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Quantifying Feedstock Availability Using a Geographical Information System

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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. 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.*

Extensive research has been undertaken to evaluate various renewable feedstocks 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 (USDOE, 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

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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 switchgrass 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 from 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

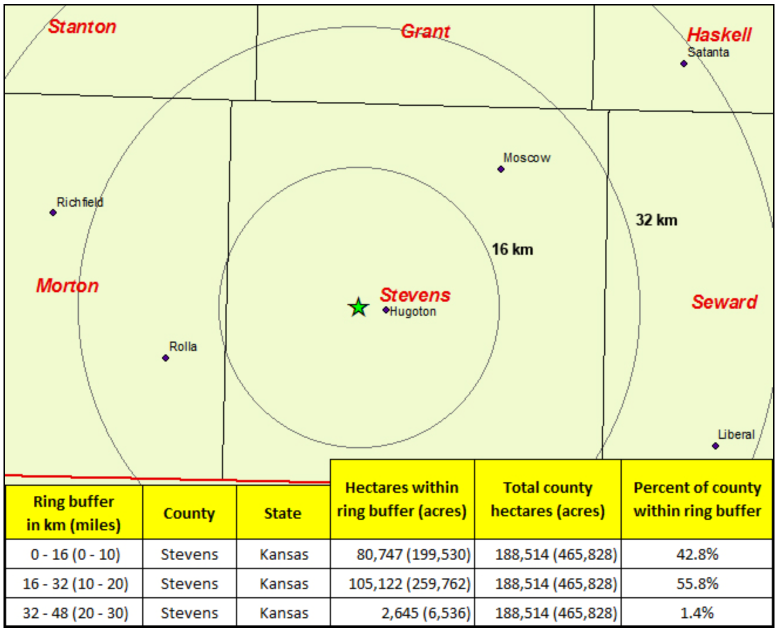
The reference location for this case study was the Abengoa Bioenergy Hybrid of Kansas facility near Hugoton, Kansas, which is in a high-density corn production area.

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 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.

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



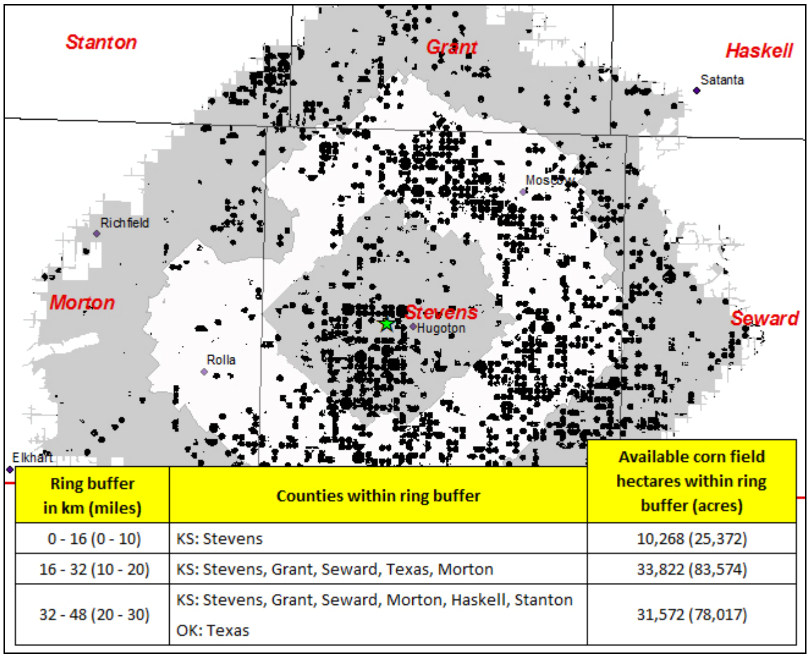
Ring buffer in km (miles)	County	State	Hectares within ring buffer (acres)	Total county hectares (acres)	Percent of county within ring buffer
0 - 16 (0 - 10)	Stevens	Kansas	80,747 (199,530)	188,514 (465,828)	42.8%
16 - 32 (10 - 20)	Stevens	Kansas	105,122 (259,762)	188,514 (465,828)	55.8%
32 - 48 (20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

Figure 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.

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^{-1} (2 DT ac^{-1}) as the biomass conversion factor. Ileleji (2007) later suggested 7.4 DT ha^{-1} (3 DT ac^{-1}). 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^{-1} (72 gal DT^{-1}). 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^{-1} (3 DT ac^{-1}) and a biomass yield of 272.5 L DT^{-1} (72 gal DT^{-1}). 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 Geospatial Data Gateway (USDA-NRCS, 2010). The CDL satellite images were merged



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)

Figure 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.

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 (fig. 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.

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 Agri-

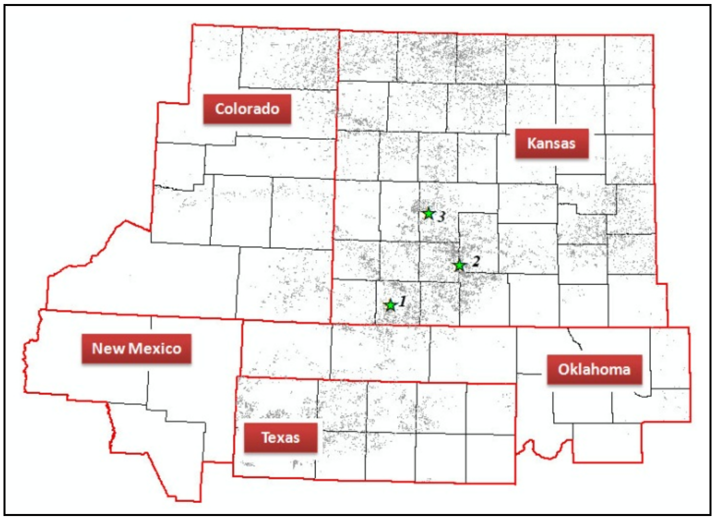


Figure 3. Location 1 of the facility near Hugoton, Kansas, and the two alternate locations (2 and 3) chosen for validation purposes. The black dots indicate actual corn hectares as recorded by satellite image within the selected study area boundary, which included the states of Colorado, Kansas, Oklahoma,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

culture 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 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.

Results and Discussion

Table 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 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 feedstock (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

Table 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)										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										
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^{-1} (ac year^{-1}).

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 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. 4). The first part of table 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 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 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

Table 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

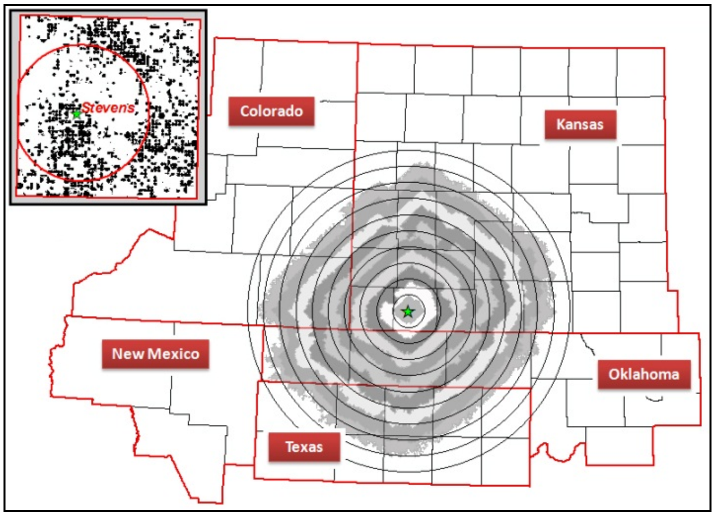
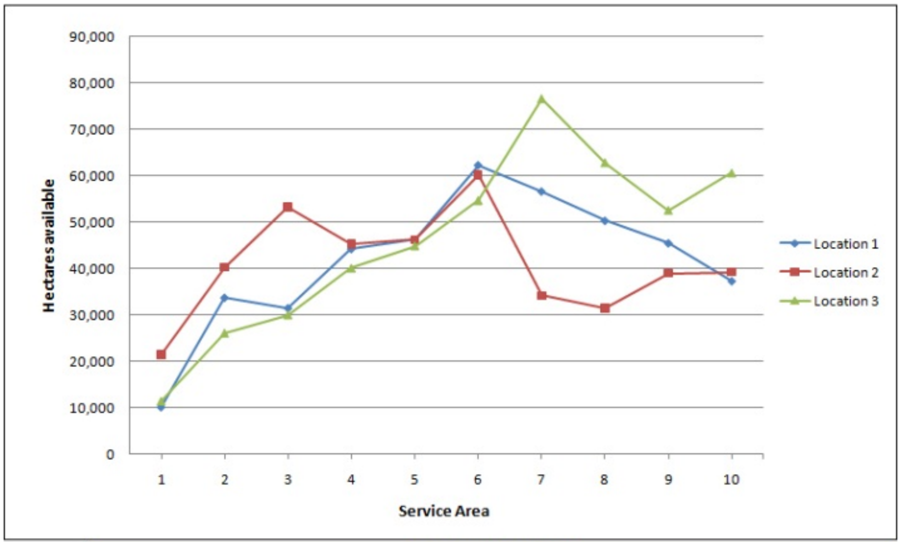


Figure 4. Overlay of the respective 16 km (10 mi) service areas surrounding plant location 1 calculated using method 1 (concentric ring buffers) versus method 2 (GIS-based ring buffers). Stevens County is shown in the upper left corner, with the black dots indicating actual corn hectares as recorded by satellite image in 2009.

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.

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



	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)

Figure 5. Predicted hectare availability per 16 km (10 mi) service area from three different plant locations using method 2.

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.

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

As expected, a shift in hectare availability per service area was observed when relocating the plant from its original location. Figure 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

Table 3. Estimated hectares and percent of hectare availability per 16 km (10 mi) service area from two additional plant locations for five plant capacitates 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}).

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).

These pattern variations affected the percent of hectare availability per service area. Table 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 serviced 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.

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.

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