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

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HIGHLIGHTS

- A spatial modeling framework for biorefinery sites and biofuel production estimation.
- Local geography, infrastructure and three types of biomass considered for analysis.
- Biorefineries using miscanthus could meet significant portion of US biofuel mandate.
- National-scale assessment enhances decision-making for large-scale biofuel production.

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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.

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

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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
Wj	Weight assigned to jth criterion from the AHP analysis

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 predefined 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 cities 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.

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