
	Modified Values									
	LCC 1		LCC 2		LCC 3		LCC 4		County	
Baca, CO	9.10	9,644	8.72	9,488	8.27	8,692	7.89	9,084	8.59	
	(143)	(8,487)	(137)	(8,349)	(130)	(7,649)	(124)	(7,994)	(135)	
Ford, KS	11.77	11,760	11.33	11,883	8.59	9,334	6.62	7,651	10.88	
	(185)	(10,349)	(178)	(10,457)	(135)	(8,214)	(104)	(6,733)	(171)	
Greeley, KS	11.39	11,159	8.40	9,090	7.45	8,130	6.05	7,213	10.37	
	(179)	(9,820)	(132)	(7,999)	(117)	(7,154)	(95)	(6,347)	(163)	
Meade, KS	11.84	12,307	10.37	10,826	9.67	10,398	--	--	10.95	
	(186)	(10,830)	(163)	(9,527)	(152)	(9,150)			(172)	
Stevens, KS	12.22	12,522	10.37	10,585	8.59	9,185	5.09	5,920	10.50	
	(192)	(11,020)	(163)	(9,315)	(135)	(8,083)	(80)	(5,210)	(165)	
Beaver, OK	9.23	9,411	8.59	8,782	6.11	6,990	7.32	8,241	7.38	
	(145)	(8,282)	(135)	(7,728)	(96)	(6,151)	(115)	(7,252)	(116)	
Cimarron, OK	--	--	11.45	11,914	11.14	12,231	6.36	7,211	10.50	
			(180)	(10,484)	(175)	(10,763)	(100)	(6,346)	(165)	
Hutchinson, TX	--	--	11.84	11,838	9.48	10,128	--	--	10.31	
			(186)	(10,417)	(149)	(8,913)			(162)	
Lipscomb, TX	--	--	10.82	11,590	10.18	10,925	7.95	8,538	9.10	
			(170)	(10,199)	(160)	(9,614)	(125)	(7,513)	(143)	
Roberts, TX	10.18	10,216	11.33	11,984	9.48	9,611	7.19	8,009	8.53	
	(160)	(8,990)	(178)	(10,546)	(149)	(8,458)	(113)	(7,048)	(134)	
	Percent Difference between HWYlds and Percent of Soil Hectares Without a Yield per LCC									
	LCC 1		LCC 2		LCC 3		LCC 4		County	
Baca, CO	5.1	55.5	2.2	48.4	0.8	20.3	0.8	38.8	2.3	40.7
Ford, KS	0.5	4.2	1.1	7.2	1.5	13.3	0.0	19.8	1.7	7.2
Greeley, KS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Meade, KS	0.0	0.0	0.0	1.6	0.0	38.8	--	--	0.6	7.1
Stevens, KS	1.0	13.7	0.6	10.1	0.0	99.9	0.0	65.1	4.6	27.5
Beaver, OK	0.0	0.0	0.7	16.0	1.0	66.3	0.0	72.6	6.5	43.8
Cimarron, OK	--	--	2.2	35.1	0.0	99.2	0.0	59.4	1.2	67.9
Hutchinson, TX	--	--	0.5	5.8	1.4	45.6	--	100.0	8.5	31.9
Lipscomb, TX	--	100.0	1.7	39.7	0.0	32.2	0.0	90.1	9.5	64.0
Roberts, TX	0.0	43.5	2.2	22.7	0.0	10.8	1.8	95.2	17.8	64.5

Improvements to GIS-Based Method

Table 4.3 shows estimated residue availability per 16-km (10-mile) service area from plant location (Hugoton, KS) for five plant capacities (151, 227, 378, 567, and 757 MLY; 40, 60, 100, 150, and 200 MGY) and estimated annual feedstock requirements using both GIS-based methods. The first part of table 4.3 shows residue availability per 16-km (10-mile) service area using the constant rate removal (CRR) method. In the case of a plant with a 151 MLY (40 MGY) capacity and 100% residue removal, the first service area (0-16 km; 0-10 miles) was estimated to provide 13.7% of the annual feedstock requirements, while the second (16-32 km; 10-20 miles) and third (32-48 km; 20-30 miles) service areas would provide 45.1% and 41.2%, respectively. Accordingly, a plant with a 151 MLY (40 MGY) capacity would meet its annual feedstock requirements within the third service area (32-48 km; 20-30 miles). In the case of other capacity plants (227, 378, 567 and 757 MLY; 60, 100, 150 and 200 MGY), the total annual feedstock requirements would be met in the fourth (48-64 km; 30-40 miles), sixth (80-96 km; 50-60 miles), seventh (96-112 km; 60-70 miles), and ninth (128-144 km; 80-90 miles) service areas, respectively.

The second part of table 4.3 shows the residue availability per 16-km (10-mile) service area using the variable rate removal (VRR) method using intensive tillage by removing 100% of the residue. The supply area for the lower capacity plants (151 and 227 MLY; 40 and 60 MGY) remained the same while it decreased (i.e., 16 km; 10 miles) for higher capacity plants (378, 567 and 757 MLY; 100, 150, and 200 MGY) due to an increase in residue availability per service area. In the case of the 151 MLY (40 MGY) plant, the first service area (0-16 km; 0-10 miles) provided roughly the same annual feedstock requirement (19.7%) as the CRR method. However, an increase of 107,060 DT of residue in the second service area (16-32 km; 10-20 miles) increased the service area’s supply capability to 64.4%. The third service area (32-48 km; 20-30 miles) provided the remaining 15.9% of residue needed to meet the annual feedstock requirement. The total annual feedstock requirements for the other capacity plants (227, 378, 567 and 757 MLY; 60, 100, 150 and 200 MGY) would be met in the fourth (48-64 km; 30-40 miles), fifth (64-80 km; 40-50 miles), sixth (80-96 km; 50-60 miles), and seventh (96-112 km; 60-70 miles) service area, respectively.

Table 4.3 Estimated hectare and residue availability per 16-km (10-mile) service area from plant location (Hugoton, KS) for five plant capacities using the constant removal rate (CRR) and variable removal rate (VRR) GIS-based method and an estimated annual feedstock requirement using a corn biomass yield of 272.5 L/DT (72 gal/DT).[a]

Plant Capacity	Annual Feedstock Required	Service Area in km (miles)										Total (%)
		0–16 (0–10)	16–32 (10–20)	32–48 (20–30)	48–64 (30–40)	64–80 (40–50)	80–96 (50–60)	96–112 (60–70)	112–128 (70–80)	128–144 (80–90)	144-160 (90–100)	
		Hectares Available per Service Area (acres)										
		10,268 (25,372)	33,821 (83,574)	31,572 (78,017)	44,298 (109,462)	46,290 (114,385)	62,350 (154,071)	56,696 (140,100)	50,378 (124,486)	45,548 (112,551)	37,388 (92,387)	
		Residue Available per Service Area (dry tons) using Intensive Tillage Practices by Removing 100%										
CRR Method		76,116	250,722	234,050	328,386	343,155	462,213	420,301	373,459	337,653	227,162	
151 (40)	555,556	13.7	45.1	41.2	--	--	--	--	--	--	--	100
227 (60)	833,333	9.1	30.1	28.1	32.7	--	--	--	--	--	--	100
378 (100)	1,388,889	5.5	18.1	16.9	23.6	24.7	11.3	--	--	--	--	100
567 (150)	2,083,333	3.7	12.0	11.2	15.8	16.5	22.2	18.7	--	--	--	100
757 (200)	2,777,778	2.7	9.0	8.4	11.8	12.4	16.6	15.1	13.4	10.4	--	100
		Residue Available per Service Area (dry tons) using Intensive Tillage Practices by Removing 100%										
VRR Method		109,381	357,782	300,646	453,468	472,214	633,969	532,763	495,015	481,460	400,359	
151 (40)	555,556	19.7	64.4	15.9	--	--	--	--	--	--	--	100
227 (60)	833,333	13.1	42.9	36.1	7.9	--	--	--	--	--	--	100
378 (100)	1,388,889	7.9	25.8	21.6	32.6	12.1	--	--	--	--	--	100
567 (150)	2,083,333	5.3	17.2	14.4	21.8	22.7	18.7	--	--	--	--	100
757 (200)	2,777,778	3.9	12.9	10.8	16.3	17.0	22.8	16.2	--	--	--	100
		Residue Available per Service Area (dry tons) using Conservation Tillage with at least 30% Soil Coverage at 2nd Year Planting										
VRR Method		77,198	253,877	205,024	326,007	337,960	457,547	352,378	346,109	335,562	275,824	
151 (40)	555,556	13.9	45.7	36.9	3.5	--	--	--	--	--	--	100
227 (60)	833,333	9.3	30.5	24.6	35.7	--	--	--	--	--	--	100
378 (100)	1,388,889	5.6	18.3	14.8	23.5	24.3	13.6	--	--	--	--	100
567 (150)	2,083,333	3.7	12.2	9.8	15.6	16.2	22.0	16.9	3.5	--	--	100
757 (200)	2,777,778	2.8	9.1	7.4	11.7	12.2	16.5	12.7	12.5	12.1	3.1	100

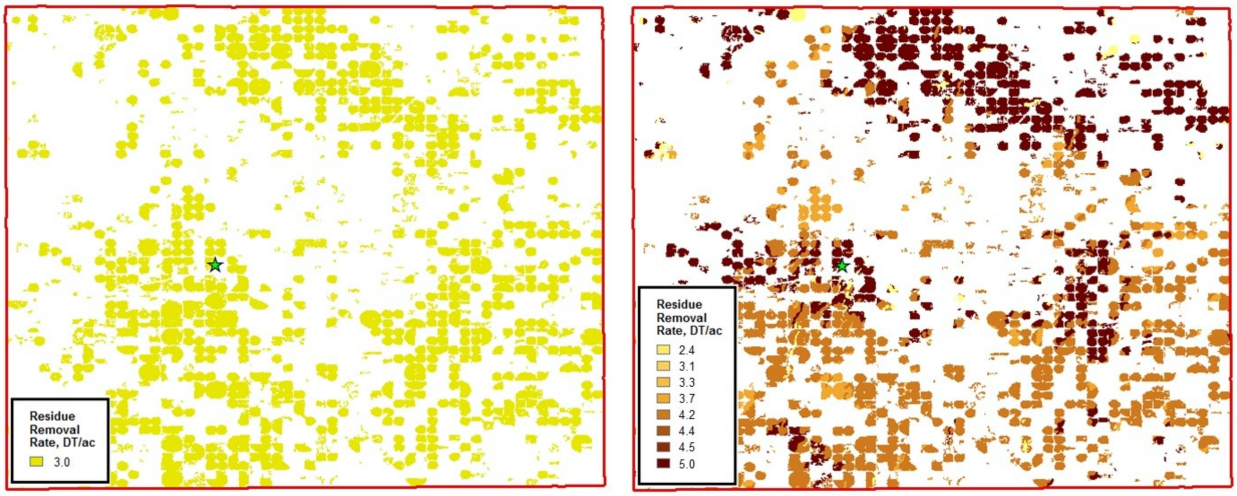
[a] Plant capacity is in million liters per year (million gallons per year), and annual feedstock required in dry tons/year.

When comparing both methods using intensive tillage by removing 100% of the residue, table 4.3 shows that even though hectare availability is the same for each service area the VRR method estimated on average 113,384 ± 38,770 DT more residue available per service area compared to the CRR method. Difference in residue availability was attributed to the use of soil characteristics, field-level yield, and field management when estimating residue removal rates instead of using a constant removal rate of 7.4 DT/ha (3 DT/ac). The residue removal rates within the study area averaged 9.4 ± 1.7 DT/ha (3.8 ± 0.7 DT/ac), with a 5.7 to 13.3 DT/ha (2.3 to 5.4 DT/ac) range.

In the case of Stevens County, its average residue removal rate was 9.4 ± 2.2 DT/ha (3.8 ± 0.9 DT/ac), with a 5.9 to 12.3 DT/ha (2.4 to 5.0 DT/ac) range (figure 4.3). Even though Stevens County had one of the lowest residue removal rates (i.e., 5.9 DT/ha; 2.4 DT/ac) among its hectares, this residue removal rate only applied to 0.1% of the total county hectares (45,857 hectares; 111,314 acres). The three predominant residue removal rates in Stevens County were 9.1, 10.4, and 12.3 DT/ha (3.7, 4.2, and 5.0 DT/ac), which relate to 8.1, 53.8, and 35.8% of the county's total hectares, respectively. These high residue removal rates can be attributed to Stevens County's high corn yields and good quality soil characteristics. Even though higher residue removal rates can be achieved using intensive tillage by removing 100% of the residue, it is not a recommended practice because it can lead to erosion problems and loss in soil productivity due to the lack of nutrient cycling among other factors. Therefore, it is advisable to use conservation tillage, which is a soil cultivation method that leaves the previous year's crop residue on fields before and after planting the next crop to reduce soil erosion and runoff, and improve soil productivity. To provide these conservation benefits, at least 30% of the soil surface must be covered with residue after planting the next crop.

The effect of conservation tillage on the amount available for removal was also simulated. The third part of table 4.3 shows residue availability per 16-km (10-mile) service area for the VRR method using conservation tillage practices. When comparing this scenario to the CRR method using intensive tillage, differences in residue availability per service area were observed for all service areas for all five plant capacities. On average, there was a 13,573 ± 22,195 DT decrease in the amount of residue available predicted per service area. As a result, the average residue removal rate in the study area decreased to 5.9 ± 2.2 DT/ha (2.4 ± 0.9 DT/ac), with a 2.5 to 9.6 DT/ha (1.0 to 3.9 DT/ac) range.

Figure 4.3 Estimated residue removal rates for Stevens County (Kansas) using the constant removal rate (CRR) and variable residue removal (VRR) method based on intensive tillage practices by removing 100% of residue available.



This slight decrease in average residue availability per service area increased the number of total service areas needed to meet annual feedstock requirements by one service area for 151, 567 and 757 MLY (40, 150, and 200 MGY) plant capacities, yet remained the same for 227 and 378 MLY (60 and 100 MGY) plant capacities. It is important to note that only 3.5% or less of the total annual feedstock requirements was provided by these additional service areas. Therefore, the VRR method required practically the same number of service areas as the CRR method to procure total annual feedstock requirement, thus making it the preferred approach.

Sustainability is achieved by the use of two improvement parameters in the VRR methodology. Rather than using a constant removal rate of 7.4 DT/ha (3 DT/ac) and intensive tillage where 100% of the residue is removed, the VRR method predicts residue availability as a function of yield and soil variability. Table 4.4 shows a matrix of how residue availability is affected by yield and soil type as field management (table 4.1) remains the same throughout. It can be observed that as yield and soil quality decrease, residue availability decreases. Of these two variables, yield had a greater effect. It is important to note that in some of the scenarios, the lower quality soil resulted in higher residue availability. This was a result of higher average yields simulated by WEPS compared to the target yield. For example, the target input yield for LCC 3 (Y3) was 8.59 MT/ha (135 bu/ac). The WEPS simulation run output predicted an average yield of 8.40 MT/ha (132 bu/ac) for the first soil type (Y3-S1), 8.91 MT/ha (140 bu/ac) for the second soil type (Y3-S2), and 8.53 MT/ha (134 bu/ac) for the third and fourth soil type (Y3-S3, and Y3-S4).

Table 4.4 Effect of yield and soil type on residue availability in Stevens County using the same field management for all scenarios.[a][b]

		Soil Type (Map Unit Symbol and Name)			
		5210 - Belfon	5220 - Dalhart	5236 - Eva	5236 - Optima
Yield	LCC	1	2	3	4
12.22 (192)	1	9,643 (8,486)	9,241 (8,132)	9,375 (8,250)	9,264 (8,152)
10.37 (163)	2	7,681 (6,759)	7,376 (6,491)	7,061 (6,214)	7,163 (6,303)
8.59 (135)	3	4,367 (3,843)	4,597 (4,045)	4,442 (3,909)	4,436 (3,904)
5.09 (80)	4	2,403 (2,115)	2,315 (2,037)	2,338 (2,057)	2,383 (2,097)

[a] Yield is in metric tons per hectare (bushels per acre).
[b] Estimated residue availability is in kilograms per hectare (pounds per acre).

Validation of Hectare Weighted Yields

NASS is a USDA service that provides national, state, and county crop estimates. Producers, agricultural organizations, trade groups, financial institutions and other entities rely on NASS yield estimates for decision making. Decisions such as planting and marketing, pricing commodities, storing, and crop insurance are made based on NASS yield estimates. National and State estimates are known to be more statistically sound than county-level estimates mainly because of the limited number of responses. According to NASS guidelines, in cases where there are fewer than 30 responses from an individual county, an estimate for “combined counties” is published. Nevertheless, a recent report by the USDA Office of Inspector General (OIG) concluded that NASS’ current methodology for estimating county yields does provide reasonably accurate and reliable information (USDA, 2011b). According to this report, about 20% of NASS county estimated corn yields differed from Risk Management Agency (RMA) corn yield estimates by more than ± 10% for 346 counties, from 2006 to 2008. Having good county yield estimates helps agencies such as the RMA and the FSA to cross-check county-level estimates to determine program benefits. This is important because over- or under-estimating yields will affect how much crop insurance indemnity is needed. For reference, RMA's county average crop insurance indemnities totaled nearly $1.1 billion from 2007-2009.

In our particular case study, county HWYlds were validated against the NASS irrigated corn yield averages. Prior to this validation, acquired NASS yield estimates were cross-checked against 7-year FSA irrigated corn yield estimates. Data showed that only 10% (3 out of 31) of counties of NASS irrigated corn yield estimates differed from FSA irrigated corn yield estimates by greater than ±10%. This corroborates conclusions reached by USDA OIG in their 2011 report. Once NASS yield estimates were cross-checked, they were used to validate county HWYlds. Validation of county HWYlds at the same percent difference (i.e., no greater than ±10%) showed that 65% (20 out of the 31 Counties) fell outside the established yield estimate difference range.

Conclusions

The results of this case study emphasized the importance of using two additional parameters (i.e., field-level yields and residue removal rates) to further improve quantifying feedstock availability to supply a biorefinery. Residue removal was maximized based on location, yield, soil characteristics, and field management without causing soil erosion and while maintaining soil productivity.

The following are specific conclusions reached from this study:

- If more than 20% of the study area counties have more than 35% of their soil hectares without a yield value, calculating modified HWYLd values will offer a more accurate representation of a county's LCC HWYlds, which is used to predict residue removal rates.
- The implementation of field-level yield estimates based on soil characteristics and variable residue removal estimates based on location, soil characteristics, crop yield, and field management gives the user of the VRR method a sustainable approach as to how much residue could potentially be removed without causing soil erosion and/or affecting soil productivity in the years to come.
- When using intensive tillage practices by removing 100% of the crop residue available, the VRR method predicted on average 113,384 ± 38,770 DT of additional residue for

harvest compared to the CRR method. This increase in residue availability resulted in a higher removal rate (9.4 ± 1.7 DT/ha [3.8 ± 0.7 DT/ac] average; 5.7 to 13.3 DT/ha [2.3 to 5.4 DT/ac] range) in the study area compared to the constant rate used by the CRR method of 7.4 DT/ha (3 DT/ac).

- Intensive tillage practices are not recommended because they can lead to erosion problems and loss in soil productivity. Conservation tillage practices will help offset these negative effects and thus is recommended instead. Conservation benefits are provided when at least 30% of the soil surface is covered with residue after planting the next crop.
- When using conservation tillage practices, the VRR method estimated on average 13,373 ± 22,195 DT less per service area than the CRR method using intensive tillage by 100% removal. Even though this created the need for additional service area for some plant capacities, these service areas would only supply 3.5% or less of the total annual feedstock requirements. Therefore, procurement area was considered practically the same for the VRR method using conservation tillage and the CRR method using intensive tillage with 100% residue removal. Consequently, the VRR method turned out to be a more sustainable approach in the quantification of biomass feedstock availability.

Chapter 5 - Quantification of Biomass Feedstock Availability to a Biorefinery Based on Multi-Crop Rotation Cropping Systems Using a GIS-Based Method[1]

A. Martinez-Kawas, and 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. Previous research showed improvements on quantification of feedstock availability supply for a biorefinery by introducing the effect of field-level yield spatial variance and variable removal rates (VRR) 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 VRR GIS-based method. Researchers observed on average a 3,793 ± 5,733 DT per service area difference when increasing the number of crop-specific VRR rates used to estimate feedstock quantification. The supplementary use of crop-specific VRR rates affected residue availability given a crop's residue removal rate is influenced by crop yield, crop rotation, soil characteristics, as well as field location and management. Also, the amount of hectares available for the three main crops analyzed in this case study affected residue availability. Corn represented 26.2% (440,636 hectares; 1,101,591 acres), sorghum 12.9% (217,432 hectares; 543,579 acres), and wheat 60.9% (1,024,607 hectares; 2,561,518 acres) of the hectares in the study area. The validation study showed the importance of taking into account crop residue seasonal availability when estimating procurement service areas given that in some cases feedstock requirements were not met.*

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

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[1] This chapter was submitted on August 2, 2013 under the same title by A. Martinez and D. E. Maier to Biological Engineering Transactions of ASABE and is still under review.

Introduction

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 cost.

A feedstock's dispersed spatial and seasonal availability are amongst the challenges 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 (USDA, 2003) and several other studies (De Mol et al., 1997; Sokhansanj and Turhollow, 2002; Ravula et al., 2003; Cundiff et al., 2004; Krishnakumar and Ileleji, 2010). Ultimately, correct facility location selection will result in more precisely quantifying feedstock availability and predicting 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 geo-reference, crop-specific satellite imagery. This GIS-based approach was subsequently improved by Martinez and Maier (in review) by taking into account the effect of field-level yield spatial variance based on soil characteristics, and variable residue removal rates based on erosion, soil characteristics, yield, and conservation field management practices. The researchers concluded that the variable residue removal (VRR) method using conservation tillage was deemed a more sustainable approach in the quantification of feedstock availability compared to the constant residue removal (CRR) method which used intensive tillage with 100% residue removal. While the deployment of these improvement parameters in the GIS-based feedstock sourcing method proved feasible, the next logical step was to improve its 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 a previously developed GIS-based feedstock sourcing method, and to utilize 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. 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 is typically dictated by location, soil characteristics, duration of crop 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 would be cereal crops (e.g., corn, wheat) followed by leguminous plants (e.g., soybean, alfalfa). Using a corn-soybean rotation as an example, corn requires additional nitrogen for development so by subsequently planting soybeans, which has 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) also observed an increase in crop productivity when they evaluated the impact of various corn and soybean cropping patterns on yields in a 9-year field study. Researchers 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. It was also observed that yield did not differ between a monoculture of either crop when alternating two different cultivars annually and 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. 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 soil organic matter levels which help improve a soil's structure, 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 on continuous sorghum, continuous soybean, and sorghum-soybean rotations. Researchers concluded that crop management systems that include rotations with a high residue-producing crop 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 best practice, because that will lead to erosion problems and loss in 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. Researchers found a positive linear response between grain and stover yield and amount of residue on the soil surface. They estimated that each Mg/ha of residue removed resulted in about a 10% (0.10 Mg/ha) reduction in grain yield and a 30% (0.30 Mg/ha) reduction in residue yield. It was 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. Researchers observed that residual effects of the 150% residue treatment increased grain production 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 removable rates (CRR) 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 which was estimated by multiplying average corn yield of 8.27

MT/ha (130 bu/ac; 6.36-10.18 MT/ha; 100-160 bu/ac), corn grain dry matter content (0.85), and stover to grain ratio (1:1), this equated to a CRR of 7.7 DT/ha (3.1 DT/ac). Mukunda et al. (2006) used a similar CRR of 7.4 DT/ha (3 DT/ac) 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, VRR rates are needed. Martinez and Maier (in review) developed a methodology that estimates VRR rates with respect to erosion, soil characteristics, field-level crop yield, and field management. Researchers observed that the procurement area was simliar for the VRR method using conservation tillage as the CRR method using intensive tillage with 100% residue removal. Consequently, the VRR method was a more sustainable approach in the quantification of biomass feedstock availability.

Most studies examine residue removal based on 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 they are related, a 30% residue removal rate is not the same as 70% soil cover, regardless of when soil cover is measured (USDA, 1998). Several tillage practices exist, with the three main ones being intensive, reduced, and conservation tillage. They differ by the percent of soil coverage the first year crop residue provides at the time the second year crop is planted. Intensive tillage would provide less than 15% cover, reduced tillage between 15 and 30%, and conservation tillage a minimum of 30%.

Material 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 Martinez and Maier (in review) used to quantify accuracy gained as a result of utilizing field-level yield spatial variance and variable residue removal rates as improvement parameters.

Cropland Data Layers and Service Areas

CDLs 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 and then imported into CropScape® using the “import area of interest” feature. Subsequently, the CDLs for years 2008 to 2012 were downloaded based on available data given our area of interest. Study area service areas were then created, using the Network Analyst tool in ArcGIS, in 16-km

(10-mile) increments up to 160 km (100 miles) starting from the selected facility location (Hugoton, KS) as the reference point.

Crop Rotation Identification and Sequencing

To simplify crop identification and sequencing, crop ArcGIS attribute values for the five acquired CDL years were first reclassified. Corn was given a reclassification value of C, sorghum S, wheat W, and fallow F. The Combine tool in ArcGIS was then used to sequence 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 into a spreadsheet to be identified and manually re-labeled. Crop rotations were re-labeled according to their numerical crop value sequence. For example, a W-C-W-C-W five-year crop value sequence would be identified as a “corn-wheat” crop rotation and be re-labeled as a C-W-C. If the crop value sequence could not be clearly identified it would be 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 in ArcGIS. Continuous corn (i.e., C-C-C rotation), corn-wheat (i.e., C-W-C rotation), and sorghum-wheat-fallow (i.e., S-W-F rotation) were the representative rotations in the study area. Cells with a C-C-C, C-W-C, and a S-W-F crop rotation value were then separately extracted and converted into polygons with their corresponding crop rotation sequence value assigned in the new layer. The layer with only polygons in a C-C-C rotation was labeled “CrpRot_CCC”, in a C-W-C rotation “CrpRot_CWC”, in a S-W-F rotation “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 (in review) VRR methodology. In brief, VRR rates were estimated using the USDA-ARS WEPS. Factors such as weather, soil characteristics, crop yield, and field management were taken into account when running wind erosion simulation for soils NRCS classified as LCC 1, 2, 3, or 4 for each county in the study area. The soil with the highest hectare extent in each LCC was chosen to represent that LCC. Hectare-weighted yields (HWYlds) were then calculated and a field management chosen (table 5.1). Other WEPS parameters of importance were “region”, “location”, and “simulation run”. The “region” was set to 64 hectares (160 acres), which is a quarter section of a typical square mile Kansas field, for WEPS simulation in a C-W-C and S-W-F crop rotation, and set at 52 hectares (130 acres) for WEPS simulations in a C-C-C 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 (50 for this case study) to be simulated, was chosen for all simulations. Simulations were run for all possible crop rotation, crop type, soil type, and LLC HWYld combination scenarios. They were then joined to the main soil thematic map from which four crop- and rotation-based residue removal maps were created.

Table 5.1 Field managements used to simulate residue removal rates using conservation tillage.

Crop rotation	Date, m/d/y	WEPS Operation	Crop
Continuous corn (C-C-C)	Apr 01, 01	Sprayer, kill crop	
	Apr 20, 01	Fertilizer application – anhydrous w/ knife 30 in	
	Apr 20, 01	Planter, double disk opener, fluted coulter	Corn
	Jun 20, 01	Sprayer, post emergence	
	Jul 20, 01	Sprayer, insecticide post emergence	
	Oct 01, 01	Harvest, killing crop 20% standing stubble	
	Oct 02, 01	Rake or windrower	
	Oct 05, 01	Bale straw or residue	
Corn – Wheat (C-W-C)	Apr 25, 01	Planter, double disk opener w/ coulter	Corn
	Jul 01, 01	Sprayer, post emergence	
	Jul 15, 01	Sprayer, insecticide post emergence	
	Oct 01, 01	Harvest, killing crop 30% standing stubble	
	Oct 02, 01	Rake or windrower	
	Oct 03, 01	Bale straw or residue	
	Oct 15, 01	Drill or airseeder, double disk, fluted coulters	Wheat
	Apr 15, 02	Sprayer, post emergence	
	Jul 10, 02	Harvest, killing crop 30% standing stubble	
	Jul 11, 02	Rake or windrower	
	Jul 12, 02	Bale straw or residue	
Sorghum – Wheat – Fallow (S-W-F)	May 01, 01	Sprayer, post emergence	
	Jun 16, 01	Planter, double disk opener, fluted coulter	Sorghum
	Jul 15, 01	Sprayer, post emergence	
	Oct 01, 01	Harvest, killing crop 30% standing stubble	
	Oct 02, 01	Rake or windrower	
	Oct 03, 01	Bale straw or residue	
	Oct 04, 01	Sprayer, post emergence	
	Oct 15, 01	Drill or airseeder, double disk, fluted coulters	Wheat
	Apr 15, 02	Sprayer, insecticide post emergence	
	Jun 15, 02	Harvest, killing crop 30% standing stubble	
	Jun 16, 02	Rake or windrower	
	Jun 17, 02	Bale straw or residue	

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 one with only sorghum fields labeled "CDL_Sorghum", and the last one with only wheat fields labeled "CDL_Wheat". For scenario 1, all corn fields were assumed to have a C-C-C crop rotation sequence, so a copy of the "CDL_Corn" layer was created then re-named "Sc1_C_CCC". The same procedure was done for sorghum and wheat fields resulting in two additional layers, one which contained sorghum fields in a S-W-F rotation (Sc1_S_SWF), and a second layer with wheat fields in a S-W-F rotation (Sc1_W_SWF). For scenario 2, the previously created layer which only contained cells in a C-W-C crop rotation sequence (i.e., layer "CrpRot_CWC") was clipped from the layer "CDL_Corn" outputting a layer with only corn fields in a C-W-C rotation (Sc2_C_CWC). This newly created layer would then be subtracted from the layer "CDL_Corn" to output a layer with only corn fields in a C-C-C crop rotation sequence (Sc2_C_CCC), which included corn fields that were re-labeled "RndRot" during crop rotation identification and sequencing. The same procedure was done for the wheat fields resulting in two additional layers, one which only contained wheat fields in a C-W-C rotation (Sc2_W_CWC), and a second layer with only wheat fields in a S-W-F rotation (Sc2_W_SWF). All sorghum fields were assumed to have a S-W-F crop rotation sequence, so a copy of the "CDL_Sorghum" layer was created then re-named "Sc2_S_SWF".

Estimating Feedstock Availability

The corn, sorghum and wheat fields with specific crop rotations where then overlayed with corresponding residue removal maps creating a crop- and rotation-specific map with fields assigned a corresponding residue removal rate. The output layer was subsequently intersected with the previously created service area polygons to generate maps with fields and their corresponding residue removal rate according to service area. This allowed for the quantification of residue in each 16-km (10-mile) service area. To calculate 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: corn stover 491.4 L/DT (130 gal/DT), sorghum stalk 428.3 L/DT (113 gal/DT), and wheat straw 483.8 L/DT (128 gal/DT). Theoretical ethanol yields were calculated using 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 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 a five year period between 2008 and 2012. The study area consists of 31 counties with a total area of 8,442,951 hectares (21,107,377 acres). The majority of the hectares (58.1%; 4,908,659 hectares; 12,271,648 acres) comprised developed land, rangeland or pasture were no crops where grown in the specified five-year period. The remaining 41.9% (3,533,950 hectares; 8,834,874 acres) of the hectares had at least one crop planted in the specified five-year period, i.e., 9.6% (339,718 hectares; 849,296 acres) of the hectares had a C-C-C rotation, 14.3% (504,369 hectares; 1,260,923 acres) a C-W-C rotation, 27.5% (973,173 hectares; 2,432,932 acres) a S-W-F rotation, and the remaining 48.6% (1,716,690 hectares; 4,291,724 acres) less typical rotations for that specific study area. Therefore, the C-C-C, C-W-C, and S-W-F 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 5.2 shows estimated residue availability per 16-km (10-mile) service area from plant location (Hugoton, KS) 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 5.2 shows residue availability per 16-km (10-mile) service area using three different VRR rates (i.e., scenario 1). The VRR rate for corn was obtained using the C-C-C rotation WEPS simulation; the VRR rates for sorghum and wheat were obtained using the S-W-F rotation WEPS simulation. In the case of a plant with a 151 MLY

(40 MGY) capacity in scenario 1, the first service area (0-16 km; 0-10 miles) was estimated to provide 37.8% of the annual feedstock requirement, while the second (16-32 km; 10-20 miles) 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 (16-32 km; 10-20 miles). In the case of other capacity plants, the total annual feedstock requirement would be met in the second service area (16-32 km; 10-20 miles) for the 227 MLY (60 MGY) capacity plant, and the third service area for plant capacities of 378, 567 and 757 MLY (100, 150 and 200 MGY).

Table 5.2 Estimated hectare and residue availability with standard deviation per 16-km (10-mile) service area from plant location (Hugoton, KS) for five plant capacities using the multi-crop variable residue removal (MC-VRR) GIS-based method and estimated annual feedstock requirements using crop hectare-weighted theoretical ethanol yields of 491.4 L/DT (130 gal/DT) for corn stover, 428.3 L/DT (113 gal/DT) for sorghum stalk, and 483.3 L/DT (128 gal/DT) for wheat straw for two scenarios.[a]

Plant Capacity	Annual Feedstock Required	Service Area in km (miles)					Total (%)
		0–16 (0–10)	16–32 (10–20)	32–48 (20–30)	48–64 (30–40)	64–80 (40–50)	
		Hectares Available per Service Area (acres)					
		10,268 (25,372)	33,821 (83,574)	31,572 (78,017)	44,298 (109,462)	46,290 (114,385)	
		Residue Available per Service Area (dry tons) using Conservation Tillage Practices Conserving at least 30% Soil Coverage at 2nd Year Planting					
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 gallons per year), theoretical ethanol yield is in liters per dry ton (gallons per dry ton), and annual feedstock required in dry tons per year.

The second part of table 5.2 shows the residue availability per 16-km (10-mile) service area using five VRR rates (i.e., scenario 2). The VRR rates for corn were obtained using the C-C-C and C-W-C rotation WEPS simulations, the wheat VRR rates from the C-W-C and S-W-F rotations, and the sorghum VRR rate from the S-W-F 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 a decrease in residue availability (by 2.39%, 2.41%, 0.04%, respectively) while service areas four and five had an increase (by 0.32% and 0.39%, respectively). Residue availability for the first service area (0-16 km; 0-10 miles) decreased by 2,863 DT, by 9,580 DT for the second service area (16-32 km; 10-20 miles), by 212 DT for the third service area (32-48 km; 20-30 miles), and increased by 2,610 DT for the fourth service area (48-64 km; 30-40 miles), and by 3,702 DT for the fifth service area (64-80 km; 40-50 miles). Differences in residue availability was 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 5.3 shows estimated annual hectare and residue availability per 16-km (10-mile) service area from plant location (Hugoton, KS) for crop rotations used in scenario 1 and 2 using the multi-crop variable residue removal (MC-VRR) GIS-based method. It can be observed that the percent residue availability per service area differs within scenario due to the amount of residue 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 C-C-C rotation, with sorghum stalk (8.1 and 8.3%) and wheat straw (27.1 and 26.2%) from a S-W-F rotation making up the remainder. A 28.9% decrease in corn stover availability is observed between the second service area (16-32 km; 10-20 miles) and the fifth service area (64-80 km; 40-50 miles), which is counterbalanced with an increase in sorghum stalk (4.0%) and wheat straw (24.9%). Scenario 2 follows the same pattern yet VRR rates for corn and wheat were obtained from more than one rotation. The five-year average for the first service area (0-16 km; 0-10 miles) in scenario 2 indicates 50.0% of the corn stover came from a C-C-C rotation and 12.9% from a C-W-C rotation. In the case of wheat straw, 19.6% came from a S-W-F rotation and 9.2% from a C-W-C rotation. Note that in scenario 2 the percent total corn stover (62.9%) and wheat straw (28.8%) 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).

Table 5.3 Estimated annual hectare and residue availability per 16-km (10-mile) service area from plant location (Hugoton, KS) for crop rotations used in scenario 1 and 2 using the multi-crop variable residue removal (MC-VRR) GIS-based method.

Year	Crop	Rotation	Service Area in km (miles)									
			0–16 (0–10)		16–32 (10–20)		32–48 (20–30)		48–64 (30–40)		64–80 (40–50)	
			Hectares Available per Service Area (acres)									
			10,268 (25,372)		33,821 (83,574)		31,572 (78,017)		44,298 (109,462)		46,290 (114,385)	
			Residue Available per Service Area using Conservation Tillage Practices Conserving at least 30% Soil Coverage at 2nd Year Planting for Scenario 1 and 2									
			Sc 1	Sc 2	Sc 1	Sc 2	Sc 1	Sc 2	Sc 1	Sc 2	Sc 1	Sc 2
2008	Corn	C–C–C	70.0	55.8	67.9	53.1	47.4	40.5	44.2	30.6	38.0	25.1
		C–W–C	--	12.7	--	13.2	--	14.8	--	11.5	--	10.8
	Sorghum	S–W–F	8.1	8.3	8.4	8.6	10.7	13.0	12.0	11.8	15.8	15.7
	Wheat	S–W–F	22.0	18.2	23.7	19.4	41.9	24.1	43.8	30.6	46.2	29.8
		C–W–C	--	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	C–C–C	61.4	48.0	62.6	47.6	44.6	31.2	40.0	28.0	34.4	22.6
		C–W–C	--	11.4	--	13.0	--	11.2	--	10.2	--	9.6
	Sorghum	S–W–F	7.7	7.9	8.1	8.2	7.5	7.5	9.5	9.5	8.9	8.9
	Wheat	S–W–F	30.9	22.7	29.3	21.8	47.9	37.9	50.5	42.5	56.7	48.5
		C–W–C	--	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	C–C–C	69.0	48.2	67.6	48.7	53.6	33.2	47.4	29.4	39.7	21.9
		C–W–C	--	18.7	--	16.8	--	18.0	--	16.1	--	15.6
	Sorghum	S–W–F	7.9	8.2	9.6	9.9	10.6	10.7	13.1	13.2	14.2	14.4
	Wheat	S–W–F	23.0	18.1	22.8	16.3	35.9	29.6	39.5	33.3	46.1	39.9
		C–W–C	--	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	C–C–C	64.4	52.1	68.2	52.9	52.0	37.3	46.7	33.0	38.2	24.7
		C–W–C	--	10.4	--	13.1	--	12.4	--	11.7	--	12.1
	Sorghum	S–W–F	8.1	8.2	6.0	6.1	8.2	8.1	8.4	8.4	10.0	9.9
	Wheat	S–W–F	27.6	18.4	25.9	16.4	39.8	29.3	44.8	35.2	51.8	41.4
		C–W–C	--	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	C–C–C	59.5	46.6	61.6	46.7	45.1	31.5	41.2	28.6	33.3	21.6
		C–W–C	--	10.6	--	12.7	--	11.1	--	10.8	--	9.7
	Sorghum	S–W–F	8.6	8.7	9.3	9.4	8.8	8.7	11.0	11.0	12.9	12.8
	Wheat	S–W–F	31.9	20.8	29.1	18.4	46.1	35.0	47.8	38.3	53.8	44.0
		C–W–C	--	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	34.3	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	8.1	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	45.4	36.2	51.1	41.0
		1–3–1	--	9.2	--	9.6	--	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

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. Overall residue removal rate in scenario 1 for corn stover averaged 5.8 ± 2.0 DT/ha

(2.3 ± 0.8 DT/ac), 3.8 ± 1.5 DT/ha (1.5 ± 0.6 DT/ac) for sorghum stalk, and 3.8 ± 1.0 DT/ha (1.5 ± 0.4 DT/ac) 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 (2.0 ± 0.6 DT/ac) for corn stover in a C-W-C rotation and 4.5 ± 1.3 DT/ha (1.8 ± 0.5 DT/ac) for wheat in a C-W-C rotation. The supplementary use of VRR rates affected overall residue removal rates in scenario 2 by decreasing corn stover to 5.5 ± 2.0 DT/ha (2.2 ± 0.8 DT/ac) and increasing wheat straw to 4.0 ± 1.0 DT/ha (1.6 ± 0.4 DT/ac). Sorghum stalk residue removal rates remained the same (3.8 ± 1.3 DT/ha; 1.5 ± 0.5 DT/ac) given that only sorghum VRR rates for the S-W-F rotation were used.

The difference between crop residue removal rates in different rotations was furthered investigated by analyzing the effect of soil characteristics (i.e., land capability classification or LCC), crop yield and rotation on estimated residue removal rates within the study area. The study area average corn stover residue removal difference between a C-C-C and C-W-C rotation 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 a C-W-C and S-W-F rotation 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 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 5.4 shows the effect 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 C-C-C rotation is typically supplemented with nitrogen given that corn is a nitrogen-demanding crop. In contrast, corn in a C-W-C rotation might not necessarily be supplemented with as much nitrogen given that wheat is expected to counterbalance some of corn’s demand for nitrogen. Hence, corn in a C-C-C rotation would have a higher grain yield potential and consequently more residue would be available for harvest.

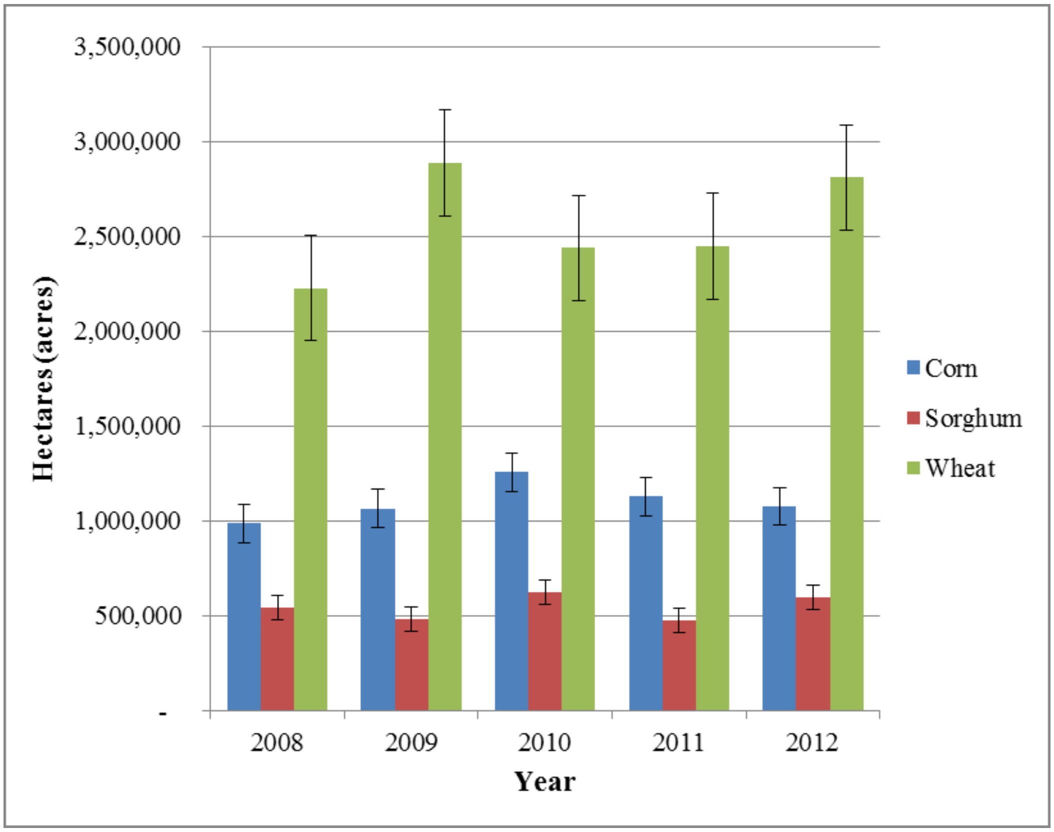
Table 5.4 Effect of soil characteristics, crop yield, and crop rotation on estimated residue removal rates using conservation practices for corn in a C-C-C and C-W-C rotation and for wheat in C-W-C and S-W-F rotation in Stevens County.[a]

	Corn				Wheat			
LCC	Yield	VRR C-C-C	VRR C-W-C	% Diff	Yield	VRR C-W-C	VRR S-W-F	% 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 kilograms per hectare (pounds per acre).

The amount of residue available for harvest is a function of number of crop-specific hectares available in the study area. The higher the number of hectares the more crop residue would be available, assuming soil quality remains constant. It was estimated, on average for years 2008 to 2012, that the 100-mile service area had 1,682,675 hectares (4,206,687 acres) planted to corn, sorghum, or wheat. Corn represented 26.2% (440,636 hectares; 1,101,591 acres) of the total, sorghum 12.9% (217,432 hectares; 543,579 acres), and wheat 60.9% (1,024,607 hectares; 2,561,518 acres). Figure 5.1 shows 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 the wheat hectares had a drastic increase in 2009 then leveled off and rise 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.

Figure 5.1 Five-year estimate of hectares planted to corn, sorghum, and wheat in the 100-mile service area.

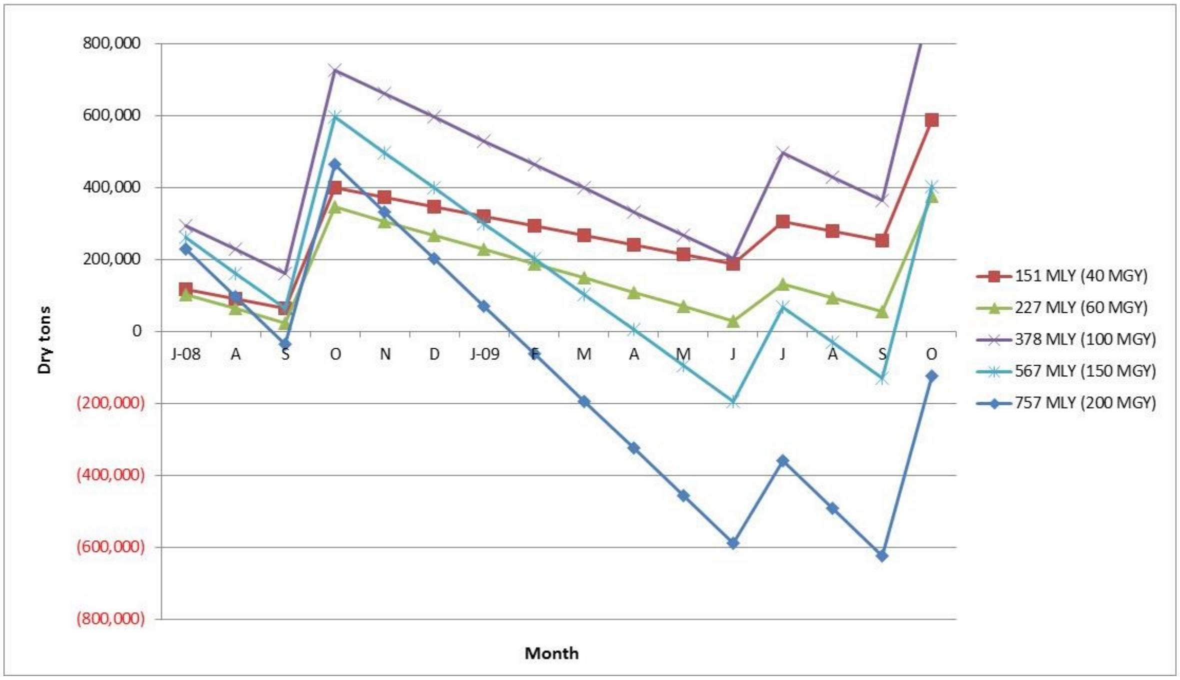


Validation of Estimated Procurement Area for Different Plant Capacities

Given that crop residue has seasonal availability, the procurement area previously estimated with the MC-VRR method using scenario 2 (table 5.2) was validated to ensure monthly feedstock requirement of the five plant capacities was met. First, monthly feedstock requirement was calculated for each plant capacity by dividing the previously calculated annual feedstock requirement by twelve. Monthly feedstock requirements were: 26,332.7 DT for a 151 MLY (40 MGY); 39,499.0 DT for a 227 MLY (60 MGY); 65,831.7 DT for a 378 MLY (100 MGY); 98,747.5 DT for a 567 MLY (150 MGY); 131,663.3 DT for a 757 MLY (200 MGY). Residue harvest month for each crop was obtained from the field management used to estimate VRR rates (table 5.1). Therefore, wheat straw was harvested in July and corn stover and sorghum stalk 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 5.2 shows the monthly dry ton feedstock balance for the five plant capacities. It can be observed that plant capacities 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 they procured feedstock within two service areas for plant capacities 151 and 227 MLY (40 and 60 MGY), and three service areas for plant capacity 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 requirement are more than what the previously estimated service areas could provide. Therefore, an additional service area would be required for both plant capacities to meet their annual demands.

Figure 5.2 Monthly dry tons feedstock balance for five plant capacities with plant operations starting July 2008 through October 2009.



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 starting 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 start 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 from this study:

- The implementation of multi-crop rotation-based VRR rates gives the user of this MC-VRR method a sustainable approach as to how much residue could potentially be removed without causing soil erosion and/or affecting soil productivity.
- A difference of 3,793 ± 5,733 DT was observed in estimated residue availability using conservation tillage practices, which ensures at least 30% of the soil surface is covered with the first year crop at the time the second year crop is planted, between scenario 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 C-C-C, C-W-C, and S-W-F rotations were considered the representative rotations for the study area because the total 3,533,950 hectares (8,834,874 acres) of cropland were comprised of 9.6% (339,718 hectares; 849,296 acres) hectares having a C-C-C rotation, 14.3% (504,369 hectares; 1,260,923 acres) a C-W-C rotation, 27.5% (973,173 hectares; 2,432,932 acres) a S-W-F rotation, and the remaining 48.6% (1,716,690 hectares; 4,291,724 acres) 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 (2.3 ± 0.8 DT/ac) in scenario 1 to 5.5 ± 2.0 DT/ha (2.2 ± 0.8 DT/ac) 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 (1.5 ± 0.4 DT/ac) in scenario 1 to 4.0

± 1.0 DT/ha (1.6 ± 0.4 DT/ac) in scenario 2 (+5.3%). Average residue removal for sorghum remained the same given that only sorghum VRR rates from the S-W-F rotation simulation were used.

- Crop-specific residue availability per service area affects residue availability. In scenario 1 and 2, the majority of the residue in the first (0-16 km; 0-10 miles) and second (16-32 km; 10-20 miles) service areas was corn stover (64.9% for SA1Sc1; 62.9% for SA1Sc2; 65.5% for SA2Sc1; 63.5% for SA2Sc2), with sorghum stalk (8.1% for SA1Sc1; 8.3% for SA1Sc2; 8.3% for SA2Sc1; 8.5% for SA2Sc2) and wheat straw (27.1% for SA1Sc1; 28.8% for SA1Sc2; 26.2% for SA2Sc1; 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 (16-32 km; 10-20 miles) and the fifth service area (64-80 km; 40-50 miles) which was counterbalanced with an increase in some sorghum stalk and mostly wheat straw.
- Crop-specific hectare availability per service area also affected residue availability given that these were not evenly distributed throughout the service areas. Corn represented 26.2% (440,636 hectares; 1,101,591 acres), sorghum 12.9% (217,432 hectares; 543,579 acres), and wheat 60.9% (1,024,607 hectares; 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 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 initially predicted service areas could provide. Therefore, an additional service area was needed to supply both plant capacities.

Chapter 6 - Assessing Site Suitability of Potential Feedstock Storage Locations for a Biorefinery Using a Geographical Information System Location-Allocation Analysis

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ABSTRACT. *The feasibility of utilizing cellulosic biomass such as corn stover as an energy feedstock is dominated by factors such as facility location, feedstock availability, and transportation logistics. Previous research showed improvements on quantification of feedstock availability supply for a biorefinery by introducing the effect of field-level yield spatial variance and variable residue removal rates as improvement parameters into a GIS-based analysis. While the GIS-based feedstock sourcing method proved feasible, the next logical step was to find suitable sites to store the remainder of the harvested residue that was not initially delivered to the biorefinery. In this case study a location-allocation analysis was performed on two different scenarios to select an optimal number of candidate feedstock storage locations (FSL) to supply a Kansas-based biomass conversion facility. The FSLs were evaluated based on an 8-km (5-mile; scenario 1) and a 16-km (10-mile; scenario 2) service area. The quantity of residue allocated to each FSL in scenario 1 was on average 14,134 ± 8,947 DT of corn stover (53.4%), 2,279 ± 1,917 DT of sorghum stalk (9.7%), and 8,213 ± 4,552 DT of wheat straw (36.9%). In scenario 2, each FSL was allocated on average 27,300 ± 17,520 DT of corn stover (49.6), 5,296 ± 3,294 DT of sorghum stalk (11.5%), and 18,161 ± 8,162 DT of wheat straw (39.0%). A sensitivity analysis performed on the proposed scenarios showed that scenario 2 would reach 98.1% of demand points (i.e., crop fields) with fewer FSLs (35) compared to scenario 1 (62.1% demand points; 50 FSLs). However, on a daily basis it would take longer to transport corn stover and sorghum stalk bales (16.0 hour) and wheat straw bales (8.9 hours) in scenario 2 compared to scenario 1 (5.8 hours and 3.1 hours). Despite the higher transportation costs and time, the fact that fewer FSLs are needed and more demand points can be serviced, scenario 2 is presumed to be the more cost-effective option.*

Keywords. *Biomass, Feedstock availability, Location-allocation analysis, Transportation logistics, GIS*

Introduction

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 availability are amongst the challenges associated with the quantification of feedstock availability. This influences optimized selection of a facility's location and transportation costs as reported in the Biomass Road Map (USDA, 2003) and several other studies (De Mol et al., 1997; Sokhansanj and Turhollow, 2002; Ravula et al., 2003; Cundiff et al., 2004; Krishnakumar and Ileleji, 2010). Ultimately, correct facility location selection will result in more precisely quantifying feedstock availability and predicting 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 geo-reference, crop-specific satellite imagery. This GIS-based approach was subsequently improved by Martinez and Maier (in review[1]) by taking into account the effect of field-level yield spatial variance based on soil characteristics, and variable residue removal rates based on erosion, soil characteristics, yield, and conservation field management practices. The variable residue removal (VRR) method using conservation tillage was deemed a more sustainable approach in the quantification of feedstock availability compared to the constant residue removal (CRR) method which used intensive tillage with 100% residue removal. While the GIS-based feedstock sourcing method proved feasible, the next logical step was to find suitable locations to store the remainder of the harvested residue that was initially not delivered to the biorefinery.

The main goal of this case study was to develop a methodology for siting feedstock storage locations, and to utilize a GIS location-allocation analysis to optimize the number of candidate FSLs to supply a Kansas-based biomass conversion facility.

Siting Parameters Used in Literature

Geographical Information Systems (GIS) have been used by researchers to predict siting of storage locations for existing or planned biomass processing facilities. Accurately predicting

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[1] Chapter 5 of this dissertation.

sites for feedstock storage will help supply conversion facilities with biomass in an economically feasible manner throughout the year. A review of the literature revealed different parameters used for siting storage locations.

A spatial analysis to site satellite storage locations (SSLs) for herbaceous biomass in the Southeast of the United States was done by Resop et al. (2011). A SSL was defined as an open area of land that could be used to store excess switchgrass bales collected from production fields. Each SSL was given a 3.2-km (2.0-mile) radius service area, which was the same radius used by Morey et al. (2010). The following suitability parameters were used to site SSLs: 1) minimum of 40 ha of switchgrass production available within the proposed service area; 2) SSLs must be on state-maintained, primary/secondary roads; 3) land should be classified as non-forested; and 4) terrain average slope must be less than 10%.

Judd et al. (2012) used similar siting parameters yet employed geoprocessing to find suitable locations by taking into account a road network system and the spatial distribution of urban/residential areas as well as that of streams/lakes. The following suitability parameters were used to site SSLs: 1) minimum of 40 ha of switchgrass production available within the proposed service area; 2) SSLs must be on a state-maintained, primary/secondary roads; 2) SSLs should not be within 100 meters of primary water bodies; 3) SSLs should not be within 500 meters of urban locations; 4) terrain average slope must be less than 10%; and 5) land should be classified as scrubland or grassland.

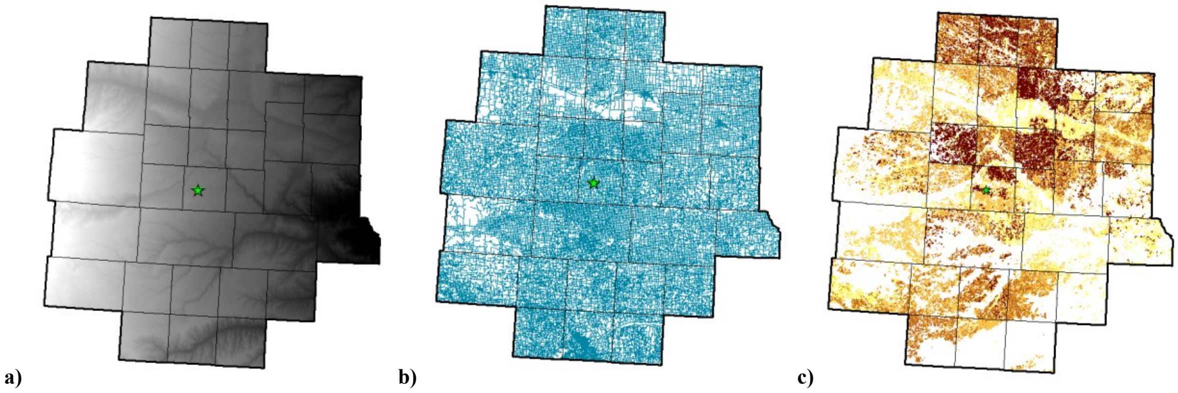
Producing a Suitability Map

In this case study, a suitability map was produced to site FSLs by taking into account similar suitability parameters as Resop et al. (2011) and Judd et al. (2012). Substantially more than 40 ha of biomass residue was available in this study. FSLs were sited on state-maintained, primary/secondary roads, were not within 100 m of water bodies, and were not within 500 m of urban locations. Additionally, terrain average slope was specified to be less than 10%, and the land was classified as scrubland, grassland, and barren land.

Siting Parameters

The first siting parameter considered to produce a suitability map was percent slope. This parameter was selected because terrain preparation (i.e., leveling) costs can be reduced if FSLs are located on terrain with a slope equal to or less than 10%. A percent slope map is created from a National Elevation Dataset (NED), which is a raster representation of a continuous surface usually referencing the surface of the earth (figure 6.1a). The second siting parameter considered to produce a suitability map was street accessibility. This parameter was selected because accessibility to fields, where harvested feedstock is located, is key for reducing overall transportation costs of the operation. Accessibility can be estimated by creating a buffer of the street network map which is a detailed real road network system that displays actual roads on which vehicles can travel on (figure 6.1b). The third siting parameter considered to produce a suitability map was residue availability. It is important to know the spatial distribution of residue in the study area to better locate FSLs given that having FSL sites close to where residue is located will further reduce transportation cost. The use of residue availability maps provides an accurate spatial distribution reference based on crop type, crop yield, crop rotation, climate, and field management (figure 6.1c).

Figure 6.1 National Elevation Dataset (NED) of the study area showing terrain elevation as a color gradient with lowest values in white color and highest in black color (a), street network map of the study area showing streets in light blue color (b), spatial residue availability map of the study area where most of the corn stover, sorghum stalk, and wheat straw is located as a color gradient with lowest availability in yellow, medium in brown, and highest in red (c). The green star indicates the location of the biorefinery near Hugoton, KS.



Re-classification of Siting Parameters

Fuzzy logic is a computing approach based on "degrees of truth" rather than the usual "true or false" (i.e., 1 or 0) used in Boolean logic. Fuzzy logic can be used in ArcGIS as an overlay analysis technique to solve traditional overlay analysis applications such as site selection and suitability models (ArcGIS, 2013b). With Fuzzy logic, propositions can be represented with degrees of truthfulness and falsehood. In ArcGIS, the fuzzy classes are used to define the transformation or remap of the input values to new values based on a specified function. The transformation process is referred to as fuzzification and establishes the fuzzy membership for each input value. The transformed values range from 0 to 1, defining the possibility of membership to a specified set, with 1 being absolutely in the set. Each fuzzy class is defined by a transformation function which captures a different type of transformation to achieve a desired effect. For example, one function is more appropriate when the values closer to a specified value have a higher possibility of being a member of the set, while another function might be more appropriate if the higher values are more likely to be members of the set. There are seven fuzzy classes available in ArcGIS. Once all input parameters have been transformed, the relationship between them can be established and analyzed with the ArcGIS Fuzzy Overlay tool.

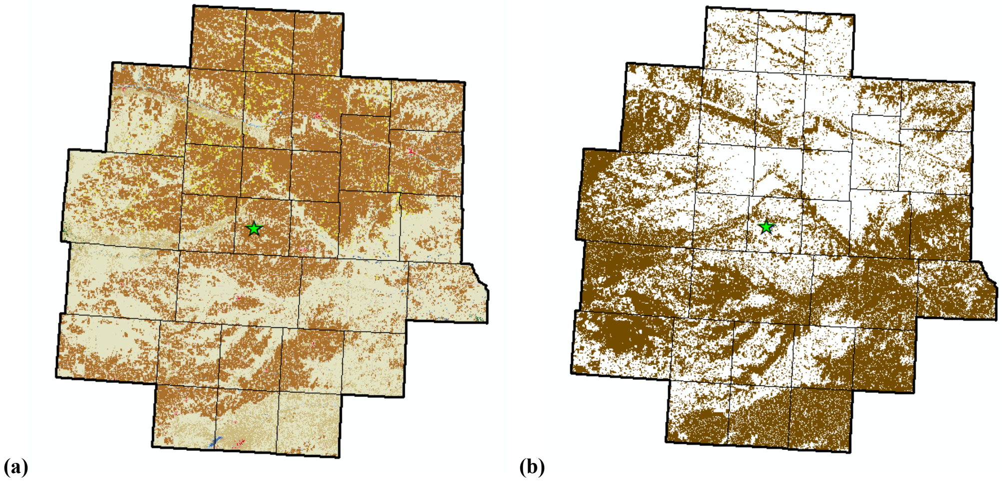
Refinement of Siting Sites

The NLCD is a 21-class statewide land cover classification scheme developed by the US Geological Survey (USGS; figure 6.2a). Out of the 21 classes available, three were chosen (figure 6.2b) to refine siting locations. Scrubland and grassland were chosen based on work by Resop et al. (2011), and barren land was chosen because it was considered a land classification capable of siting a FSL which would not drive the terrain preparation (i.e., leveling) costs too high.

Sensitivity Analysis of FSL Service Area Using Location-Allocation Analysis

A sensitivity analysis was performed on two different FSL service area sizes to quantify how much residue would be allocated to each FSL. This analysis was deemed necessary given that the number of sited FSLs will affect the siting location's surface area requirements as well as transportation costs. For example, if fewer FSLs are chosen, a location's surface area requirement would increase because more residue will need to be stored due to the increase in number of crop fields allocated to the FSL. This will also cause an increase in average driving distance for both farmers (i.e., from crop fields to FSLs) and the biorefinery (i.e., from FSLs to biorefinery). Consequently, the purpose of this sensitivity analysis is to quantify the effect of FSL service area size on number of FSLs required, percent of the demand points (i.e., crop fields) served, and a siting location's surface area requirements.

Figure 6.2 The acquired National Land Cover Data (NLCD) map shows 21 available land cover classifications of the study area (a) from which three land classes (brown color) were deemed suitable for siting feedstock storage depots (b). The green star indicates the location of the biorefinery near Hugoton, KS.



Material 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 Martinez and Maier (in review) used to quantify accuracy gained as a result of utilizing field-level yield spatial variance and variable residue removal rates as improvement parameters. The biorefinery's service areas were created in 16-km (10-mile) increments up to 64-km (40-miles) starting from the selected facility location (Hugoton, KS) as the reference point using the ArcGIS Network Analyst tool.

Suitability Map

The suitability map was created using the percent slope, street network, and residue availability maps as siting parameters. All acquired maps had the Universal Transverse Mercator

(UTM) zone 14 projection/coordinate system, were re-sampled to the coarsest resolution of 56 meters, clipped to the study area, and re-classified using Fuzzy logic in a degree of truthfulness with 0 being least suitable and 1 being most suitable to site a FSL. Suitable sites were further narrowed down using the National Land Cover Data (NLCD) produced in 2006 and re-classified to the same spatial resolution (i.e., 56 m), from which only sites on land classified as barren land, shrub/scrub, or grassland/herbaceous were selected.

The percent slope map was produced from NEDs acquired from the USDA NRCS Geospatial Data Gateway (USDA, 2012), which are produced by the US Geography Survey. The acquired NEDs were first merged then clipped to the study area. A percent slope map was then created using the ArcGIS Slope tool. Consequently, the percent slope map values (0 to 80.2% range) were re-classified using the ArcGIS Fuzzy Membership tool using a negative linear transformation function with a minimum value of 10% and maximum value of 30%.

The street network maps were acquired from the USDA NRCS Geospatial Data Gateway (USDA, 2012a). These maps are spatial extracts from the US Census Bureau Topologically Integrated Geographic Encoding and Referencing (TIGER) database. The ArcGIS Euclidean Distance tool was used to create a 0.8 and 1.6 km (0.5 and a 1 mile) buffer away from the street network. Distances were then re-classified using the Fuzzy Membership and a Fuzzy Small transformation function with a midpoint of 800 m (0.5 miles) and a spread of 5.

The residue availability map was produced using the methodology developed by Martinez and Maier (in review). In brief, variable residue removal (VRR) rates for corn, sorghum, and wheat were first estimated using the USDA Agricultural Research Service (ARS) Wind Erosion Prediction System (WEPS; USDA, 2012b). Factors such as weather, soil characteristics, crop yield, and field management were taken into account when running wind erosion simulations for soils NRCS classified as Land Capability Classification (LCC) 1, 2, 3, or 4 for each county in the study area. Estimated residue removal rates were then joined to a soil thematic map, which was then intersected with the crop hectare availability map. The ArcGIS Focal Statistics tool using a neighborhood setting of 87 cell height and width (equivalent to approximately 23 square km; 9 square miles) was used to generalize where the majority of the corn, sorghum, and wheat residue was located for years 2008 to 2012. The Weighted Sum tool in ArcGIS was then used to overlay residue availability maps by crop type to get a 5-year average. The Weighted Sum tool was used again to calculate a residue availability map of corn stover, sorghum stalk, and wheat straw which was weighted based on the percent dry tonnage estimated within the biorefinery's 64-km (40-mile) service area. The weighted residue availability map was then re-classified using the Fuzzy Membership tool in ArcGIS using a positive linear transformation function.

Once the suitability map has been produced, suitable sites are further narrowed down based on land classification of the NLCD. The ArcGIS Extract by Attribute tool was used to only extract suitable sites that overlayed the three selected land classification - barren land (rock/sand/clay), shrub/scrub, grassland/herbaceous (figure A.1).

Sensitivity Analysis of FSL Service Area Using Location-Allocation Analysis

The ArcGIS Network Analyst tool was used for the location-allocation analysis. First, the GIS coordinates of the facilities (candidate FSLs) and demand points (i.e., crop fields) were loaded into ArcGIS (figure A.2). All facilities were then set as "candidate facility" except for the Abengoa biorefinery which was set to "required facility" under facility type setting. Under the analysis setting, the impedance was set to 8 km (5 mi) and 16 km (10 mi), for scenario 1 and 2 respectively, with an impedance power transformation and an impedance parameter of 2 given that equity of service was a concern due to the spatial distribution of the crop fields. This way, a minority of crop fields is not burdened with comparatively excessive travel distances. Other analysis settings considered were travel which was set from "demand to facility" (i.e., crop fields to FSLs) and U-turns which were only allowed at dead ends.

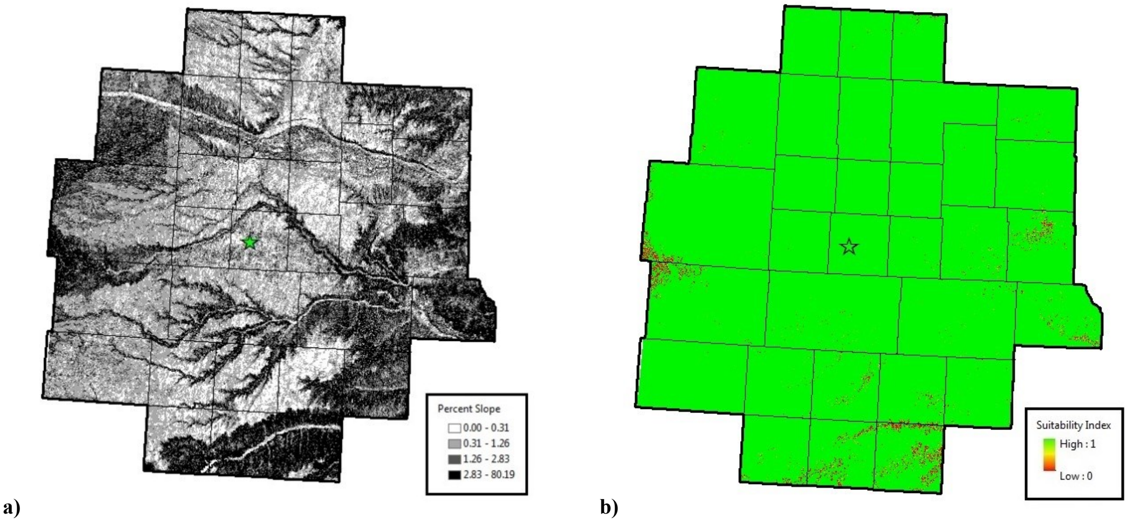
Results and Discussion

Assessing Suitability Map Parameters

The suitability map was created based on three parameters that assured the siting criteria for the FSLs were met. They reflected that FSLs were built on terrain with characteristics capable of supporting infrastructure, had easy access via the road network system, and were located close to high residue availability areas.

The first siting parameter analyzed was terrain characteristics (i.e., percent slope). Figure 6.3 shows the percent slope map of the study area and the suitability map produced using a negative Fuzzy Linear transformation function with the ArcGIS Fuzzy Membership tool. This transformation function was chosen because slope values would be most suitable until 10% then would decrease linearly until they reach 30%. Thereafter the location was deemed not suitable. Percent slope of the terrain in the study area was analyzed by classifying its data in four classes using the Quantile method. Results showed that 98.5% of the study area had a slope equal or less than 10%, with an average percent slope of 1.8 ± 2.6 and range of 0 to 80.2% (figure 6.3a). Terrain with a slope equal or less than 10% is ideal because leveling increases construction costs. Thus, most of the study area is suitable for siting FSLs (figure 6.3b). The suitability index is shown as a color gradient with lowest suitability in red, medium in yellow, and highest in green. Even though percent slope is an important parameter to consider when producing a site location suitability map, it was not a determining factor in this case study.

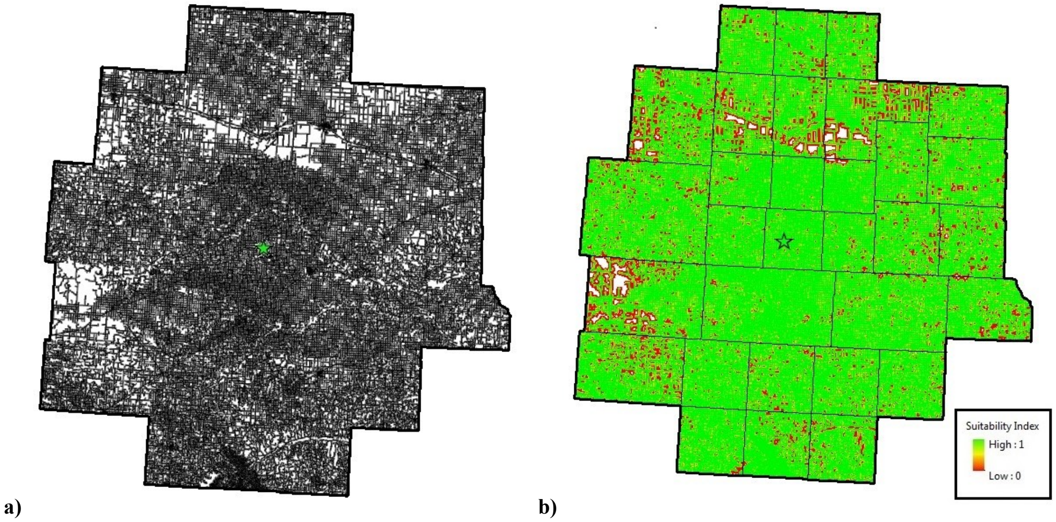
Figure 6.3 Percent slope map of the study area classified in four different classes using the Quantile method (a), and the FSL siting suitability map produced using Fuzzy logic shown with suitability index as a color gradient with lowest suitability in red, medium in yellow, and highest in green (b). The green star indicates the location of the biorefinery near Hugoton, KS.



The second siting parameter analyzed was ease of access via the road network system. Figure 6.4 shows the street network map of the study area and the suitability map produced using a Fuzzy Small transformation function with the ArcGIS Fuzzy Membership tool. This transformation function was chosen because accessibility values gradually decrease in suitability as the distance from the street increases until a value where they are no longer suitable. Given the well-developed road network most of the study area had a high suitability index (figure 6.4b).

Thus, accessibility proved not to be a determining factor in this case study. Nonetheless, it is an important parameter to consider when producing a FSL siting suitability map given that transportation cost would increase if fields are located further away from FSL locations than optimal.

Figure 6.4 Street network map of the study area (a), and the FSL siting suitability map produced using Fuzzy logic shown with suitability index as a color gradient with lowest suitability in red, medium in yellow, and highest in green (b). The green star indicates the location of the biorefinery near Hugoton, KS.



a) **b)**

The third siting parameter analyzed was residue availability. Table 6.1 shows annual hectare and residue availability per 16-km (10-mile) service area from plant location (Hugoton, KS). These were estimated using the multi-crop variable residue removal (MC-VRR) GIS-based method developed by Martinez and Maier (in review). Residue availability differed between service areas and years due to spatial distribution of crop fields and a crop's residue removal rate, which is estimated based on field management practices (e.g., rotation and soil preparation).

The 5-year average of the biorefinery's 64-km (40-mile) service area indicates that the majority of the residue is corn stover (51.2%), with wheat straw (39.2%), and sorghum stalk (9.6%) making up the remainder. It was observed that the first two service areas had a higher than average percent availability of corn stover (64.9 and 65.5%, respectively). A major shift was observed in the third service area (32-48 km; 20-30 miles) with corn stover availability decreasing by 16.9% (from 65.5 to 48.6%) and wheat straw making up the majority of this difference with an increase of 16.1% (from 26.2 to 42.3%). Sorghum stalk made up the remaining difference of 0.8% (from 8.3 to 9.1%). This shift in percent residue availability can be attributed to the spatial distribution of crop fields.

Even though the first two service areas have similar percent residue availability, dry tonnage availability is significantly different. The first service area (0-16 km; 0-10 mi) has a 5-year average total of 119,554 ± 7,475 DT, comprised of corn stover (77,754 ± 7,562 DT), wheat straw (32,364 ± 5,685DT) and sorghum stalk (9,636 ± 675DT). The second service area's (16-32 km; 10-20 mi) total average (397,248 ± 24,910 DT) is comprised of corn stover (260,308 ± 16,400 DT), wheat straw (103,960 ± 14,087 DT) and sorghum stalk (32,981 ± 7,255 DT). This difference in dry tonnage can be attributed to the surface area of the biorefinery's service areas and a crop's residue removal rate.

The biorefinery's service areas were calculated based on 16-km (10-mile) driving distance from the biorefinery using a road network and the ArcGIS Network Analysts tool. While a larger service area should indicate a larger number of crop fields, it might not necessarily be the case because crop fields have an aggregate spatial distribution. Crop residue removal rates were estimated using the MC-VRR GIS-based method developed by Martinez and Maier (in review). The 5-year average of the biorefinery's 64-km (40-mile) service area indicates corn in a continuous corn rotation had a higher removal rate (5,915 ± 615 kg/ha; 5,205 ± 541 lb/ac) compared to wheat in a sorghum-wheat-fallow rotation (3,691 ± 239 kg/ha; 3,248 ± 210 lb/ac), and sorghum in a sorghum-wheat-fallow rotation (3,708 ± 156 kg/ha; 3,263 ± 137 lb/ac).

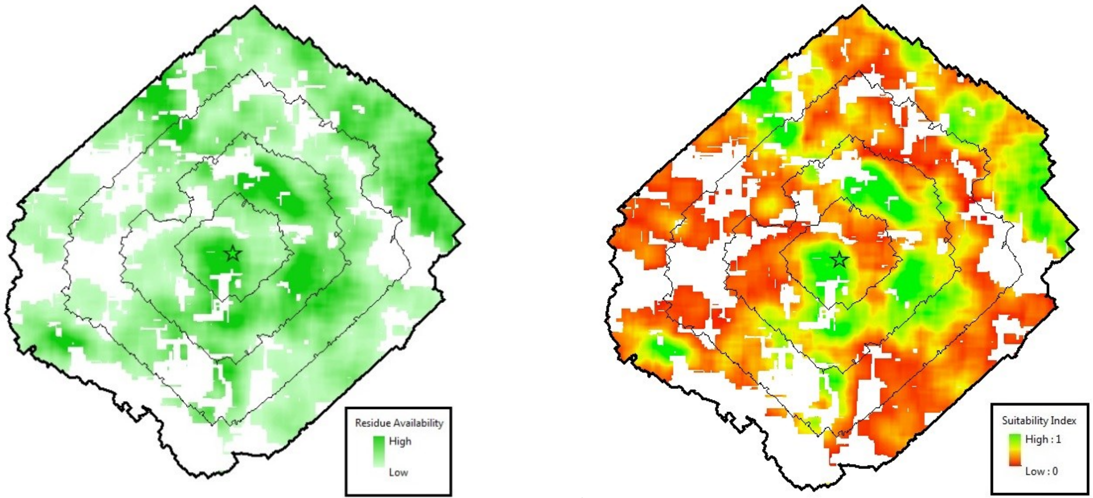
Figure 6.5 shows spatial residue availability of 5-year corn stover, sorghum stalk, and wheat straw residue maps weighted based on the percent dry tonnage estimated within the biorefinery's 64-km (40-mile) service area. The FSL siting suitability map was produced using a positive Fuzzy Linear transformation function with the ArcGIS Fuzzy Membership tool. Figure 6.5a shows residue availability as a color gradient with the lowest availability in light green and the highest in dark green. Based on this map, it was concluded that residue availability has an aggregated spatial distribution which was influenced by location, climate, and crop rotation among other factors. Figure 6.5b demonstrates this conclusion by showing green clusters that indicate higher residue availability followed by medium availability in yellow and lowest availability in red. Therefore, residue availability is clearly a determining parameter for choosing suitable FSL sites. It should be noted that this residue availability is specific to this case study. It is based on spatial distribution of crop fields, representative crop rotations, and average percent dry tonnage per crop type.

Table 6.1 Estimated annual hectare and residue availability per 16-km (10-mile) service area from plant location (Hugoton, KS) using the multi-crop variable residue removal (MC-VRR) GIS-based method developed by Martinez and Maier (in review [a]).

Year	Crop Residue	Biorefinery Service Area in km (miles)								Total	
		0–16 (0–10)		16–32 (10–20)		32–48 (20–30)		48–64 (30–40)			
		Hectares Available per Biorefinery Service Area (acres)									
		10,268 (25,372)		33,821 (83,574)		31,572 (78,017)		44,298 (109,462)			
		Residue Available per Service Area using Conservation Tillage Practices Conserving at least 30% Soil Coverage at 2nd Year Planting									
		Dry Tons	%	Dry Tons	%	Dry Tons	%	Dry Tons	%	Dry Tons	%
2008	Corn stover	79,153	70.0	253,495	67.9	188,626	47.4	304,904	44.2	826,178	52.5
	Sorghum stalk	9,110	8.1	31,254	8.4	42,374	10.7	82,489	12.0	165,227	10.5
	Wheat straw	24,846	22.0	88,479	23.7	166,806	41.9	302,526	43.8	582,657	37.0
	Total	113,109	100.0	373,228	100.0	397,806	100.0	689,919	100.0	1,574,062	100.0
2009	Corn stover	74,091	61.4	252,188	62.6	218,910	44.6	341,632	40.0	886,821	47.5
	Sorghum stalk	9,323	7.7	32,422	8.1	36,832	7.5	81,213	9.5	159,790	8.6
	Wheat straw	37,268	30.9	118,031	29.3	234,999	47.9	430,943	50.5	821,241	44.0
	Total	120,682	100.0	402,641	100.0	490,741	100.0	853,788	100.0	1,867,852	100.0
2010	Corn stover	90,092	69.0	289,626	67.6	281,448	53.6	404,316	47.4	1,065,482	55.0
	Sorghum stalk	10,332	7.9	40,985	9.6	55,414	10.6	111,321	13.1	218,052	11.3
	Wheat straw	30,058	23.0	97,681	22.8	188,362	35.9	336,802	39.5	652,903	33.7
	Total	130,482	100.0	428,292	100.0	525,224	100.0	852,439	100.0	1,936,437	100.0
2011	Corn stover	72,092	64.4	252,624	68.2	253,058	52.0	383,230	46.7	961,004	53.7
	Sorghum stalk	9,018	8.1	22,158	6.0	39,790	8.2	69,252	8.4	140,218	7.8
	Wheat straw	30,868	27.6	95,823	25.9	193,411	39.8	367,799	44.8	687,901	38.4
	Total	111,978	100.0	370,605	100.0	486,259	100.0	820,281	100.0	1,789,123	100.0
2012	Corn stover	72,343	59.5	253,605	61.6	242,369	45.1	366,087	41.2	934,404	47.7
	Sorghum stalk	10,397	8.6	38,084	9.3	47,126	8.8	98,136	11.0	193,743	9.9
	Wheat straw	38,780	31.9	119,787	29.1	247,888	46.1	424,381	47.8	830,836	42.4
	Total	121,520	100.0	411,476	100.0	537,383	100.0	888,604	100.0	1,958,983	100.0
Average ± SD	Corn stover	77,554 ± 7,562	64.9 ± 4.6	260,308 ± 16,400	65.5 ± 3.2	236,882 ± 35,105	48.6 ± 4.1	360,034 ± 38,450	43.9 ± 3.3	934,778 ± 89,254	51.3 ± 3.5
	Sorghum stalk	9,636 ± 675	8.1 ± 0.3	32,981 ± 7,255	8.2 ± 1.4	44,307 ± 7,269	9.1 ± 1.4	88,482 ± 16,381	10.8 ± 1.9	175,406 ± 30,580	9.6 ± 1.4
	Wheat straw	32,364 ± 5,685	27.1 ± 4.5	103,960 ± 14,087	26.2 ± 3.0	206,293 ± 33,915	42.3 ± 4.8	372,490 ± 55,453	45.4 ± 4.1	715,108 ± 108,178	39.2 ± 4.1
	Total	119,554 ±7,745	100.0	397,248 ± 24,910	100.0	487,483 ± 54,700	100.0	821,006 ± 77,163	100.0	1,825,291 ± 155,292	100.0

[a] Chapter 5 in this dissertation.

Figure 6.5 Spatial residue availability of weighted 5-year average corn stover (51.2%), sorghum stalk (9.6%), and wheat straw (39.2%) residue availability maps within the biorefinery's 64-km (40-mile) service area (a), and the FSL siting suitability map produced using Fuzzy logic shown with suitability index as a color gradient with lowest suitability in red, medium in yellow, and highest in green (b). The green star indicates the location of the biorefinery near Hugoton, KS.



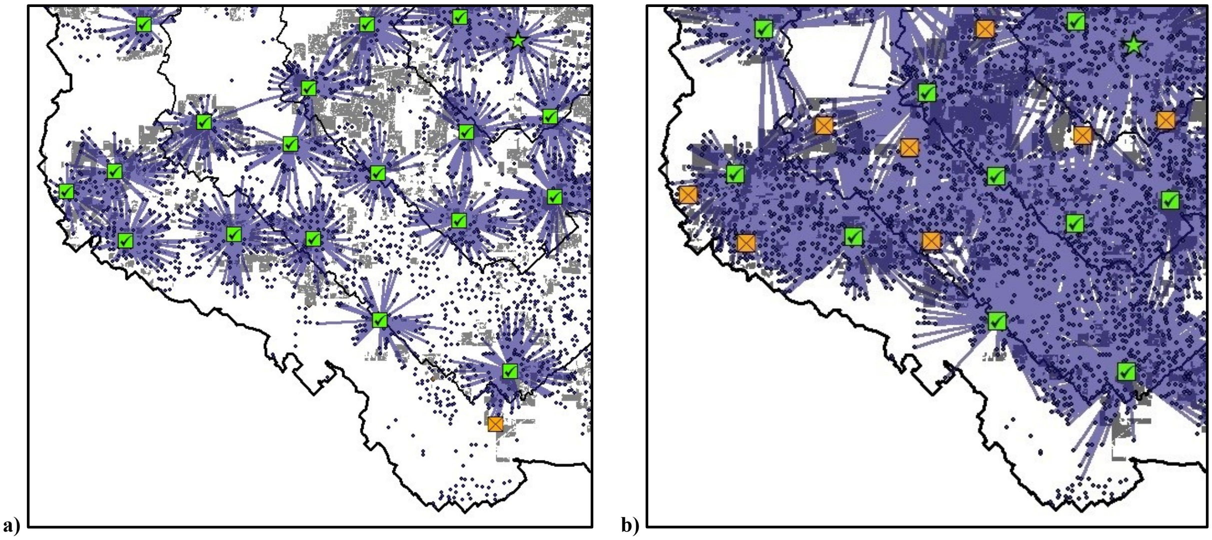
a) **b)**

Sensitivity Analysis of FSL Service Area

Market Share Analysis

Results of a 5-year market share analysis for scenarios 1 and 2 shows demand points (black dots) allocated (blue lines) to the chosen FSLs (green box) in the southwestern part of the study area (figure 6.6). Scenario 1 indicated that, on average, 62.1% of the demand points would be reached requiring 49 FSLs (figure 6.6a). In scenario 2, it was estimated that on average 98.1% of the demand points would be reached requiring only 35 FSLs (figure 6.6b). This decrease in the required number of FSLs resulted because more demand points were allocated to each FSL due to the increase in FSL service area (from 8 to 16 km; 5 to 10 miles). Even with the increase in FSL service area, not all demand points could be allocated to a FSL because they were still beyond the FSL 16-km (10-mile) service area. This could be solved by either increasing the number of FSLs within the biorefinery's 64-km (40-mile) service area or increasing the size of the FSL service area.

Figure 6.6 Market share analysis showing demand points (black dots) allocated (blue lines) to the chosen FSLs (green box) in the southwestern part of the study area for scenario 1 (a) and scenario 2 (b). The green star indicates the location of the biorefinery near Hugoton, KS.



The first option will increase overall costs because as the number of FSLs increase, more site preparation will be needed. In scenario 1, even with the addition of 78 FSLs (128 FSLs in total) only 97.3% of the demand points were reached. This was due to the inexistence of a suitable location near demand points that were not allocated to a FSL. Scenario 2 will require 5 additional FSLs to reach 100% of the demand points bringing the total to 40 required FSLs.

The second option will increase transportation costs because as the FSL service area increases, further FSLs will be needed to meet demand. Analysis of larger FSL service areas indicated the following demand coverage and required number of FSLs: 18-km (11 miles; 99.1% demand cover; 33 FSLs), 19-km (12 miles; 99.7% demand cover; 31 FSLs), 21-km (13 miles; 99.9% demand cover; 28 FSLs), and 12.5-km (14 miles; 100% demand cover; 24 FSLs). Therefore, FSL service areas would need to be increased to 14 miles to cover 100% of the demand points which would results in increased travel distances for both the farmers (fields to FSLs) and to the biorefinery (FSLs to biorefinery).

Table 6.2 **Estimated corn stover, sorghum stalk, and wheat straw availability for feedstock storage locations (FSLs) in scenario 1 (8-km; 5-mile FSL service area) and scenario 2 (16-km; 10-mile FSL service area) using the multi-crop variable removal rate (MC-VRR) GIS-based method developed by Martinez and Maier (in review [a]).**

Facility No.	Biorefinery Service Area	Residue Available using Conservation Tillage Practices Conserving at least 30% Soil Coverage at 2nd Year Planting.											
		Scenario 1						Scenario 2					
		Corn Stover		Sorghum Stalk		Wheat Straw		Corn Stover		Sorghum Stalk		Wheat Straw	
		Dry Tons ± SD	%	Dry Tons ± SD	%	Dry Tons ± SD	%	Dry Tons ± SD	%	Dry Tons ± SD	%	Dry Tons ± SD	%
1	1	22,295 ± 6,947	81.3	878 ± 654	3.1	4,408 ± 1,157	15.6	45,993 ± 7,764	69.5	5,372 ± 495	8.1	14,772 ± 2,632	22.3
28	1	16,774 ± 4,800	66.5	1,748 ± 427	6.9	6,714 ± 1,773	26.6	25,213 ± 5,332	58.7	3,559 ± 727	8.3	14,215 ± 3,450	33.1
14	2	25,369 ± 8,069	63.4	4,093 ± 2,061	10.2	10,562 ± 1,685	26.4	55,031 ± 10,149	58.7	12,590 ± 3,199	13.4	26,142 ± 3,607	27.9
24	2	21,029 ± 5,875	68.9	2,391 ± 571	7.8	7,087 ± 1,131	23.2	37,856 ± 3,233	61.3	5,723 ± 729	9.3	18,145 ± 4,361	29.4
36	2	21,808 ± 2,148	72.1	1,258 ± 241	4.2	7,193 ± 1,765	23.8	56,591 ± 4,486	70.0	3,628 ± 2,349	4.5	20,638 ± 4,491	25.5
3	3	23,567 ± 4,498	67.3	1,050 ± 746	3.0	10,392 ± 1,690	29.7	38,506 ± 6,606	50.9	3,679 ± 1,571	4.9	33,420 ± 3,100	44.2
13	3	10,573 ± 755	58.4	1,504 ± 659	8.3	6,027 ± 499	33.3	20,963 ± 2,137	59.8	2,793 ± 773	8.0	11,277 ± 1,875	32.2
20	3	12,418 ± 2,466	51.0	4,695 ± 2,323	19.3	7,233 ± 2,733	29.7	26,829 ± 5,266	54.4	5,915 ± 1,155	12.0	16,538 ± 2,514	33.6
46	3	3,736 ± 259	30.2	1,456 ± 585	11.8	7,178 ± 3,743	58.0	7,571 ± 1,283	24.8	3,828 ± 1,798	12.5	19,140 ± 2,885	62.7
2	4	5,649 ± 1,376	27.6	1,648 ± 876	14.3	9,045 ± 1,122	58.1	5,502 ± 1,082	25.6	3,482 ± 1,454	16.2	12,523 ± 2,063	58.2
9	4	8,940 ± 3,671	37.3	3,338 ± 2,191	13.9	11,683 ± 2,967	48.8	16,648 ± 3,898	38.1	6,239 ± 2,239	14.3	20,842 ± 1,888	47.7
10	4	19,011 ± 3,600	41.0	5,895 ± 1,885	13.1	21,842 ± 3,265	45.9	27,129 ± 4,945	40.1	10,328 ± 3,330	15.3	30,193 ± 5,195	44.6
21	4	1,785 ± 199	21.5	840 ± 469	13.1	5,673 ± 1,268	68.4	4,950 ± 3,497	32.7	2,564 ± 647	16.9	7,618 ± 3,796	50.3
41	4	7,279 ± 5,604	61.6	1,117 ± 760	10.1	3,413 ± 1,961	28.9	13,417 ± 5,603	50.3	4,449 ± 2,920	16.7	8,791 ± 6,844	33.0
Dry Ton Average ± SD		14,134 ± 8,947		2,279 ± 1,917		8,213 ± 4,552		27,300 ± 17,520		5,296 ± 3,294		18,161 ± 8,162	
% Average ± SD		53.4 ± 18.7		9.7 ± 4.6		36.9 ± 16.0		49.6 ± 15.1		11.5 ± 4.3		38.9 ± 12.5	

[a] Chapter 5 of this dissertation.

Quantification of Residue Allocation to FSLs

The amount of residue allocated to each FSL is another variable that needs to be considered when selecting a FSL service area. Table 6.2 shows estimated quantity of residue allocated to 14 facilities within the biorefinery's 64-km (40-mile) service area for scenarios 1 and 2. The amount of crop residue allocated to each facility varies greatly between FSL and the biorefinery's service area for both scenarios. This high variation in residue allocation can be attributed to spatial distribution of crop fields, FSL siting, and crop residue availability which is dictated by crop type, crop yield, crop rotation, soil characteristics, location, climate, and field management.

In scenario 1 each FSL was allocated on average 14,134 ± 8,947 DT of corn stover (53.4 ± 18.7%), 2,279 ± 1,917 DT of sorghum stalk (9.7 ± 4.6%), and 8,213 ± 4,552 DT of wheat straw (36.9 ± 16.0%). In scenario 2, FSLs were allocated on average 27,300 ± 17,520 DT of corn stover (49.6 ± 15.1%), 5,296 ± 3,294 DT of sorghum stalk (11.5 ± 4.3%), and 18,161 ± 8,162 DT of wheat straw (38.9 ± 12.5%). An interesting shift in percent crop residue allocated was noticed for FSLs no. 2, 9, 10, 21, and 46. This shift was attributed to these FSLs being sited within the biorefinery's third and fourth service areas, given that a significant decrease in corn stover (16.9%) and increase in wheat straw (16.1%) availability occurred from the second (16-32 km; 10-20 miles) to the third (32-48 km; 20-30 miles) service area (table 6.1).

Estimated Required FSLs Based on Plant Capacity

The number of required FSLs will also be affected by plant capacity. As plant capacity increases so does its annual feedstock requirement. Consequently, the biorefinery's procurement area will increase. Martinez and Maier (in review) estimated percent of feedstock per service area for five facility capacities ranging from 151 to 757 million liters per year (MLY; 40 to 200 MGY) based on estimated residue available per service area and plant annual feedstock requirement. It was concluded that plants with a 151 and 227 MLY (40 and 60 MGY) capacities would meet its annual feedstock requirement in the second service area (16-32 km; 10-20 miles), a plant with a 378 MLY (100 MGY) capacity in the third service area (32-48 km; 20-30 miles), and the 567 and 757 MLY (150 and 200 MGY) capacity plants in the fourth service area (48-64 km; 30-40 miles).

The required number of FSLs based on plant capacity were estimated using residue availability in the biorefinery's 64-km (40-mile) service area (table 6.1) and the amount of corn stover, sorghum stalk, and wheat straw allocated on average per FSL (table 6.2) for scenarios 1 and 2 FSLs. The first service area (0-16 km; 0-10 miles) required 5 FSLs for scenario 1 and 2 for scenario 2. The second service area (16-32 km; 10-20 miles) required 16 and 8 FSLs, the third service area (32-48 km; 20-30 miles) 20 and 10 FSLs, and the fourth service area (48-64 km; 30-40 miles) 33 and 16 FSLs for scenarios 1 and 2, respectively. Therefore, it was concluded based on service area requirements that plants with a 151 and 227 MLY (40 and 60 MGY) capacities would require 21 FSLs for scenario 1 and 10 FSLs for scenario 2. The 378 MLY (100 MGY) capacity plant would require 41 and 20 FSLs, and the larger plant capacities (567 and 757 MLY; 150 and 200 MGY) would require 74 and 36 FSLs for scenarios 1 and 2, respectively. Due to the larger procurement area, larger plant capacities would require more FSLs, thus increasing overall transportation cost.

Surface Area Requirements Based on Residue Allocation to FSLs

Surface area required to store the residue allocated is another important factor that needs consideration. The amount of surface area required would depend on the amount of residue allocated, type of bale, bale density, bale stack configuration, seasonal availability, and possibly other factors. To estimate the surface area required for the average amount of residue allocated to each FSL for scenarios 1 and 2, the following assumptions were made:

- Wheat straw is harvested in July; corn stover and sorghum stalks in October.
- Only large square bales are harvested in the study area. Large square bale dimensions are 0.91 meters wide, 0.91 meters high, and 2.4 meters long (3 feet wide, 3 feet high, and 8 feet long), and have on average 160.5 kg of dry matter per cubic meter (10 pounds of dry matter per cubic foot; Edwards, 2011).
- Stack configuration consists of 2,214 large square bales (figure 6.7). Stack dimensions are 5.5 m high, 14.6 m wide and 54.9 meters long (18 feet high, 48 feet wide and 180 feet long). Stack configuration is similar to the one the Abengoa Bioenergy Hybrid of Kansas facility has in Moscow, KS.
- Area requirement per bale stack is 0.2 hectares (0.5 acres; figure 6.8), which includes spacing between bale stacks of 1x the width on the shorter side and 1.5x

the width on the long side for safety reasons and to leave room to load and unload bales. Area requirement is similar to the FSL the Abengoa Bioenergy Hybrid of Kansas facility has in Moscow, KS.

Figure 6.7 Stack configuration dimensions are 5.5 m high, 14.6 m wide and 54.9 m long (18 ft high, 48 ft wide and 180 ft long). Large square bale dimensions are 0.91 m wide, 0.91 m high, and 2.4 m long (3 ft wide, 3 ft high, 8 ft long).

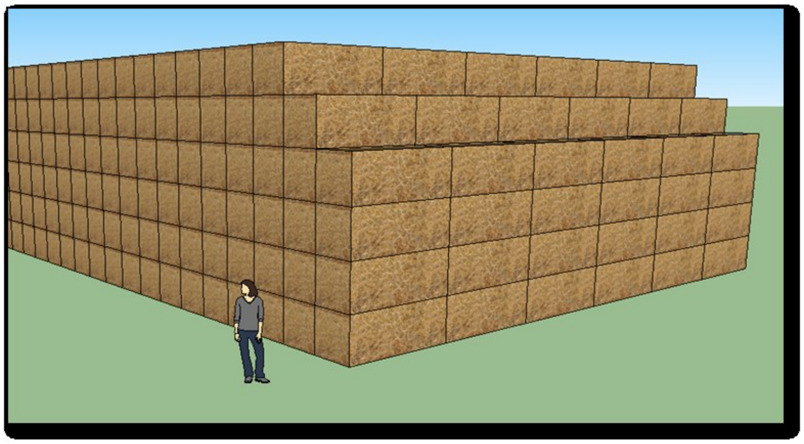


Figure 6.8 Surface area requirement based on a stack configuration 14.6 m wide and 54.9 m long (48 ft wide and 180 ft long) and spacing requirements between stacks of 1x the width on the shorter side and 1.5x the width on the long side.

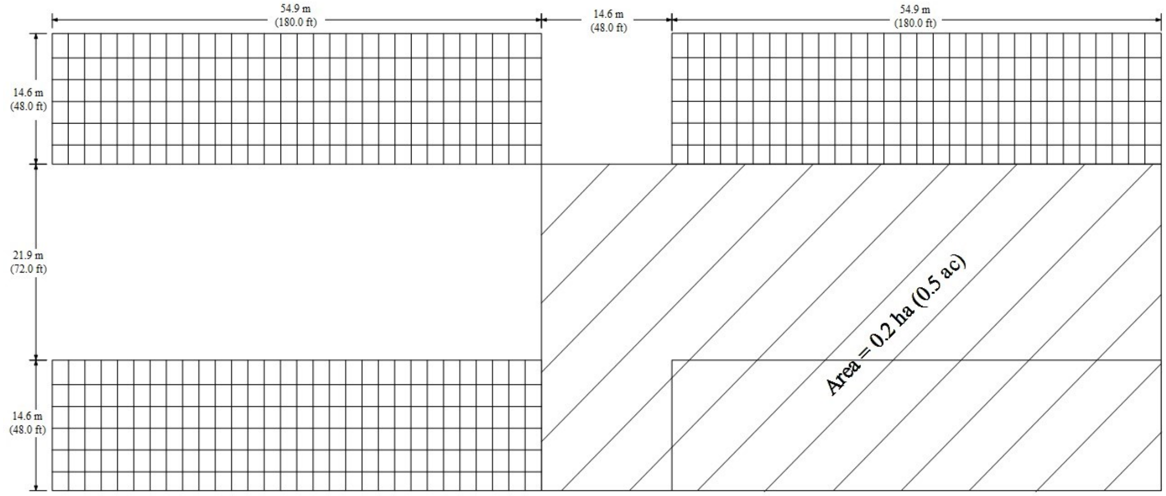


Table 6.2 shows estimated number of bales, stacks, and hectares needed to store the average estimated residue allocated to each FSL in scenarios 1 and 2. If FSLs have a 8-km (5-

mile) service area (scenario 1) the surface area per location required to store 16,413 DT of corn stover and sorghum stalk would be 4.7 ha (11.5 acres), and 2.4 ha (6.0 acres) to store 8,213 DT of wheat straw. FSLs with a 16-km (10-mile) service area (scenario 2) require 9.1 ha (22.5 acres) to store 32,599 DT of corn stover and sorghum stalk, and 5.1 ha (12.5 acres) to store 18,161 DT of wheat straw. The surface area of 50 candidate FSLs was estimated using the ArcGIS Dimension tool. The average surface available per location was 55.6 ± 20.9 ha (139.1 ± 52.3 ac). Consequently, either scenario is realistic given that estimated FSL surface area requirement is less than the average surface available per FSL (52.7 ± 23.2 ha; 131.8 ± 58.1 ac).

Table 6.3 Estimated residue availability, bales, stacks, and hectares (acres) needed on average for each FSL in scenarios 1 and 2.

Crop Residue	Scenario 1				Scenario 2			
	Dry Tons	Bales	Stacks	Hectares (Acres)	Dry Tons	Bales	Stacks	Hectares (Acres)
Corn Stover + Sorghum Stalk	16,413	50,151	23	4.7 (11.5)	32,596	99,599	45	9.1 (22.5)
Wheat Straw	8,213	25,095	12	2.4 (6.0)	18,161	55,492	25	5.1 (12.5)

Transportation Requirements Based on Residue Allocation to FSLs

The next question was whether it was logistically feasible to transport the estimated amount of residue. To answer this question, the following assumptions were made:

- Trucks are allowed a maximum load weight of 21 tons (Edwards, 2011).
- Large square bales weigh 0.57 tons (1,244 lb) on a wet basis.
- Duration of residue harvest is 8-14 weeks.
- FSLs operate 6 days per week during the harvest season.

Table 6.3 shows the total, weekly, and daily number of truck loads needed based on the estimated number of bales for scenarios 1 and 2. Scenario 1 indicated a total of 21 truckloads would be needed daily, over the average 11-week duration of residue harvest, to haul the total estimated 50,151 corn stover and sorghum stalk large square bales from the demand points (i.e., crop fields) to the FSLs, and 11 daily truckloads for the total estimated 25,095 large square bales of wheat straw. Scenario 2 indicated 42 daily truckloads to haul the total estimated 99,599 corn stover and sorghum stalk large square bales, and 23 daily truckloads for the total estimated 55,492 large square bales of wheat straw. To calculate the number of hours needed to haul the daily truckload requirement, the following assumptions were made: the average roundtrip distance from a FSL to the biorefinery is 8 km (5-miles) for scenario 1 and 16-km (10-miles) for scenario 2, the bale load and unload operation takes 10 minutes, and the truck's average hauling speed is 72 km/h (45 m/h; Judd et al., 2012). Consequently, on a daily basis it would take 5.8 hours to transport all the corn stover and sorghum stalk bales, and 3.1 hours to transport the wheat straw bales from the crop fields to the FSL in scenario 1. In scenario 2, it would take 16.0 hours for corn stover and sorghum stalk bales, and 8.9 hours for wheat straw bales.

Table 6.4 Estimated total, weekly, and daily truck loads needed on average for each FSL in scenarios 1 and 2.

Crop Residue	Truck Loads					
	Scenario 1			Scenario 2		
	Total	Weekly	Daily	Total	Weekly	Daily
Corn Stover + Sorghum Stalk	1,393	127	21	2,767	252	42
Wheat Straw	697	63	11	1,541	140	23

Conclusions

The results of this case study emphasized the importance of re-classifying siting parameter values using Fuzzy logic to produce a suitability map for siting FSLs and a location-allocation analysis to select optimal number of candidate FSLs to supply a biorefinery.

The following are specific conclusions reached from this study:

- Residue availability was the most determining factor out of three considered to produce the suitability map. Percent slope and street network were not considered determining factors in this case study although they may be important factors to consider when producing a suitability map.
- Residue availability differed between service areas and years due to spatial distribution of crop fields and a crop's residue removal rate. The majority of the residue in the biorefinery's 64-km (40-mile) service area was corn stover (51.2%), with wheat straw (39.2%), and sorghum stalk (9.6%) making up the remainder. Additionally, corn in a continuous corn rotation was found to have a higher removal rate (5,915 ± 615 kg/ha;

5,205 ± 541 lb/ac) compared to wheat in a sorghum-wheat-fallow rotation (3,691 ± 239 kg/ha; 3,248 ± 210 lb/ac), and sorghum in sorghum-wheat-fallow rotation (3,708 ± 156 kg/ha; 3,263 ± 137 lb/ac).

- Attempting to reach100% of the demand points for scenarios 1 and 2 required either increasing the number of FSLs within the biorefinery's 64-km (40-mile) service area or increasing the size of the FSL service area. Even with the addition of 78 FSLs (128 FSLs total) scenario 1 only reached 97.3% of the demand points due to the non-existence of a suitable location near demand points that were not allocated to a FSL. Scenario 2 required 5 additional FSLs (40 FSLs total) to reach 100% of the demand points. The analysis of larger FSL service areas indicated they would need to be increased to 22.5 km (14 mi) to cover 100% of the demand points.
- Plant capacity affects the number of required FSLs because as plant capacity increases so does its annual feedstock requirement. It was estimated that plants with 151 and 227 MLY (40 and 60MGY) capacities would require 21 FSLs for scenario 1 and 10 FSLs for scenario 2. The 378 MLY (100 MGY) capacity plant would require 41 and 20 FSLs, and the larger plant capacities (567 and 757 MLY; 150 and 200 MGY) would require 74 and 36 FSLs for scenarios 1 and 2, respectively.
- Surface area requirements need to be factored in when selecting FSL service areas size. Scenarios 1 and 2 proved feasible with regards to surface area requirements given that estimated FSL surface area requirements, based on average residue allocated per FSL, was much less than the average surface available per FSL (52.7 ± 23.2 ha; 131.8 ± 58.1 ac).
- Transportation also needs to be factored in when selecting FSL service areas size. It was estimated that on a daily basis it would take 5.8 hours to transport all corn stover and sorghum stalk bales, and 3.1 hours to transport the wheat straw bales from the crop fields to the FSL in scenario 1. In scenario 2, it would take 16.0 hours for corn stover and sorghum stalk bales, and 8.9 hours for wheat straw bales.
- Despite the higher transportation costs and time, the fact that fewer FSLs are needed and more demand points can be serviced, scenario 2 is presumed to be the more cost-effective option.

Chapter 7 - Research Conclusions

The main objective of this research was accomplished with the development of a GIS-based method that will generate more accurate biomass residue availability data as input data to biomass supply chain logistics models. The GIS-based method developed will be more accurate by using a real road network dataset, geo-referenced cropland satellite images, field-level yields, erosion control assessments, variable residue removal rates, and satellite storage depots to provide biomass in order to estimate residue availability in a feasible and sustainable way.

In chapter 3, a new method was developed to quantify biomass availability using a Geographical Information System (GIS) and was compared to a method developed by Mukunda et al. (2006). The results of this case study emphasized the importance of using an improved method to quantify the feedstock availability supply for a biorefinery. Data collected showed that quantification of feedstock availability using the GIS-based method was possible, and was more accurate than the method used by Mukunda et al. (2006). Consequently, using the proposed method to predict the feedstock supply area for existing or planned biomass-based processing facilities will be faster and more reliable. The following were specific conclusions reached from this study:

- Area calculation using method 2 was 1.5 times more accurate compared to method 1 because a map-based road network was used to calculate service areas instead of concentric circles.
- The estimation accuracy of hectare availability increased by a factor of 1.45 because the CDL satellite images used in method 2 were field-level accurate instead of being based on county-level statistics as in method 1.
- The use of GIS tools reduced human calculation error and processing time by 50% when using method 2.
- The use of a map-based road network dataset eliminated the use of a tortuosity factor, used later in method 1, to calculate driving distances in a discrete logistics model.
- Method 2 allows for calculating biomass sourcing costs based on more accurate transportation distances and times.

In chapter 4, the developed GIS-based method was improved by estimating variable residue removal rates based on location, climate, erosive force, soil characteristics, field-level yield, and field management. The results of this case study emphasized the importance of using two additional parameters (i.e., field-level yields and residue removal rates) to further improve quantifying feedstock availability to supply a biorefinery. Residue removal was maximized based on location, yield, soil characteristics, and field management without causing soil erosion and while maintaining soil productivity. The following were specific conclusions reached from this study:

- If more than 20% of the study area counties have more than 35% of their soil hectares without a yield value, calculating modified HWYLd values will offer a more accurate representation of a county's LCC HWYlds, which is used to predict residue removal rates.
- The implementation of field-level yield estimates based on soil characteristics and variable residue removal estimates based on location, soil characteristics, crop yield, and field management gives the user of the VRR method a sustainable approach as to how much residue could potentially be removed without causing soil erosion and/or affecting soil productivity in the years to come.
- When using intensive tillage practices by removing 100% of the crop residue available, the VRR method predicted on average 113,384 ± 38,770 DT of additional residue for harvest compared to the CRR method. This increase in residue availability resulted in a higher removal rate (9.4 ± 1.7 DT/ha [3.8 ± 0.7 DT/ac] average; 5.7 to 13.3 DT/ha [2.3 to 5.4 DT/ac] range) in the study area compared to the constant rate used by the CRR method of 7.4 DT/ha (3 DT/ac).
- Intensive tillage practices are not recommended because they can lead to erosion problems and loss in soil productivity. Conservation tillage practices will help offset these negative effects and thus is recommended instead. Conservation benefits are provided when at least 30% of the soil surface is covered with residue after planting the next crop.

- When using conservation tillage practices, the VRR method estimated on average 13,373 ± 22,195 DT less per service area than the CRR method using intensive tillage by 100% removal. Even though this created the need for additional service area for some plant capacities, these service areas would only supply 3.5% or less of the total annual feedstock requirements. Therefore, procurement area was considered practically the same for the VRR method using conservation tillage and the CRR method using intensive tillage with 100% residue removal. Consequently, the VRR method turned out to be a more sustainable approach in the quantification of biomass feedstock availability.

In chapter 5, the developed GIS-based method was further improved by utilizing multiple crops as biomass sources and estimating variable residue removal rates based on crop rotation. The results of this case study emphasized 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 were specific conclusions reached from this study:

- The implementation of multi-crop (MC) rotation-based VRR rates gives the user of this MC-VRR method a sustainable approach as to how much residue could potentially be removed without causing soil erosion and/or affecting soil productivity.
- A difference of 3,793 ± 5,733 DT was observed in estimated residue availability using conservation tillage practices, which ensures at least 30% of the soil surface is covered with the first year crop at the time the second year crop is planted, between scenario 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 study area's 3,533,950 hectares (8,834,874 acres) of cropland were comprised of 9.6% (339,718 hectares; 849,296 acres) hectares having a C-C-C rotation, 14.3% (504,369 hectares; 1,260,923 acres) a 1-3-1 rotation, 27.5% (973,173 hectares; 2,432,932 acres) a 2-3-4 rotation, and the remaining 48.6% (1,716,690 hectares; 4,291,724 acres)

less typical rotations. Therefore, the C-C-C, C-W-C, and S-W-F rotations were considered representative rotations for this case study area.

- The supplementary VRR rates in the analysis caused a decrease in average residue removal of corn from 5.8 ± 2.0 DT/ha (2.3 ± 0.8 DT/ac) in scenario 1 to 5.5 ± 2.0 DT/ha (2.2 ± 0.8 DT/ac) 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 (1.5 ± 0.4 DT/ac) in scenario 1 to 4.0 ± 1.0 DT/ha (1.6 ± 0.4 DT/ac) in scenario 2 (+5.3%). Average residue removal for sorghum remained the same given that only sorghum VRR rates from the 2-3-4 rotation simulation were used.
- Crop-specific residue availability per service area affects residue availability. It was observed in scenario 1 and 2 that the majority of the residue in the first and second service areas was corn stover, with sorghum stalk and wheat straw 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 (16-32 km; 10-20 miles) and the fifth service area (64-80 km; 40-50 miles) which was counterbalanced with an increase in some sorghum stalk and mostly wheat straw.
- Crop-specific hectare availability per service area also affected residue availability given that crop-specific hectares were not evenly distributed throughout the service areas. Corn represented 26.2% (440,636 hectares; 1,101,591 acres), sorghum 12.9% (217,432 hectares; 543,579 acres), and wheat 60.9% (1,024,607 hectares; 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 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 was needed to supply both plant capacities.

In chapter 6, the suitability of potential storage sites to store multi-crop biomass remotely was assessed based on a spatial analysis of the study area and utilize these satellite storage depots to reduce on-site inventory of a biomass conversion facility. The results of this case study emphasized the importance of re-classifying siting parameters values using Fuzzy logic to produce a suitability map for siting FSLs and a location-allocation analysis to select optimal number of candidate FSL to supply a biorefinery. The following are specific conclusions reached from this study:

- Residue availability was the most determining factor out of three considered to produce the suitability map. Percent slope and street network were not considered determining factors in this case study although they may be important factors to consider when producing a suitability map.
- Residue availability differed between service areas and years due to spatial distribution of crop fields and a crop's residue removal rate. The majority of the residue in the biorefinery's 64-km (40-mile) service area was corn stover (51.2%), with wheat straw (39.2%), and sorghum stalk (9.6%) making up the remainder. Additionally, corn in a continuous corn rotation was found to have a higher removal rate (5,915 ± 615 kg/ha; 5,205 ± 541 lb/ac) compared to wheat in a sorghum-wheat-fallow rotation (3,691 ± 239 kg/ha; 3,248 ± 210 lb/ac), and sorghum in sorghum-wheat-fallow rotation (3,708 ± 156 kg/ha; 3,263 ± 137 lb/ac).
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- Plant capacity affects the number of required FSLs because as plant capacity increases so does its annual feedstock requirement. It was estimated that plants with 151 and 227 MLY (40 and 60MGY) capacities would require 21 FSLs for scenario 1 and 10 FSLs for

scenario 2. The 378 MLY (100 MGY) capacity plant would require 41 and 20 FSLs, and the larger plant capacities (567 and 757 MLY; 150 and 200 MGY) would require 74 and 36 FSLs for scenarios 1 and 2, respectively.

- Surface area requirements need to be factored in when selecting FSL service areas size. Scenarios 1 and 2 proved feasible with regards to surface area requirements given that estimated FSL surface area requirements, based on average residue allocated per FSL, was much less than the average surface available per FSL (52.7 ± 23.2 ha; 131.8 ± 58.1 ac).
- Transportation also needs to be factored in when selecting FSL service areas size. It was estimated that on a daily basis it would take 5.8 hours to transport all corn stover and sorghum stalk bales, and 3.1 hours to transport the wheat straw bales from the crop fields to the FSL in scenario 1. In scenario 2, it would take 16.0 hours for corn stover and sorghum stalk bales, and 8.9 hours for wheat straw bales.
- Despite the higher transportation costs and time, the fact that fewer FSLs are needed and more demand points can be serviced, scenario 2 is presumed to be the more cost-effective option.

Chapter 8 - Future Research Recommendations

Even though the development of the GIS-based method enhanced quantification of feedstock availability, opportunities to further refine the approach exist. Thus, the following are future research recommendations:

- A sensitivity analysis should be done to examine how the MC-VRR method and the FSD suitability analysis perform in a different study area.
- With regards to the MC-VRR method, the following is recommended to improve its quantification capability:
    - Increase number of crops analyzed
    - Increase number of crop rotations analyzed
    - Build a model in ArcGIS
- With regards to the FSL suitability analysis, the following is recommended to improve its siting capability:
    - Examine different FSL service areas
    - Make transportation cost an impedance
    - Build a model in ArcGIS
- Build models in ArcGIS for the MC-VRR method and the FSL suitability analysis. This should be relatively easy given that models in ArcGIS are workflows that string together sequences of geoprocessing tools. Tool selection has been well documented throughout this research. The following would be the benefits of building ArcGIS models for the MC-VRR methodology:
    - MC-VRR method
        - Reduced human calculation error and overall processing time
        - Improved data classification and sorting
        - Increased number of bioenergy crops analyzed
        - Increased number of crop rotations that could be analyzed
        - Ability of the user to simulate more complex scenarios
    - FSD suitability analysis
        - Reduced human calculation error and overall processing time

    - Increased number of parameters used to produce suitability map
    - Increased number of FSD analyzed
- Work also has to be done to make the output of the model compatible with the existing biomass supply chain logistics models such as the Integrated Biomass Supply Analysis and Logistics Model (IBSAL), which is being developed by the Oak Ridge National Laboratory.

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Appendix A - Chapter 6

Figure A.1 Redefined suitability map based on land classification of the National Land Cover Dataset (NLCD). The ArcGIS Extract by Attribute tool was used to extract only suitable sites that overlayed the three selected land classification - barren land (rock/sand/clay), shrub/scrub, grassland/herbaceous.

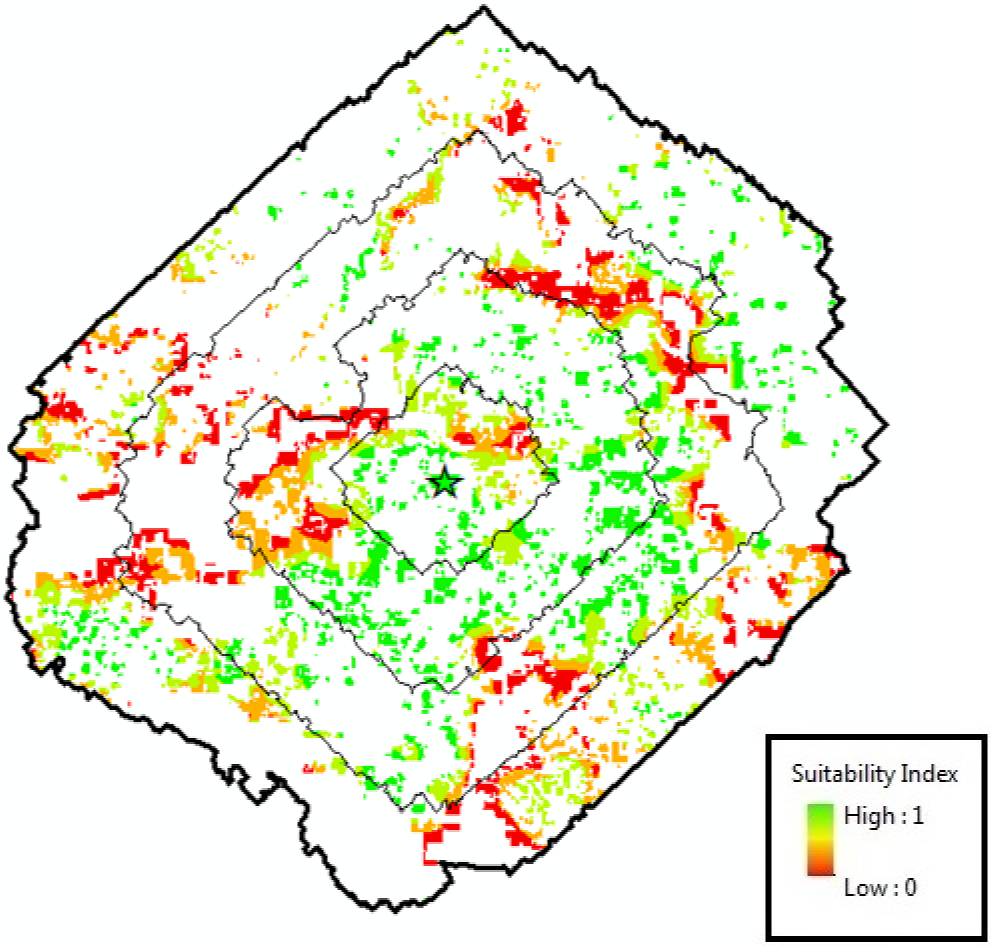

Figure A.2 Inset of the redefined suitability map showing the biorefinery's location near Hugoton, KS (green star) and candidate facilities (orange box) located on primary/secondary roads. Suitable locations are also shown with suitability index as a color gradient with below average suitability in orange, above average in light green, and highest in dark green.