Spatial modeling framework for bioethanol plant siting and biofuel production potential in the U.S.

B. Sharma^{a*}, S. Birrell^b, and F. E. Miguez^c

^{a*}Post-doctoral Research Associate, Department of Agronomy, 1203 Agronomy Hall, Iowa State University, Ames, Iowa, 50011. E-mail: sharmabhavnak@gmail.com

^bProfessor, Department of Agricultural and Biosystems Engineering, 2323 Elings Hall, Iowa State University, Ames, Iowa, 50011. E-mail: sbirrell@iastate.edu

^cAssociate Professor, Department of Agronomy, 1206 Agronomy Hall, Iowa State University, Ames, Iowa, 50011. E-mail: femiguez@iastate.edu

*Corresponding author. Tel.: +1 4052351259. E-mail address: sharmabhavnak@gmail.com (B. Sharma). Postal Address: 1203 Agronomy Hall, Iowa State University, Ames, Iowa, 50011

Abstract. Because of rising fuel prices and increasing energy demand, bioethanol has been recognized as an important future renewable energy source. The goals and mandates developed for renewable fuel production will require construction of several bioethanol plants throughout the U.S. Using high-resolution geospatial data from Geographic Information Systems-Multi Criteria Evaluation (GIS-MCE) a biorefinery suitability model has been developed for identifying feasible sites and appropriate biofuel production capacity in the U.S. The biomass feedstocks considered for analysis were switchgrass, miscanthus and corn stover. We conducted a spatial exclusion and preference GIS analysis subjected to environmental and infrastructure criteria combined with biomass yield estimates and identified 164 basic sites and 17 co-location scenarios. Biorefineries using miscanthus feedstock could produce biofuel satisfying a significant portion of the U.S. mandate. This national-scale assessment enhances strategic decision-making capabilities and understanding of spatial distribution of biorefineries.

Keywords: Ethanol, Biorefinery, Suitability analysis, Geographic Information Systems, Multi-criteria Evaluation, Biomass

1. Introduction

Biofuels have been proposed as an alternative to partially replace petroleum-based gasoline in the U.S. because they can reduce dependence on imported oil, protect the environment, and boost the rural economy. The Renewable Fuel Standard (RFS) was passed in 2007 as part of the Energy Independence and Security Act, thereby mandating the production of 36 Billion Gallons

(BG) of biofuels by 2022. Of the mandated production, the conventional biofuels (corn ethanol) production goal of 15 BG has already been achieved, and the remaining 21 BG are to be derived from advanced biofuels, with 16 BG from cellulosic feedstock. Even with government support the commercialization of cellulosic ethanol is facing technical and economic challenges [1], so the standards have been revised and updated as the expected yearly cellulosic ethanol production goals failed to be met. In 2010, the RSF mandates were updated and the cellulosic biofuel production goal for 2010 was reduced from 1 BG to 0.0065 BG [2]. However, during 2010 and 2011 no commercial production of cellulosic biofuel was reported, and during 2012 and 2013 the production was 20,069 and 281,819 gallons, respectively [3]. An increase in production is anticipated through three plants beginning commercial production (DuPont Cellulosic Ethanol, Nevada, Iowa; Abengoa Bioenergy, Hugoton, Kansas and POET Biorefining, Emmetsburg, Iowa) with a combined capacity of 80 Million Gallons (MG). An updated RFS also guarantees a market for biofuels and provides indirect subsidies for capital investment in the construction of biofuel plants [4]. Therefore, to meet the 16 BG target for cellulosic ethanol, several new plants will be constructed in the U.S. Specifying suitable locations for bioethanol plants is crucial for successful implementation of a second-generation biofuel industry in the U.S.

Industrial site selection represents a critical strategic decision because success and failure of an industry depends to a great extent on its location [5, 6]. Establishing a new facility is a complex process requiring a large investment and detailed analysis of location requirements that considers economic, environmental, regulatory, social, and technical factors. The main objective of industrial site selection is to determine the most suitable site meeting pre-defined selection criteria. Industrial site selection is a spatial decision problem that can be solved using Geographical Information Systems (GIS). GIS spatial analysis is often used in conjunction with other methods such as Analytical Hierarchy Process (AHP) for Multi-Criteria Decision Making (MCDM)/ Multi-Criteria Evaluation (MCE). Social, technical, environmental, political, and economic criteria dependent on the industry type are taken into account during development, planning and construction phases [7].

Ensuring the initial feasibility and eventual profitability of these bioethanol refineries, however, can be a complex and multifaceted problem. Generally, two type of modeling approaches are used for facility siting: spatial and integrated models. In the past majority of studies used geospatial modeling techniques to determine suitable locations of bioenergy plants

(Table 1) [8-14], while others have circumvented to the use of integrated models by combining mathematical and geographical modeling techniques for bioenergy plant siting (Table 1) [15-22]. These studies of bioenergy plant siting have been conducted at county, district, state, and regional levels. For example, Wilson [14] developed a Biofuels Facility Location Analysis Modeling Endeavor (BIOFLAME) software package with the ability to conduct suitability analysis, feedstock analysis, and facility siting for the southeastern U.S. They identified user-specified inputs, including study area, facility capacity, crop prices, and driving distance limits for switchgrass biomass and the ideal site/s that minimize transportation and farm gate costs. However, in that analysis only switchgrass biomass feedstock with county-level yield data adjusted to the sub-county level was considered, and only cropland was considered for switchgrass cultivation. In addition, only road, water, power line, and city data were used for the suitability analysis, and potential bioethanol sites were assumed to be located on an even grid of points 5 miles apart.

Table 1
Studies on bioenergy facility siting, biomass and bioenergy type, analysis approach and application area

Reference	Biomass type	Bioenergy type	Approach	Application area
Noon et al, 2002 [8]	Switchgrass	Ethanol	GIS	Alabama, U.S.
Sultana et al, 2012 [10]	Wheat, barley and oat	Pellets	GIS	Province of Alberta, Canada
Koikai, 2008 [11]	Maize	Ethanol	GIS	Nyanza province in western Kenya
Zhang et al, 2011 [12]	Woody biomass	Ethanol	GIS	Upper Peninsula of Michigan, U.S.
Perpiñá et al, 2013 [13]	Agriculture and forest biomass	Biomass plants	GIS	Utiel-requena province of Valencia, Spain
Wilson, 2009 [14]	Switchgrass	Ethanol	GIS	Southeast U.S.
Li et al, 2012 [15]	Miscanthus	Ethanol	GIS and optimization model	Illinois, U.S.
Parker et al, 2010 [16]	Agricultural, forest, urban, and energy crop biomass	Ethanol	GIS and optimization model	Western U.S.
Voivontas et al, 2001 [17]	Agricultural residues	Electricity production	GIS decision support tool	Island of Crete, Greece
Wu et al, 2011 [18]	Woody biomass	Ethanol	GIS and compromise programming method	West Virginia, U.S.
Dong, 2008 [19]	Agricultural biomass	Biomass power plants	GIS and optimization model	Region of Waterloo, Ontario, Canada
Vukašinović and Gordić, 2016 [20]	Forest biomass potential	Biofuels, thermal power, district heating and cogeneration plants	GIS and optimization model	Municipality of Ivanjica, South-West Serbia

Wang, 2013 [21]	Switchgrass	Ethanol	GIS and multi-objective mathematical model	Tennessee, U.S.
Sahoo et al, 2016 [22]	Cotton stalk	Fuel pellets	GIS and optimization model	Georgia, U.S.
Zhang et al, 2016 [23]	Woody biomass	Biofuel production	GIS, optimization and simulation model	Northern part of Michigan's Lower Peninsula, U.S.

Gordon, et al, [24] developed a combination of spatial and mathematical models that included 23 different biomass feedstocks, three (rail, road, and barge) modes of transportation, and 17 states located in the Western U.S. to generate biomass and biofuel supply curves over a one-year planning horizon [24]. Parker, et al., [25], developed the Geospatial Bioenergy System Model (GBSM) with spatial analysis (resource assessment, transportation costs, fuel demand, and fuel distribution) and biorefinery costs serving as input data for this optimization model that locates, sizes, and allocates feedstock while maximizing industrial profitability. However, to help deal with the complexity of the problem, several assumptions were made in this analysis [24, 25] with regard to biomass availability (county-level yields were used), transportation network (transportation cost calculated at the county-level), and site suitability (population, co-location with existing refinery, road and railroad criteria were used). In the regional studies it has been clearly stated that preprocessing time and disk space have been factors limiting expansion of suitability analysis to the national level. Even regional studies have ignored details of local geography when assessing biomass and infrastructure availability for biorefineries, and such details directly influence the estimation of biorefinery location sustainability indicators. In the 2016 Billion-Ton Report, potential biorefinery facilities were located at points on a 50-mile spaced grid to keep computational complexity manageable at a national scale. The county level feedstock estimates were also allocated to county centroids where they served as feedstock supply locations in the Supply Characterization Model (SCM). In reality, however, other factors such as infrastructure (water, power, road) availability, skilled labor, and tax incentives from local and state government also play a crucial role in determining the biorefinery sites [26]. Therefore, conducting a national scale biorefinery suitability analysis considering local infrastructure, geography, and biomass availability is crucial.

Switchgrass (*Panicum virgatum* L.) and miscanthus (*Miscanthus × giganteus* Greef et Deu.) are two leading dedicated biomass feedstocks often considered for biofuel production. Miscanthus is a genus comprised of 16 species and closely related to sugarcane [27, 28]. Its high

biomass yield, capability for production on marginal lands, and low input requirements have spurred research interest in commercial cultivation of this crop for biofuel production [29]. Switchgrass species are native to North America and have been widely adapted. In addition, research and farming experience over about 70 years of switchgrass production shows it to be a very promising bioenergy feedstock in the U.S. [30]. Current production of corn (*Zea mays*, L.) stover could immediately provide the largest quantity of biomass residue for biofuel production [31]; it is estimated that 75 million tons per year of corn stover could be sustainably harvested for biofuel production [32], and the major biomass source for three commercial ethanol plants in the U.S. is corn stover. It can be anticipated that the availability of corn stover as feedstock would be an important source for new bioethanol plants, so in the present analysis switchgrass, miscanthus, and corn stover were considered to be suitable biomass feedstocks for biorefineries.

Previous studies have not conducted detailed biorefinery siting assessment in part due to the processing time and disk space requirements needed for a comprehensive analysis. A detailed suitability analysis considering local geographic, infrastructural, and social factors is crucial to predicting capital investment and eventual success of the biorefinery. For example, construction of a new 2-lane undivided 500 m road in a rural or an urban area can cost about \$780,000 or \$1,200,000, respectively. Similarly, construction of railroad connection, digging of water wells, laying of natural gas pipelines, and soil removal for biorefinery construction are all cost-intensive operations and should be part of criteria in the suitability analysis. Previously conducted regional and national level bioenergy siting studies have not considered these criteria (Table 1). In addition, previous studies have used county level yield data for biomass assessment, not taking into account spatial variability of biomass yield at the sub-county level. To address these limitations, in the present study a comprehensive set of geographic, environmental, and infrastructure criteria is considered to determine suitable sites for biorefinery at national scale. One of the important tasks in site suitability analysis is developing a combination of different preference criteria by providing weightage factors for each. While the Analytic Hierarchy Process (AHP) [33] the most common approach for incorporating weightage of criteria into suitability analysis. However, assigning importance to each of the criteria in AHP is subjective and has a modular bias with respect to weight selection. Therefore, in the present study input from both industry experts (DuPont cellulosic ethanol plant, Nevada, Iowa) and academic experts was used to assign weights to each preference criterion. This makes this study unique

because previously no combined industrial and academic perspective has been taken into account in identifying locations for biorefinery plants. No work, to our knowledge, has attempted to provide a spatial model that considered a diverse set of biomass feedstocks with real-world geographic data for identifying potential biorefinery sites. Therefore, in the present study a comprehensive biorefinery suitability analysis was conducted that considered spatial variability in biomass supply at sub-county level; and high-resolution geographic and infrastructure spatial data. The purpose of this study was to conduct a national-level GIS-MCE analysis for identifying and prioritizing bioethanol plant siting for future investment and development in the U.S. The specific objectives of the study were:

- To identify factors/constraints related to bioethanol plant siting
- To develop a GIS-MCE based bioethanol plant siting model for the U.S.
- To determine biorefinery production capacity utilizing different types of biomass feedstock in the U.S.

2. Methodology

2.1. Study area

We chose to restrict our analysis to the contiguous U.S. for three reasons. First, biofuel mandates require the production of 16 BG of advanced biofuels by 2022; this will require the construction of cellulosic ethanol plants throughout the U.S. [2] Second, only three commercial cellulosic ethanol plants presently exist in the U.S., representing a combined capacity of approximately 80 Million Gallons (MG) [34]. Finally, it has been estimated that 680 million dry tons of biomass materials can be sustainably produced each year within the U.S. by 2030 which could be used for biofuel production [35].

2.2. Determining suitable sites for bioethanol facilities

The methodology proposed for the analysis includes a suitability analysis (exclusion and preference analysis) and biomass availability assessment (corn stover, switchgrass, and miscanthus). The architecture of the GIS based MCE approach for biorefinery site selection has two major phases: site screening (identifying criteria and thresholds) and site evaluation (normalizing criteria, calculating weights, and combining maps) (Fig. 1)

Figure 1. Flowchart of the conceptual model for suitability analysis

2.2.1. Selecting spatial criteria: factors and constraints

The bioethanol GIS-based site selection criteria considered for the analysis, based on previous studies, were transportation, co-location, construction site, water, energy, and biomass availability [3-8]. The suitability criteria define the required level of satisfaction that each eligible site must achieve.

- Transportation is one of the crucial factors affecting the cost of plant development, feedstock delivery, and ethanol marketing [36]. Biomass feedstock delivery via the road network was assumed, while ethanol can be shipped to markets via truck, rail, or barge. Only road and railroad were considered for this study as the two modes of transportation to be used.
- Co-location with an existing ethanol facility or a coal-fired power plant is often considered as a possible strategy for making cellulosic ethanol economically viable. Co-location provides opportunities for achieving significant economic and environmental benefits in terms of infrastructure and feedstock sharing, cost savings, and compliance with local regulations [37]. The principal benefits of co-location for a bioethanol plant

are: 1) significant capital cost savings utilizing an existing boiler/turbogenerator, and 2) additional cost savings in terms of labor, warehousing, site development, railroad connection, storage tanks, and wastewater treatment facilities [38, 39]. The benefits of co-location with a coal-power plant are: 1) ability to sell excess steam and electricity to an ethanol plant, thus allowing the coal plant to operate at full capacity, 2) using lignin to substitute for a portion of the coal, and 3) reducing greenhouse gas emissions [38, 39]. A coal-fired power plant's generation capacity determines the relative impact of using lignin as a boiler fuel. The coal-fired power plants with capacities greater than 200 MW and all existing ethanol plants were considered in the present analysis [38].

- Topological constraints for excluding sites characterized with slopes larger than 7% of slope angle were considered. Steep slopes can create construction difficulties and increased costs because of activities like cut and fill, earthwork, and erosion prevention [40], so a slope less than 7% (see Table 2) was considered to be suitable and extreme slopes were considered not at all suitable.
- Since water quantity, quality, and infrastructure are important factors in bioethanol siting [36], accessibility to water wells and rivers were considered in the present analysis.
- Proximity to energy sources such as a natural gas pipeline provides large savings because such fuels represent a major input cost factor.
- Wetlands, conservation easements, and Indian reservation areas were considered unsuitable for bioethanol plant siting because they are protected areas. In addition, dams and airport constraints were considered to guarantee safety in such areas.

Siting analysis often requires integration of conflicting points of views in determining the criteria. The best way to accomplish this is to involve stakeholders through public debates, questionnaires, focus group discussions, and workshops in identifying and defining critical criteria [11]. In the present study, a search of previous literature related to siting facilities and a questionnaire and discussion with academic and industrial experts were conducted to determine the critical parameters of bioethanol site identification (Table 2)

Table 2
Identified criteria and their specifications for creating a buffer zone

Preference criteria	*Lower- **Upper limit	Description
Road (m)	30-1,500	Promote ease and economics of transportation

Railway (m)	30-1,000	Promote ease and economics of transportation
Co-location with ethanol plants (m)	30-1,000	Improves economics of process
Co-location with coal-fired power plants (m)	30-1,000	Improves economics of process
Slope (%)	0-7	Low grade slope leads to less construction costs
Natural gas pipelines (m)	30-1,000	Cost saving
Water wells (m)	200-1,000	Water required for plant operations
River water (m)	200-1,000	Water required for cooling operations
Exclusion criteria	*Lower-Upper Limit	Description
Protected areas (m)	0-1,000	Protect sensitive areas
Airports (m)	0-8,000	Safety of air traffic
Dams (m)	0-500	Safety
*Lower limit indicates distances below that value are not suitable for biorefinery location due to safety, future expansion and costs. For example road constraint, 30 m indicates that areas within 0-30 m are not suitable. However, areas above 30 m are suitable for biorefinery location. **Upper limit indicates distances below that limit are suitable. For example road constraints, distances within 30-1,500 m are suitable for biorefinery location. However, distances above 1500 m are unsuitable mainly due to economic reasons.		
*** Exclusion criteria exclude all areas considered for bioethanol plants		

2.2.2. Data sources and software

Geospatial data for the study was collected in vector format from several sources: the U.S. Department of Transportation Federal Highway Administration [37], the U.S. Department of Energy, the National Renewable Energy Laboratory [41], the U.S. Army Corps of Engineers [42], the U.S. Geological Survey [43], the U.S. Census. Bureau [44], and the U.S Department of Agriculture [45] (Table 3, supplementary materials).

All the data was projected in USA Contiguous Albers Equal Area Conic and with a resolution of 30 x 30 m. This projection is best suited to areas such as the U.S. that have an east-west orientation [46]. The Cropland Data Layer and National Land Cover Database were provided at a resolution of 30 m, so that resolution was selected for the entire analysis. Python scripts written to implement tasks in ArcGIS software were used to automate repetitive tasks/workflows and extend the capabilities of ArcGIS software [47]. Python 2.7 [48], ArcGIS 10.3 [49], and R (R-project citation) with RStudio 0.99.473 [50] software versions were used to perform the analysis.

2.2.3. Exclusion analysis

An exclusion analysis was conducted to define areas deemed unsuitable for biorefinery construction; this also decreases the total region size for further analysis. Buffer zones were created for each constraint and minimum distances not suitable for biorefinery construction were established. A raster map (30 m resolution) was created for each constraint and a binary image was created with '0' indicating an unsuitable cell and '1' indicating a suitable cell [10, 19]. Calculation of the final layer was performed using Eq. (1).[10]:

$$C_{e,i} = \sum_{j=1}^n C_{i,j} \quad (1)$$

where $C_{e,i}$ is the Boolean cell value (0,1) assigned to the i^{th} cell in the final exclusion map; $C_{i,j}$ is the Boolean cell value (0,1) assigned to the i^{th} cell value in the j^{th} constrained grid layer and N is the total number of exclusion constraints considered in the analysis

2.2.4. Preference analysis

Unlike exclusion analysis, preference analysis is used to determine the suitability of each factor. In preference analysis, criteria related to the spatially-defined data were used to determine the bioethanol plant sites. Spatial analysis techniques along with the Analytic Hierarchy Process (AHP)-MCDM approach was used to perform the analysis.

2.2.4.1. Normalization

Multiple buffer zones satisfying eight criteria were created (Table 2) for the preference analysis, and the criteria attributes had different measuring scales, so standardization was performed to transform attribute values to a common suitability scale. The original criteria attribute values were transformed into a common suitability scale ranging from 1-5 with a higher value indicating greater suitability (5: Most suitable, 4: Moderately suitable, 3: Less suitable, 2: Least suitable and 1: Suitable but avoided and 0: Unsuitable).

2.2.4.2. Analytic Hierarchy Process (AHP)

We assigned weights indicating the relative importance of each criteria using Analytic Hierarchy Process (AHP), a multi-criteria decision-making method [33]. that develops a pairwise comparison matrix using priority scales (Table 3). In the present study, ranking criteria were determined by seeking the expert judgment of academic and industry professionals. After developing a pairwise comparison matrix, the normalized eigenvector of the matrix (priority vector) was computed. The consistency of subjective judgment was evaluated using a Consistency Ratio (CR). If the CR value is smaller than or equal to 10%, the inconsistency is considered to be acceptable, while if the CR is greater than 10%, the subjective judgments are

revised. The AHP method determined the relative weights or importance of each criterion with respect to the others

Table 3

Scale of relative importance

Intensity of relative importance	Definition	Explanation
1	Equal importance	Two activities contribute equally
3	Moderate importance	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Demonstrated importance	An activity is strongly favored and its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	
Reciprocals of above numbers	If an activity has one of the above numbers (e.g. 3) compared with a second activity, then the second activity has reciprocal value (i.e. 1/3) when compared to the first	

2.2.4.3. Combining layers

A weighted overlay analysis was conducted to combine all the criteria maps for identifying desirable locations that satisfy the constraints using Eq. (2).

$$C_{p,i} = \sum_{j=1}^m W_j C_{i,j} \quad (2)$$

where $C_{p,i}$ is the preference score of the i^{th} cell value in the final criteria grid, W_j is the weight assigned to the j^{th} criterion from the AHP analysis, $C_{i,j}$ is the i^{th} cell value in the grid of the j^{th} preference criteria layer, and m is the total number of preference criteria considered for the analysis. The exclusion and preference analysis resulted in a suitability map with each cell value representing the suitability index calculated using Eq. (3).

$$SI_i = C_{e,i} \times C_{p,i} \quad (3)$$

where SI_i is the suitability index for the i^{th} cell in the final land suitability map, $C_{e,i}$ is the Boolean value (0,1) assigned to the i^{th} cell of the final constraint map in the exclusion analysis, and $C_{p,i}$ is the value assigned to the i^{th} cell in the final map of selective analysis [10]. The values of the cells in the suitability map range from 0-5 where “0” represents unsuitable sites and “5”

represents the most suitable locations for bioethanol plant siting.

2.2.5. Spatial biomass assessment

Biomass types considered for analysis were switchgrass, miscanthus, and corn stover. The yield of switchgrass was estimated based on the average yield data for 32 years was interpolated from 32 km to a 30 m resolution grid. The yield was extracted for barren, shrub/scrub, grassland/herbaceous, and pasture/hay land cover types found in the 2011 National Land Cover Database [52], and it was assumed that 30% of the total land in the four land cover categories could be used for switchgrass and miscanthus cultivation. The acreage surrounding a biorefinery site available for feedstock production has been reported to be 60% and 34% of the total cultivated land [53, 54] with this percentage varying depending on willingness of farmers to cultivate energy crops.

The exploitable yield was assumed to be 80% of the potential yield determined by the crop growth model [55], and 25% harvest and transportation losses were considered [56]. High, low, stable and unstable yield zones were classified based on the coefficient of variation and median of the yield. Yield risk is often measured using the coefficient of variation, the ratio of the standard deviation to the average yield. It measures the spread describing the amount of variability relative to the mean; higher values of CV indicate greater variability in yields. Four yield zones were determined: High Yield Stable Zones (HYSZ), High Yield Unstable Zones (HYUSZ), Low Yield Stable Zones (LYSZ) and Low Yield Unstable Zones (LYUSZ).

The corn yield data at 30 km resolution for the contiguous U.S. was obtained from Joshua, et al., 2015 [57]. The data was interpolated to a 30 m resolution and yield was extracted for the areas with continuous corn in the 2014 Cropland Data Layer (CDL) [58]. The resulting corn stover biomass available for the biorefinery was estimated from the corn yield data. The harvest index was assumed to be 0.5, meaning that corn stover yield is equal to corn grain yield in tons produced per acre [59]. It was assumed that 2.5 tons per acre of corn stover will be left in the field to maintain soil quality and avoid erosion [60].

3. Results and discussions

3.1. Suitable sites for bioethanol plants

Two scenarios (basic and co-location) were evaluated in the present study. The basic scenario consisted of six constraints (road, railway, natural gas pipelines, water wells, slope, and river layers). In the co-location scenario, areas adjacent to existing ethanol plants and coal-fired power plants were also considered (Table 2).

3.1.1. Pre-processing of layers

A Data Flow Diagram (DFD) presents the steps of the suitability analysis (Fig. 2). A dissolve technique was used for the road, railway, and natural gas pipeline layers to avoid map display and editing problems. The abandoned railroad routes were excluded from the analysis. Water well capacity/flow rate was not considered; only their point locations were included in the analysis. The coal-fired power plant generation capacity is crucial because it determines the relative impact of using lignin for a boiler biofuel. Very large power plants could burn the lignin from bioethanol plants with little impact on boiler operations, so co-location with a plant capacity of less than 200 MW was not considered.

316
317
318

319
320

Figure 2. Data flow diagram for the suitability analysis

3.1.2. Exclusion and preference analysis

The exclusion analysis identified unsuitable areas for locating bioethanol plants. In the preference analysis, each criteria buffer was created, reclassification was performed, and a weighed overlay tool was applied to integrate the preference criteria. Input from industry and academic experts was then considered to develop the pairwise comparison matrix (Table 4). The computed consistency ratio was 0.069, indicating that the weights (Table 4) are acceptable.

Table 4

Pair-wise comparison matrix showing relative importance of preference criteria and weights for criteria determined using Analytical Hierarchy Process AHP

Criteria	CoL with ethanol plants	CoL with coal-fired power plants	Road	Railway	Water wells	Natural gas pipelines	Slope	Water	
Relative importance matrix									Weights
CoL with ethanol plants	1.0	1.0	0.3	0.3	1.0	0.3	1.0	8.0	0.076
CoL with coal-fired power plants	1.0	1.0	0.3	0.3	1.0	0.3	1.0	8.0	0.076
Road	3.0	3.0	1.0	2.0	5.0	5.0	6.0	8.0	0.301
Railway	3.0	3.0	0.5	1.0	5.0	5.0	6.0	8.0	0.250
Water wells	1.0	1.0	0.2	0.2	1.0	1.0	1.0	8.0	0.075
Natural gas pipelines	3.0	3.0	0.2	0.2	1.0	1.0	6.0	8.0	0.141
Slope	1.0	1.0	0.2	0.2	1.0	0.2	1.0	8.0	0.067
Water	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.0	0.014

From potential locations that were close together (<80 miles) only one site was chosen. There were 164 suitable sites determined for the basic scenario, with 67% located in the southeast, midwest, and northeast regions (Fig. 3). For the co-location scenario, 17 sites were identified (Fig. 4). Presence of developed infrastructure in terms of road, railway, natural gas pipelines, and coal-fired power plants along the east coast of the U.S. resulted in more suitable sites being located in that region.

To identify potential biorefinery locations, previous large-scale studies have either used an even grid of points spaced some number of miles apart or considered some infrastructure constraints. This simplification is mainly due to computational limitations of handling large amounts of data. In this analysis, we considered the entire infrastructure for locating bioethanol plants, except for power lines, needed to support the facility, as recommended by industry and academic experts. We also performed analysis at a high resolution of 30 m to provide general information regarding areas suitable for siting biorefinery siting and to assist in stakeholder decision-making.

341
342

343
344
345
346
347
348

Figure 3. Suitable biorefinery locations in the contiguous U.S. (Basic scenario: Preference layers: Road, railway, natural gas pipelines, water wells, slope, and river; Exclusion layers: Protected areas, airports and dams)

Figure 4. Suitable biorefinery locations in the contiguous U.S. (Co-location scenario: Preference layers: Road, railway, natural gas pipelines, water wells, slope, river and co-location with coal-fired power plants and existing ethanol plants; Exclusion layers: Protected areas, airports and dams)

3.2. Biomass assessment

The threshold values for defining high/low yield zones for switchgrass and miscanthus were 5.5 and 15 Mg/ha. The coefficient of variation for classifying the stable/unstable zones was 25%. For miscanthus, HYSZ are mostly located in the southeast, parts of the central Midwest, and the northeast U.S. The LYSZ and LYUSZ are in the southwestern and western regions of the U.S. (Fig. 4).

Switchgrass yields showed similar spatial trends for yield variation, although maximum yield for switchgrass was only 20 Mg/ha; half of the micanthus maximum yield. Precipitation and soil water-holding capacity influenced regional and temporal variation in yield [51]. Biorefinery siting will be most preferable in HYSZ, because biorefineries would require a year-round and continuous supply of biomass. Designation of low yield unstable zones do not imply that biomass cannot be grown in these areas but rather shows that environmental and soil conditions are not favorable for providing a stable and continuous supply of biomass. All zones were considered for analysis in the present study. The corn stover yield was estimated from corn yield and mostly varied between 0-5 Mg/ha (Fig. 5). Since different biomass types would be expected to have different productivity depending on local climate

367 and soil type, different types of cellulosic feedstocks should be considered for efficient and large-
368 scale production of biofuels across different regions.

369 Biomass resource assessment is crucial to ensure year-round continuous operation of a
370 biorefinery. Large-scale studies of biomass resource assessment for biorefinery siting have used
371 county level biomass estimates and thus have not completely accounted for spatial variability in
372 biomass yield at the sub-county level. In this study, high-resolution (30 m) biomass availability data
373 was used and zones were identified based on yield and its variability. The resource base identified in
374 this study allows for much more realistic biomass assessment that considers weather data, soil, and
375 crop growth characteristics. These results can help policymakers, industries and farmers craft
376 strategies for identifying biomass cultivation areas and biorefinery siting.

377

378

379

380 **Figure 4.** The spatial yield zones for miscanthus

381 **Note:** HYSZ= High Yield Stable Zones, HYUSZ= High Yield Unstable Zones, LYSZ = Low Yield
382 Stable Zones and LYUSZ = Low Yield Unstable Zones

Figure 5. Corn stover biomass simulated using Decision Support System for Agrotechnology Transfer (DSSAT) model using 30 years' weather data (resolution: 30m)

3.3. Bioethanol refinery size

A 40-mile buffer was developed for each of the biorefinery locations and available biomass at the biorefinery site was calculated using the zonal statistics tool provided in ArcGIS software. While a fifty-mile radius is usually considered to be the maximum distance for economical transportation of biomass to the biorefinery [61, 62], some studies suggest that limiting the biomass supply radius to 50 miles may cause disruption in meeting a biorefinery's demand because of low biomass density and small acreage plots [63]. The corn stover supply for the DuPont cellulosic bioethanol plant at Nevada, Iowa will mostly come from within a 30-mile radius around the facility, so in the present study, a sensitivity analysis was conducted for both 30 and 50 mile radii to evaluate the impact of these distances on biorefinery size. In general, while the unit capital cost declines with an increase in biorefinery capacity the unit transportation cost tends to increase as biorefinery size increases because feedstocks are being transported from larger distances. We considered a fixed upper limit for biomass supply and evaluated its impact on biorefinery size. It was also assumed that biorefineries can accept only one type of feedstock. The maximum biorefinery size using miscanthus as feedstock for the basic scenario was 331, and the biorefinery size using switchgrass as feedstock was 178 MG (Figure 6). Studies have reported that the optimal size of a cellulosic biorefinery could be at least 7 to 10 times

greater than the largest project currently being constructed or planned [54]. The 30 MG DuPont cellulosic bioethanol facility at Nevada, Iowa is the largest cellulosic ethanol plant in the country, and 10 times its capacity would be 300 MG, close to the value found for the basic scenario with miscanthus as biomass feedstock. Bamberg, et al., [54] found that the range of biorefinery sizes using fermentation process and miscanthus as feedstock could vary from 150 to 250 MG/year assuming typical land conversion conditions. Those authors also pointed out that, if biomass is economically available and farmers are willing to convert land into energy-oriented crops, a miscanthus fermentation pathway could be profitable compared to gasoline. Wright and Brown [4] found that the optimal size range for a lignocellulosic biorefinery was 240-486 MG per year, compared to 79 MG per year for a grain ethanol plant. The miscanthus yield was on average 2.2 times greater than that for switchgrass for sites where yields were greater than 10 Mg/ha. The maximum biorefinery capacity using switchgrass was about 2 times less than that of miscanthus, mainly due to low switchgrass yield. The maximum biorefinery size using corn stover as feedstock for the basic scenario was 106 MG. The present maximum capacity of a corn ethanol biorefinery in the U.S. is 313 MG. The assumption regarding the amount of corn stover left in the field to maintain soil carbon levels and ensure sustainable harvest limited the amount of stover available for biorefinery use, even in the highest corn-producing areas in the U.S

For the basic scenario, there were 164 biorefineries using switchgrass and miscanthus as feedstocks, 65%, and 32% of biorefineries using miscanthus as feedstock produced less than 100 MG and 100-250 MG, respectively (Fig. 6), and only 3% produced more than 250 MG. For switchgrass, 93% of the biorefinery capacities were less than 100 MG, and only 6% of the biorefineries produced in the range of 100-179 MG. The higher yield of miscanthus compared to switchgrass resulted in larger-sized biorefineries. The number of biorefineries using corn stover decreased to 85, of which 95% produced less than 100 MG. The decrease in number of corn stover biorefineries was due to unavailability of corn stover biomass at the suitable sites. The reason that 71% of corn stover biorefineries had production less than 25 MG is the significant amount of corn stover left in fields to ensure sustainable corn stover harvest. The higher percentage of biorefineries with capacity less than 100 MG is consistent with the current situation of conventional corn-ethanol biorefineries in the U.S. Presently, 73% of the corn-ethanol conventional biorefineries have capacities of less than 100 MG.

The biofuel mandates require the biofuel supply to be significantly increased by 2022. The expected total annual biofuel production will be 36 BG, with 21 BG from advanced biofuel and roughly 16 BG from cellulosic biofuel by 2022 [4]. We found that, in the case of the basic scenario biofuel mandate, the demand could be met using both miscanthus and corn stover as biomass feedstocks. It has been

estimated that 68,000,000 Mg of corn stover is available in the U.S. and if 30% is used for biofuel production then about 2 BG of biofuel could be produced [64], which is consistent with our results. The high yield of miscanthus could result in meeting 87% of the total biofuel production from cellulosic ethanol anticipated for the year 2022. The land categories considered for cultivation of miscanthus were barren, shrub/scrub, grassland/herbaceous, and pasture/hay, indicating that miscanthus could meet the biofuel goals without bringing new cropland into production or negatively affecting food supply.; utilizing these land types for biofuel production, however, may impact wildlife habitat and water quality [65]. This also might impact feed/forage availability and prices. Switchgrass biomass production can meet 42% of the biofuel goal set for 2022. Overall, our analysis shows that the U.S. biofuel mandate could be met using 70% of the available production capacity from all three types of biomass feedstocks.

In the co-location scenario, the additional criteria of co-locating with existing corn ethanol biorefineries and coal-fired power plants were considered, and while this criterion drastically decreased the number of suitable biorefinery locations, co-location could provide economic advantages. The maximum sizes of miscanthus, switchgrass, and corn stover biorefineries for the co-location scenario were 250, 126, and 81 MG, respectively (Fig. 6). The number of suitable sites decreased drastically to 17 with a correspondingly drastic reduction in production capacity. If co-location is considered, combined ethanol production capacity from all three feedstocks would be 2.5 BG; only 15% of the U.S. biofuel mandate. In the near term, it is most likely that corn stover will be the primary feedstock for cellulosic biorefinery, mainly due to its availability and use in already-existing ethanol plants; this could be further extended to include a cellulosic bioethanol production line.

For the basic scenario and a 30-mile radius, the maximum sizes were found to be 182, 98, and 66 MG for biorefineries based on use of miscanthus, switchgrass and corn stover, respectively. Increasing the radius to 50 miles produced maximum size was 509, 274, and 153 MG, respectively, of biorefineries using miscanthus, switchgrass, and corn stover. The total production capacity for the basic scenario and a 30-mile radius for miscanthus, switchgrass and corn stover was 8, 4 and 1 BG, respectively. For a 50-mile radius, the production capacities were found to be 21, 10 and 3 BG, respectively. With the decrease in supply radius, the biorefinery size and total production capacity decreases and vice versa. A similar trend was found for the co-location scenario. The high yield of miscanthus resulted in high total production capacity and demonstrated its potential for satisfying a major portion of the U.S. biofuel mandate (Fig. 7). The main difficulties associated with commercialization of cellulosic ethanol are infrastructural challenges and high capital and operating

costs [66]; for larger biorefineries, transportation becomes more complex and expensive because infrastructure for transportation of large quantities of low density biomass may not be in place, and an increase in hauling distance increases transportation costs. However, the smaller the biorefinery, the longer it will take to achieve a positive return on investment [53]. Technological advances in pre-treatment and processing technology could reduce biorefinery capital costs and further reduce biorefinery size requirements and unit costs of biofuel production [53].

Figure 6. Biorefinery size distribution for basic and co-location scenario. The U.S. maps shows the biorefinery location and the size of dots represent biorefinery size (a small dot represents small sized biorefinery and a large dot represents a larger size biorefinery). The pie chart depicts the proportion of biorefineries in various size ranges.

Figure 7. GIS model theoretical bioethanol production capacity with varying biomass supply radius for basic and co-location scenario

In the present study, it was assumed that 30% of the total land type (barren, shrub/scrub, grassland/herbaceous and pasture/hay) would be used for biofuel production. Land-use constraints could vary for different land categories as more data becomes available on amount of land conversion to avoid negative on environment, biodiversity, and livestock sectors. The analysis presented here identified potential sites and could serve as an input for a mathematical model for site optimization. Furthermore, a spatial decision support system (SDSS) could be developed to evaluate different scenarios and assist decision makers in the selection of the most suitable set of actions for successful implementation of the bioethanol industry. Other siting determinants related to power transmission lines, labor availability, local regulations, area zoning policies, tax incentives from local and state governments, and environmental regulations were not considered in the present analysis, and considering such additional criteria would undoubtedly improve the facility siting decision-making process. We have presented a snapshot of the current possibilities using available data and hope to enhance this analysis in the future. This model also does not consider costs related to biomass production, logistics and transportation. Community acceptance for bioethanol facility installation in the given areas could also be evaluated. Another area of expansion for the model could be in incorporation of additional facility types such as biomass depots (pre-processing and storage) or central biomass storage facilities. These limitations could be addressed by future studies in this field.

503 **4. Conclusions**

504 We have presented a GIS-MCE based approach for identifying suitable biorefinery sites and their
505 bioethanol production capacities. Our approach uses high resolution geospatial data for developing
506 constraints and yield potential using a semi-mechanistic dynamic crop model for promising biofuel
507 feedstocks. Criteria influencing the siting of plants were identified and a suitability model was
508 developed using the AHP method. Candidate sites for plants were selected and a buffer was
509 developed around the sites to determine plant capacity using switchgrass, miscanthus, and corn stover
510 as biomass feedstocks. The southeast, parts of the central midwest, and the northeast U.S. were
511 identified as potential high yield and stable zones for switchgrass and miscanthus production and also
512 suitable zones for biorefinery siting. The co-location scenario resulted in drastically reducing the
513 number of suitable sites and the modeling results showed that biorefineries using miscanthus biomass
514 could meet a significant portion of the U.S. biofuel mandate. For this to be possible, agronomic best-
515 management practices would need to be applied to ensure that biofuel crops such as miscanthus are
516 able to produce to their full potential. The lower yield of switchgrass results in lower biofuel
517 production capacity, but future high-yielding switchgrass cultivars may greatly increase the
518 production capacity to meet biofuel targets. Similarly, with respect to corn stover, an increase in corn
519 yield will result in higher stover yields, thus increasing the potential of corn stover to contribute to the
520 US transportation sector. In the near term, it is most likely that corn stover will be the primary
521 feedstock for cellulosic biorefinery. This study provides an explicit spatial biorefinery suitability
522 model to enhance strategic decision-making capabilities and understanding of potential for the large-
523 scale biofuel production in the U.S.

524

Nomenclature

AHP	Analytical Hierarchy Process
BG	Billion Gallons
BIOFLAME	Biofuels Facility Location Analysis Modeling Endeavor
CDL	Cropland Data Layer
Ce,i	Cell value i of Boolean value (0,1) assigned to the ith cell in the final exclusion map
Ci,j	ith cell value in the grid of the jth preference criteria layer
Ci,j	Boolean cell value (0,1) assigned to the ith cell value in the jth constrained grid layer
Cp,i	Preference score of the ith cell value in the final criteria grid
CR	Consistency Ratio
DFD	Data Flow Diagram
DSSAT	Decision Support System for Agrotechnology Transfer
GBSM	Geospatial Bioenergy System Model
GIS	Geographic Information Systems
GIS-MCE	Geographic Information Systems-Multi Criteria Evaluation
HYSZ	High Yield Stable Zones

HYUSZ	High Yield Unstable Zones
LYSZ	Low Yield Stable Zones
LYUSZ	Low Yield Unstable Zones
m	Total number of preference criteria
MCDM	Multi-Criteria Decision Making
MCE	Multi-Criteria Evaluation
MG	Million Gallons
MW	Mega Watts
N	Total number of exclusion constraints
RFS	Renewable Fuel Standard
SCM	Supply Characterization Model
U.S.	United States
W _j	Weight assigned to jth criterion from the AHP analysis

Acknowledgments

We would like to acknowledge the financial support from the CenUSA Bioenergy project funded by the Agriculture and Food Research Initiative Competitive Grant No. 2011-68005-30411 from the USDA National Institute of Food and Agriculture.

References

- [1] Bowling IM, Ponce-Ortega JM, El-Halwagi MM. Facility location and supply chain optimization for a biorefinery. *Industrial & Engineering Chemistry Research*. 2011;50:6276-86.
- [2] EPA. Renewable Fuel Standard Program. 2016. Accessed on: 25 August, 2016. <https://www.epa.gov/renewable-fuel-standard-program>.
- [3] EPA. RFS2 EMTS Informational Data 2014. Accessed on: 12 June, 2014. <http://www.epa.gov/otaq/fuels/rfsdata/index.htm>.
- [4] Schnepf R, Yacobucci BD. Renewable Fuel Standard (RFS): Overview and Issues. Congressional Research Service. 2013.
- [5] Gürder F, Yılmaz Y. Geographic Information Systems in strategic decision making in logistics companies. *International Journal of Business and Social Research (IJBSR)*. 2012;2:76-86.
- [6] Sharma B, Brandes E, Khanchi A, Birrell S, Heaton E, Miguez FE. Evaluation of microalgae biofuel production potential and cultivation sites using Geographic Information Systems: A Review. *BioEnergy Research*. 2015;8:1714-34.
- [7] H Khachatryan, E Jessup, K Casavant. A GIS-based estimation of regional biomass supply and transportation costs for biofuel plant least-cost location decisions. 51st Annual Transportation Research Forum. Arlington, Virginia 2010. p. 18.
- [8] Noon CE, Zhan FB, Graham RL. GIS-Based Analysis of marginal price variation with an application in the identification of candidate ethanol conversion plant locations. *Networks and Spatial Economics*. 2002;2:79-93.
- [9] Jon McKechnie, Yimin Zhang, Akifumi Ogino, Brad Saville, Sylvia Sleep, Mark Turner, et al. Modeling and analysis impacts of co-location, co- production, and process energy source on life cycle energy use and greenhouse gas emissions of lignocellulosic ethanol. *Biofuels, Bioproducts and Biorefining*. 2011;5.

554 [10] Sultana A, Kumar A. Optimal siting and size of bioenergy facilities using geographic information
555 system. *Applied Energy*. 2012;94:192-201.

556 [11] Koikai JS. Utilizing GIS-based suitability modeling to assess the physical potential of bioethanol
557 processing plants in Western Kenya. *Papers in Resource Analysis*. Papers in Resource Analysis Saint
558 Mary's University of Minnesota University Central Services Press Winona, MN. 2008;10:1-12.

559 [12] Zhang F, Johnson DM, Sutherland JW. A GIS-based method for identifying the optimal location
560 for a facility to convert forest biomass to biofuel. *Biomass and Bioenergy*. 2011;35:3951-61.

561 [13] Perpiña C, Martínez-Llario JC, Pérez-Navarro Á. Multicriteria assessment in GIS environments
562 for siting biomass plants. *Land Use Policy*. 2013;31:326-35.

563 [14] Wilson BS. *Modeling Cellulosic Ethanol Plant Location Using GIS*. Knoxville: University of
564 Tennessee; 2009.

565 [15] Lin T, Rodríguez LF, Shastri YN, Hansen AC, Ting KC. GIS-enabled biomass-ethanol supply
566 chain optimization: model development and Miscanthus application. *Biofuels, Bioproducts and*
567 *Biorefining*. 2013;7:314-33.

568 [16] Parker N, Tittmann P, Hart Q, Nelson R, Skog K, Schmidt A, et al. Development of a biorefinery
569 optimized biofuel supply curve for the Western United States. *Biomass and Bioenergy*. 2010;34:1597-
570 607.

571 [17] Voivontas D, D. Assimacopoulos, E.G. Koukios. Assessment of biomass potential for power
572 production: a GIS based method. *Biomass and Bioenergy*. 2001;20:101-12.

573 [18] Wu J, J. Wang, M.P. Strager. A two-stage GIS-based suitability model for siting biomass-to-
574 biofuel plants and its application in West Virginia, USA. *International Journal of Forest Engineering*.
575 2011;22:28-38.

576 [19] Dong J. *GIS and Location Theory Based Bioenergy Systems Planning*. Ontario, Canada:
577 University of Waterloo; 2008.

578 [20] Vukašinović V, Gordić D. Optimization and GIS-based combined approach for the determination
579 of the most cost-effective investments in biomass sector. *Applied Energy*. 2016;178:250-9.

580 [21] Wang Z. A GIS-based multi-objective optimization of a lignocellulosic biomass supply chain: a
581 case study in tennessee. Knoxville: University of Tennessee; 2013.

582 [22] Sahoo K, Hawkins GL, Yao XA, Samples K, Mani S. GIS-based biomass assessment and supply
583 logistics system for a sustainable biorefinery: A case study with cotton stalks in the Southeastern US.
584 *Applied Energy*. 2016;182:260-73.

585 [23] Zhang F, Johnson D, Johnson M, Watkins D, Froese R, Wang J. Decision support system
586 integrating GIS with simulation and optimisation for a biofuel supply chain. *Renewable Energy*.
587 2016;85:740-8.

588 [24] Gayle Gordon, Nathan Parker, Peter Tittmann, Quinn Hart, Mui Lay, Cunningham J, et al.
589 Western Governors' Association: Strategic assessment of bioenergy development in the west -spatial
590 analysis and supply curve development. 2008.

591 [25] N. Parker, Q. Hart, P. Tittmann, B. Jenkins. *National biofuel supply analysis*. University of
592 California , Davis 2011.

593 [26] U.S. Department of Energy. 2016 Billion-Ton Report: Advancing Domestic Resources for a
594 Thriving Bioeconomy, olume 1: Economic Availability of Feedstocks. M. H. Langholtz, B. J. Stokes,
595 and L. M. Eaton (Leads), . Oak Ridge, TN: Oak Ridge National Laboratory; 2016. p. 448p.

596 [27] van der Weijde T, Alvim Kamei CL, Torres AF, Vermerris W, Dolstra O, Visser RG, et al. The
597 potential of C4 grasses for cellulosic biofuel production. *Frontiers in plant science*. 2013;4:107.

598 [28] Sharma B, Ingalls RG, Jones CL, Huhnke RL, Khanchi A. Scenario optimization modeling
599 approach for design and management of biomass-to-biorefinery supply chain system. *Bioresource*
600 *Technology*. 2013;150:163-71.

601 [29] Miscanthus (*Miscanthus x giganteus*) for Biofuel Production. 2014. Accessed on: 24 June, 2016.
602 <http://articles.extension.org/pages/26625/miscanthus-miscanthus-x-giganteus-for-biofuel-production>.

603 [30] Switchgrass (*Panicum virgatum*) for Biofuel Production. 2016. Accessed on: 26 June, 2016.
604 http://articles.extension.org/pages/26635/switchgrass-panicum-535_virgatum-for-biofuel-production.

605 [31] Vikram Koundinya. 2009. Corn Stover. Accessed on: 26 June, 2016.
606 <http://www.agmrc.org/renewableenergy/corn-stover/>.

607 [32] Corn Stover for Biofuel Production. 2014. Accessed on: 26 June, 2016.
608 <http://articles.extension.org/pages/26618/corn-stoverfor-biofuel-production>.

609 [33] Thomas L. Saaty. Decision making with the analytic hierarchy process *Int J Services Sciences*.
610 2008 1:83-98.

611 [34] EIA. Commercial-scale cellulosic ethanol plant opens. 2014. Accessed on: 31 March, 2016.
612 <https://www.eia.gov/todayinenergy/detail.cfm?id=17851>.

613 [35] U.S. Department of Energy. U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and
614 Bioproducts Industry. In: (Leads) RDPaBJS, editor. Oak Ridge National Laboratory, Oak Ridge, TN
615 2011. p. 227.

616 [36] Douglas A. Durante, Todd C. Sneller. A guide for evaluating the requirements of ethanol plants.
617 The Clean Fuels Development Coalition, The Nebraska Ethanol Board, The U.S. Department of
618 Agriculture; 2006.

619 [37] US Department of Transportation. Accessed on: 15 December, 2015.
620 http://ops.fhwa.dot.gov/freight/freight_analysis/faf/faf3/netwkdbflow

621 [38] NREL. Feasibility Study for bioethanol co-location with a coal fired power plant bbi
622 international Cotopaxi, Colorado: National Renewable Energy Laboratory; 2002.

623 [39] Bob Wallace, Mark Yancey, James Easterly. Co-locating a cellulosic biomass to ethanol plant
624 with existing coal fired power plants.

625 [40] Nas B, Cay T, Iscan F. Selection of MSW landfill site for Konya, Turkey using GIS and multi-
626 criteria evaluation. *Environ Monit Assess*. 2010.

627 [41] NREL. BioEnergy Atlas. Accessed on: 20 August, 2015.
628 http://www.nrel.gov/biomass/data_resources.html.

629 [42] U.S. Army Corps of Engineers. Ports and waterways facilities. Ports and waterways facilities.
630 Accessed on: 9 September, 2015. <http://www.navigationdatacenter.us/index.htm>.

631 [43] USGIS. National Water Information System: Web Interface. Accessed on: 10 September, 2015.
632 <http://nwis.waterdata.usgs.gov/nwis/>.

633 [44] U.S. Department of Commerce. Geography. Accessed on: 15 July, 2015.
634 <https://www.census.gov/geo/mapsdata/data/tiger-line.html>.

635 [45] CropScape and Cropland Data Layer. 2014. Accessed on: 25 April, 2015.
636 http://www.nass.usda.gov/Research_and_Science/Cropland/Release/index.php.

637 [46] ESRI. Albers equal area conic. 2013. Accessed on: : 25 April, 2015.
638 <http://resources.arcgis.com/en/help/main/10.1/index.html#//003r00000001n0000000>

639 [47] Zandbergen PA. Python scripting for ArcGIS. 1-368: Esri Press, 380 New York Street, Redlands,
640 California, 92373-8100; 2015.

641 [48] Python Software Foundation. Python 2.7. Python Language Reference. version 2.7 ed2015.

642 [49] ESRI. ArcGIS Desktop: Release 10. 2. Redlands, CA: Environmental Systems Research
643 Institute; 2014.

644 [50] RStudio Team. RStudio: Integrated Development for R. RStudio, Inc., Boston, MA 2015.

645 [51] Miguez FE, Maughan M, Bollero GA, Long SP. Modeling spatial and dynamic variation in
646 growth, yield, and yield stability of the bioenergy crops *Miscanthus × giganteus* and *Panicum*
647 *virgatum* across the conterminous United States. *GCB Bioenergy*. 2012;4:509-20.

648 [52] Homer CG, Dewitz JA, ang L, Jin S, Danielson P, Xian G, et al. Completion of the 2011
649 National Land Cover Database for the conterminous United States-Representing a decade of land
650 cover change information. *Photogrammetric Engineering and Remote Sensing*. 2015;81:345-54.

651 [53] Wright M, Brown RC. Establishing the optimal sizes of different kinds of biorefineries. *Biofuels*,
652 *Bioproducts and Biorefining*. 2007;1:191-200.

653 [54] Matthew B, Daniel LS, Timothy EL. Optimizing fermentation process miscanthus-to-ethanol
654 biorefinery scale under uncertain conditions. *Environmental Research Letters*. 2014;9:064018.

655 [55] van Ittersum MK, Cassman KG, Grassini P, Wolf J, Tittonell P, Hochman Z. Yield gap analysis
656 with local to global relevance—A review. *Field Crops Research*. 2013;143:4-17.

657 [56] Joseph E. Fargione, Richard J. Plevin, Jason D. Hill. The ecological impact of biofuels. *Annual*
658 *Review of Ecology, Evolution, and Systematics*. 2010;41.

659 [57] Joshua Elliott, Neil Best, Michael Glotter, David Kelly, Michael Wilde, Ian Foster. The Parallel
660 System for Integrating Impact Models and Sectors (pSIMS). *Proceedings of the Conference on*
661 *Extreme Science and Engineering Discovery Environment: Gateway to Discovery*. 2013;XSEDE13,
662 July 22 - 25 2013, San Diego, California, USA

663 [58] USDA National Agricultural Statistics Service Cropland Data Layer. Published crop-specific
664 data layer USDA-NASS, Washington, DC2014.

665 [59] David Ertl. Sustainable corn stover harvest. Iowa Corn Promotion Board. 5505 Northwest 88th
666 Street #100 | Johnston, Iowa 501312013.

667 [60] Michael D. Edgerton, Steve Petersen, Ty Barten, Iñigo Ibarra, Pradip Das, Kirk Remund, et al.
668 Commercial scale corn stover harvests using field-specific erosion and soil organic matter
669 targets.247-56.

670 [61] National Academy Of Sciences National Academy Of Engineering National Research Council
671 Of The National Academies. Liquid transportation fuels from coal and biomass: technological status,
672 costs, and environmental impacts. Washington, D.C.: The National Academies Press; 2009.

673 [62] A. Aden, M. Ruth, K. Ibsen, Jechura J, Neeves K, Sheehan J, et al. Lignocellulosic biomass to
674 ethanol process design and economics utilizing co-current dilute acid prehydrolysis for corn stover.
675 Golden, Colorado: National Renewable Energy Laboratory; 2002.

676 [63] Argo AM, Tan ECD, Inman D, Langholtz MH, Eaton LM, Jacobson JJ, et al. Investigation of
677 biochemical biorefinery sizing and environmental sustainability impacts for conventional bale system
678 and advanced uniform biomass logistics designs. *Biofuels, Bioproducts and Biorefining*. 2013;7:282-

679 302.

680 [64] U.S. Department of Energy and Department of Agriculture. The billion ton study, biomass as
681 feedstock for bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual
682 supply. . 2005.

683 [65] Elliott J, Sharma B, Best N, Glotter M, Dunn JB, Foster I, et al. A Spatial Modeling Framework
684 to Evaluate Domestic Biofuel-Induced Potential Land Use Changes and Emissions. Environmental
685 Science & Technology. 2014;48:2488-96.

686 [66] Sharma B, Ingalls RG, Jones CL, Khanchi A. Biomass supply chain design and analysis: Basis,
687 overview, modeling, challenges, and future. Renewable and Sustainable Energy Reviews.
688 2013;24:608-27.