A GIS-based Estimation of Regional Biomass Supply and Transportation Costs for Biofuel Plant Least-Cost Location Decisions

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ABSTRACT

In this paper we have developed a Geographic Information Systems based model to support cellulosic ethanol plant least-cost location decisions by integrating geographic distribution of biomass in the study area with associated transportation costs. As an initial step of a multi-factor spatial optimization problem, including both feedstock transportation and ethanol distribution cost, the study investigated the influence of feedstock transportation costs on optimal location decisions. To achieve that purpose, the feedstock resources, in this analysis forest biomass and agricultural crop residue, were spatially investigated relative to the road network and potential cellulosic ethanol plant locations in the state of Washington. The flexibility of the model allows spatial manipulation of the data for the least-cost location identifications considering both cumulative and separate types of feedstock utilization scenarios. Study results show that the ethanol plant transportation cost-minimizing location decisions are significantly influenced by the type of the feedstock utilized, and vary depending on the processing plant capacities.

INTRODUCTION AND BACKGROUND

Transportation costs have always been an important factor for facility location decisions for many industries. With current high fuel prices, biofuels industry has become more sensitive to facility optimal location decisions on both the cost and demand sides of the market. Utilizing the framework of location theory, this paper develops a Geographic Information Systems (GIS) approach for estimating transportation costs to evaluate ethanol plant least-cost location decisions in the state of Washington. Strategic biofuel facility location decisions involve supply chain components, such as feedstock production, feedstock logistics, biofuels distribution and alternative market locations. For the cellulosic ethanol processing sub industry particularly, the geographic distribution of feedstock resources, such as forest biomass or agricultural crop residue may, through high transportation costs, significantly influence the economic viability of the emerging industry.

Despite its technological challenges, cellulosic biomass conversion into ethanol proves to be a promising alternative to corn-based ethanol processing, which is dramatically affected by recent surging corn prices (USDA 2007). In addition to sizable environmental benefits, the main advantage of cellulose-based ethanol processing is the feedstock resource abundance, relatively higher energy returns, and competitive processing costs (McLaughlin et al. 2002). Given the mandated industrial scale of the growing biofuels sector, other factors competitively affecting cellulose-based ethanol processing include adverse environmental impacts from enhanced corn production (nitrogen fertilizer runoffs into water sources) and corn based production's contribution to increasing food prices. However, to sustain economic feasibility of locally-supplied cellulosic ethanol industry, locational factors such as feedstock transportation distances/costs, ethanol distribution markets and cost-minimizing facility locations need further investigation.

Factors that influence processing plant location strategic decisions involve several considerations, such as feedstock availability, its geographic distribution relative to the local highway networks, ethanol distribution routes and final product market proximity. As a first step of the mentioned above multi-factor spatial optimization problem, this paper identifies feedstock transportation cost-minimizing ethanol plant locations, utilizing the spatial investigation of biomass resources relative to four potential plant locations in the state of Washington.

To achieve that purpose, a GIS Network Analyst (a GIS ArcMap software extension that enables network-based georeferenced data analyses) is utilized to spatially investigate the biomass availability data layer, based on increasing driving zones from/around each processing plant. Considering the geographic dispersion of two types of biomass in the state forest and agricultural crop residue, each of the driving zones is categorized to support different capacities of ethanol processing. Further, truck transportation per ton mile costs are applied to derive the biomass delivery costs using specific detailed information about annual tons of available biomass in each driving zone. Finally, incorporating different levels of processing plant capacities, in million gallons per year (MGY), and respective feedstock transportation costs, the cost-minimizing ethanol plant locations are then identified.

RELEVANT LITERATURE

The importance of transportation costs, region-specific road infrastructure, and the nature of commodities transported that influence the distribution of particular industries was introduced in early 1900s by Weber (Weber 1929). Utilizing and contrasting different objectives of spatial optimization, location theory has been since developed and revisited by many creative researchers, including Hotelling, Smithies, Isard, Stevens, Hakimi, ReVelle et al., Francis et al., Tansel et al., Aikens and Daskin to name a few (Hotelling 1929; Smithies 1941; Isard 1956;

Stevens 1961; Hakimi 1964; ReVelle et al. 1970; Francis and McGinnis 1983; Tensel et al. 1983; Aikens 1985; and Daskin 1995).

However recently, the multi-factor (e.g. feedstock resource distribution, proximity of markets, environmental factors or populations shift) analysis of strategic location decisions pertaining to biofuels industry has received increasing attention. Simultaneously the development of GIS as a system of software and hardware that enables analyses, spatial manipulation and modeling of geographically referenced data, the understanding of the complexity of location optimization problems has been facilitated. With the new ability to take into account the spatial variability characteristic of biomass resources, many research efforts have investigated potential bioenergy feedstock locations with GIS-based models (Graham et al. 1996; Noon et al. 1996; Möller and Nielsen 2007; Graham et al. 2000; Zhan et al. 2005; Panichelli and Gnansounou 2008; Langholtz et al. 2007; and Graham et al. 1995).

Major problems in location theory, such as *median problems*, *covering problems* or *center problems* can be characterized according to the objective function (for both optimizing and non-optimizing cases), decision variables and system of parameters (Brandeau and Chiu 1989). The objective of the optimization problems include (but are not limited to) minimization of average travel time or average cost, maximization of net income, minimization of maximum travel time/cost, and maximization of minimum travel time/cost. In turn, decision variables may include facility location, facility processing/producing capacity, type of processed commodities and origin-destination transportation routes. Lastly, system parameters involve considerations, such as types of distance measures (Euclidean vs. Block Norm), type of the demand (continuous vs. discrete), and topological structure (link vs. network). The problem investigated in this paper is comparable to *p-median problem*, where the objective is to minimize the average travel distances between servers (feedstock sources) and demand points (processing plants) on a general network.

GIS APPROACH

Generally, assessment accuracy of regional biomass resources and associated transportation costs depend on number of factors, including assumptions on hauling distances, driving speed limits and truck transportation rates. Methodologies considering linear, straight-line average haul distances from processing plants may neglect local infrastructural factors, such as speed limits, elevation or road curvature that influence total driving times. In contrast, GIS-based models involve geographically referenced datasets that contain relevant geometry and attribute information for the spatial features (e.g. processing plants, roads, etc.). Spatial feature information, such as length of a road segment, or location (longitude and latitude) and name of the processing plant are stored as a shape file containing a set of vector coordinates.

A fundamental difference between GIS-based and non-GIS models is that datasets in GIS models, such as geographic distribution of biomass, highway networks and processing plant locations in the study area (state in our case) can be layered and geographically integrated. The multi-layer datasets allow spatial manipulation of that integrated information, such as extraction of biomass availability information by county, or by county and within different driving distances from multiple biorefinery locations in the study area. Considering the research question in this paper, the advantage of the GIS approach is that it provides capability to investigate the delivered feedstock costs by integrating site-specific road infrastructure and spatially variable distribution of biomass in the state.

GIS MODEL

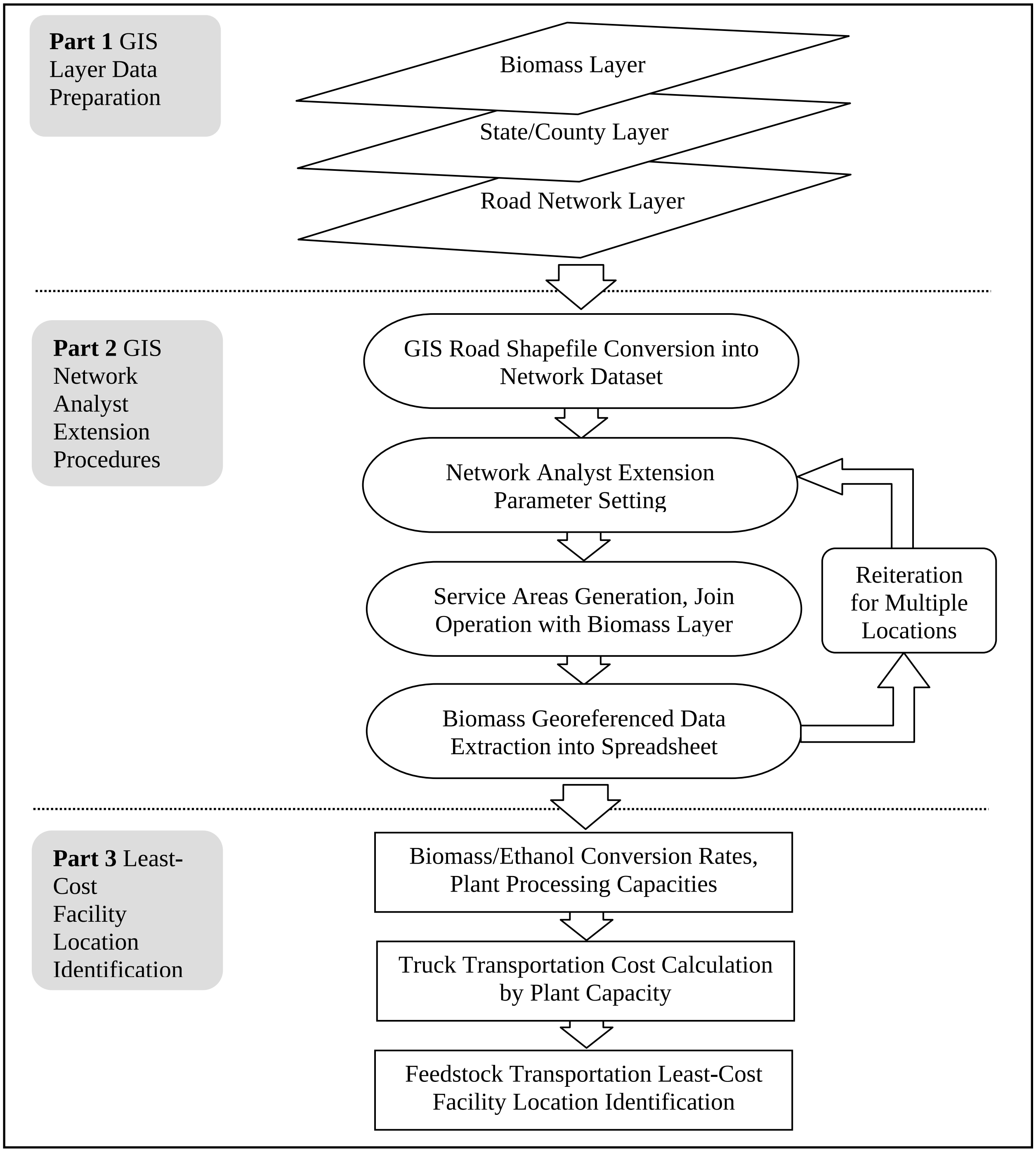
Data

The GIS data have been obtained from the National Renewable Energy Laboratory's Dynamic Maps, GIS Data and Analysis Tools webpage (NREL 2007). According to the same source, the cumulative availability of the forest biomass and agricultural crop residue in the state is over 2.7 million annual dry tons, indicating a potential to process more than 200 million gallons of ethanol annually. Crop residue procurement prices and per ton mile truck transportation costs (for both types of feedstock) have been used as derived in Khachatryan et al. (2008). For the forest biomass procurement prices, estimates from relatively recent studies have been adapted (Gan and Smith 2006; Asikainen et al. 2002; Rummer et al. 2003; Puttock 1995). Study area road shapefiles (i.e. files used in GIS that contain nontopological geometry and attribute information for the spatial features) have been obtained from the Environmental Systems Research Institute (ESRI) website (ESRI 2000).

Structure

The GIS-based model consists of three main parts. In turn, each of the parts includes several procedures (Figure 1). The first part builds a dataset by layering GIS shapefiles that are necessary for the analysis in this paper. The second part involves GIS Network Analyst extension procedures for creating service area (a shapefile of driving zones) around processing plants included in the study area, as well as for joining and relating that new shapefile (service areas) with existing GIS layers. Reiteration of the procedures is undertaken for each of the processing plant locations. The final part of the model incorporates spreadsheet operations for further analysis with the GIS-generated spatial data. In particular, it links steps where annual ethanol processing capacities (using biomass-to-ethanol conversion rates) and truck transportation costs (using per ton mile costs) are derived for the least-cost facility location identification.

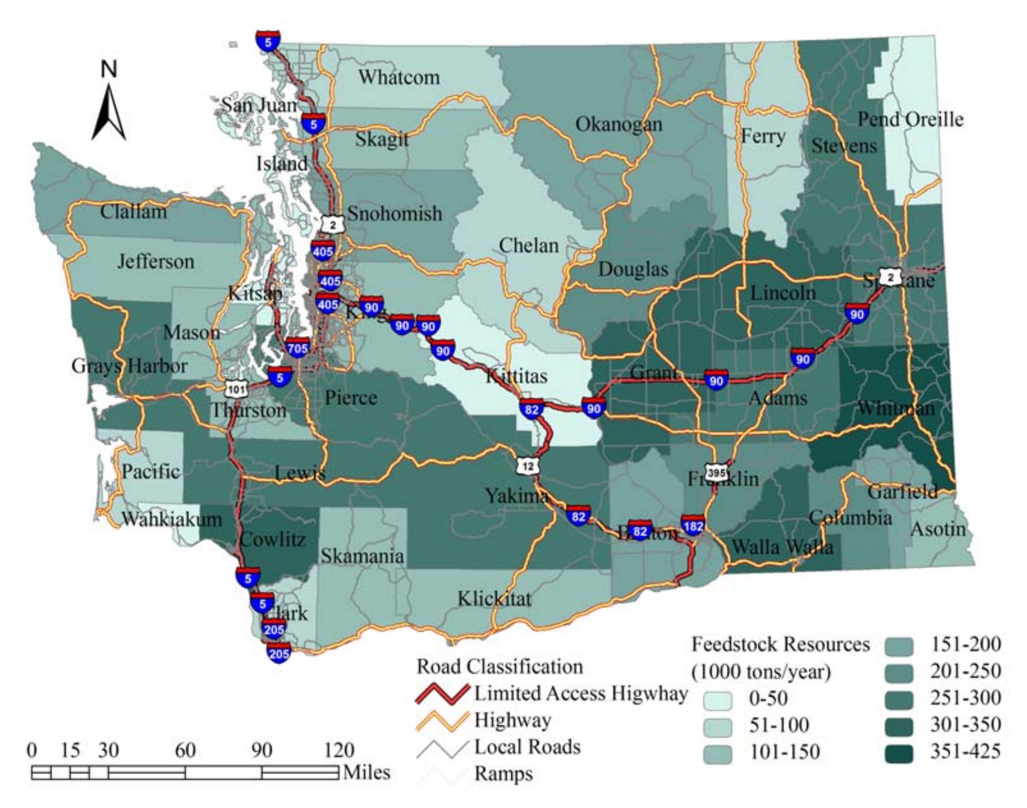
Figure 1: Flowchart of GIS-based Feedstock Transportation Least-cost Facility Location Decision Model



Procedures and Processes

This section provides details on the GIS procedures for calculating feedstock resource availability by county, and by specified haul distances. It also describes procedures for assigning driving speed limits to the road segments and for generating datasets for the feedstock transportation costs derivation. The biomass shapefile, indicated in Part 1 of Figure 1, represents a geographical layer with attribute information, such as area and boundaries of biomass distribution, and spatial information, such as latitude, longitude and type of the map projection (i.e. transformation of spheroid surface to a flat map while maintaining spatial relationships). Integration with the state/county shapefile provides annual availability information for agricultural crops residue and forest biomass by county level (cumulatively mapped in the following Figure 2).

Figure 2: Distribution of Forest Biomass and Agricultural Crop Residue in Washington

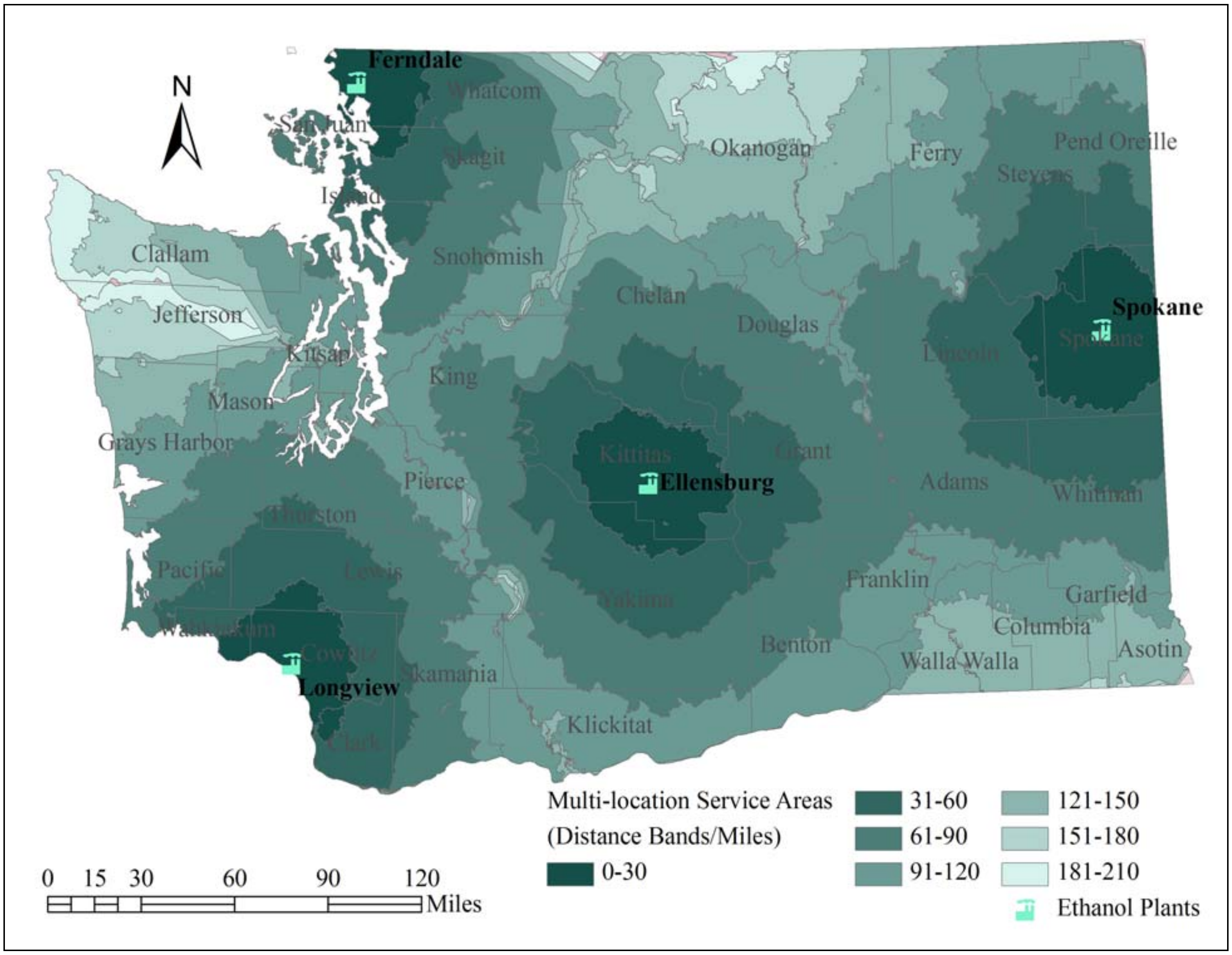


Simultaneously census feature classification codes (CFCC) were joined to the GIS roads shapefile's attribute table. This procedure assigns speed limits to each of the road segments, which in turn, allows driving distances from each processing plant to the feedstock sources to be calculated.

Procedures in Part 2 of the model involve a GIS Network Analyst extension toolset, which enables network based spatial analysis, such as finding the closest facility from a particular location, identifying routes and driving distances to reach specified areas, and generating service areas (distance-based buffer zones) around points of interest. As an initial step, the GIS road shapefile was converted into a network dataset (using GIS ArcCatalog software). GIS network datasets are constructed from spatial features – lines, points and turns, which build an advanced connectivity model for transportation networks. The next step sets parameters for the service area generation, such as driving distance bands (in miles), processing plant locations and cost attributes.

To identify the feedstock resource availability within increasing driving distances around ethanol processing plants, the service areas cover the entire state at 30-mile increments. For instance, within the 30-mile buffer, all available feedstocks will require a 30-mile length haul (maximum) to be transported from the field to the processing plant. The cost attribute for service areas generation was set as a distance in miles, and the four proposed ethanol facility locations have been loaded as points where the feedstock needs to be transported. The rationale for choosing/including mentioned processing plant locations is that all of them are currently under planning or feasibility study stage (Lyons 2008). After the generation of service areas, (depicted in Figure 3) the resulting distance based layers were joined with the biomass layer, such that for each service area the available feedstock/biomass amount in annual tons is identified at the county level.

Figure 3: Service Areas around Four Proposed Ethanol Facilities



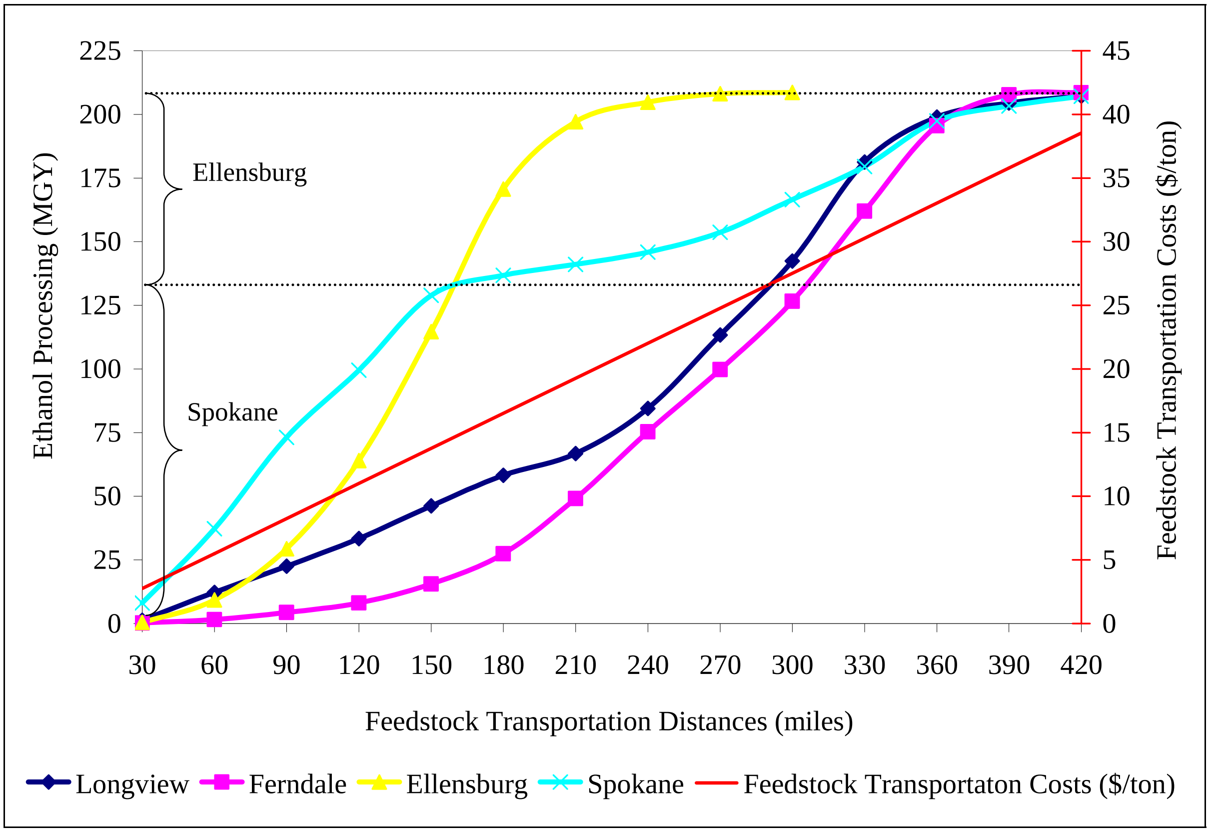
Since the biomass data were available per county, several additional steps were implemented to extract the county availability information, within each driving distance. First, the information within the service area boundaries of the merged (service area with biomass layer) layer was selected and saved as a separate layer. In this selected layer the geographic area (in square miles), for each of the service areas within boundaries of each county was calculated using GIS ArcMap Geometry Calculation tool. As the last step of Part 2, the attribute table of merged shapefile was exported into a spreadsheet. Finally, to specify the availability of biomass in each of the service areas at county level, the service area proportions were calculated by dividing service areas (in square miles, within respective counties) by the area of the county itself. Reiteration of procedures was carried out for all four processing plant locations depicted in Figure 3.

The final part of the model incorporates per ton mile transportation costs, considering loading/unloading delays, physical availability, as well as the geographic distribution of the biomass, allowing delivered feedstock costs to be derived. Using a 75 gallons of ethanol per dry ton of feedstock conversion rate, driving distances varied by different processing plant capacities (reaching to 210 MGY) were identified (U.S. DOE 2007). This finally allowed transportation costs per ton of feedstock by processing plant capacity to be derived. Integration of per ton mile transportation costs, physical availability of feedstock and its distribution enabled identifying least-cost processing plant location, as affected by the feedstock transportation costs. Further as discussed in the Results section, this approach allows ranking plant locations according to the type of feedstock utilized (agricultural crops residue vs. forest biomass) and according to the plant processing size/capacity.

RESULTS

Analytical results indicate that transportation costs differ according to the processing plant capacity, since the larger plants require more feedstock to support their production level, hence longer haul distances. Figure 4 shows the relationship between feedstock transportation costs (per ton) and processing plant capacities (MGY) for the combined (forest biomass and agricultural crop residue) feedstock utilization scenario. The location in Spokane maintains its least-cost feedstock transportation advantage for all processing capacities up to 130 MGY. For this location, a processing capacity of 100 MGY can be supported with the available biomass within only 120 miles from the plant location. To achieve the same level of ethanol processing, plants considering Longview and Ferndale locations will need to reach out twice as farther as it is required for the Spokane location.

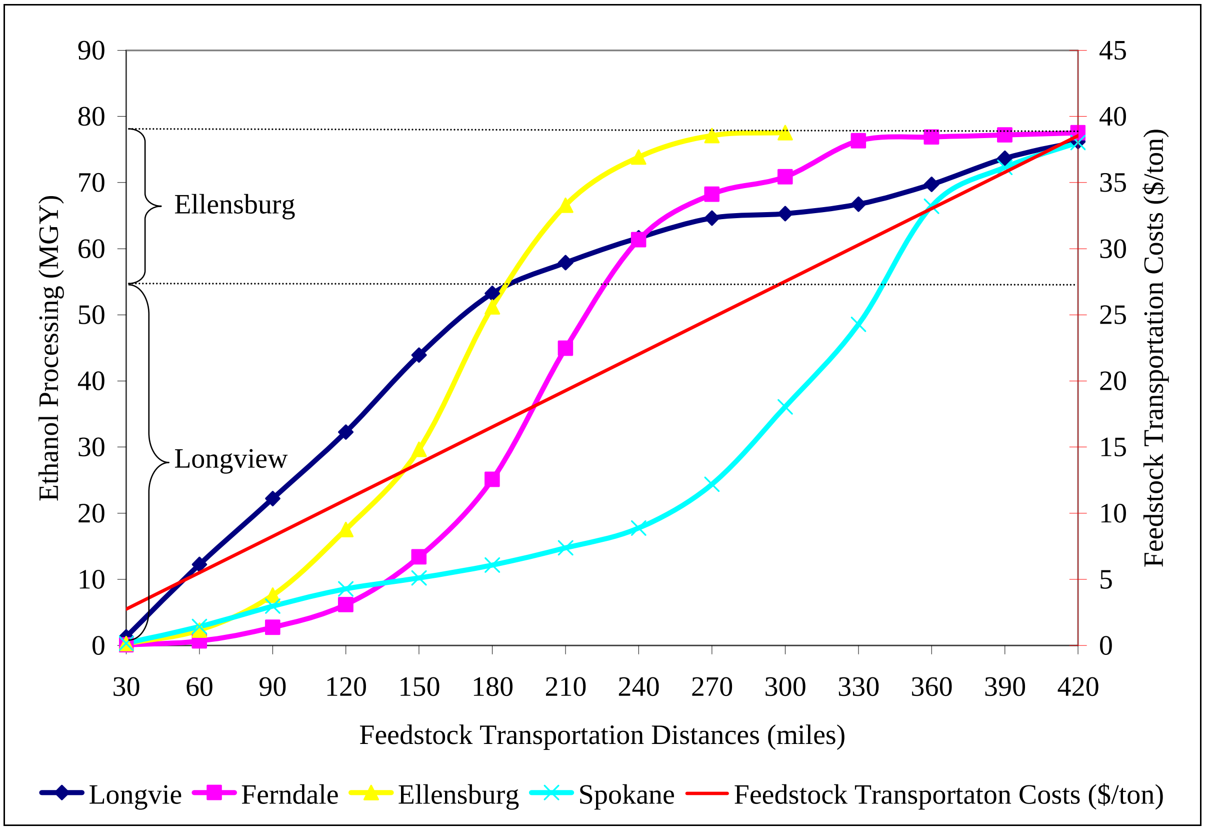
Figure 4: Feedstock Transportation Costs by Processing Plant Capacity (Forest Biomass and Agricultural Crop Residue Combined)



For the processing capacities over 130 MGY, the location with the lowest feedstock transportation cost is Ellensburg. A maximum of 210 MGY processing can be achieved using resources within 300 miles around the plant. Locations in Longview and Ferndale were not found to be competitive, in this scenario, which considers cumulative (forest and agricultural residue) availability of feedstock resources.

Depending on the type of the feedstock considered for ethanol processing, transportation costs differ, since each type has differing geographic distributions in the study area. To compare results with that of the cumulative feedstock utilization scenario, forest biomass was analyzed separately. The relationship between forest biomass transportation costs and an annual ethanol processing for the same plant locations in the study depicted in Figure 5. The previous location (Spokane) does not necessarily sustain its cost competitiveness when considering feedstocks separately. One of the obvious reasons for considering separate feedstock scenario is processing/conversion technology restrictions pertaining to types of feedstocks.

Figure 5: Feedstock Transportation Costs by Processing Plant Capacity (Forest Biomass)



As shown in Figure 5, for the processing capacities up to 55 MGY, the Longview location shows the lowest transportation costs when considering forest biomass only. This level of processing capacity can be supported by transporting feedstocks within 180 miles around the plant. For larger capacities (reaching up to 78 MGY at maximum), the Ellensburg location provides the lowest transportation costs. In contrast to the cumulative biomass scenario, the Spokane location is not cost competitive for any of the processing capacities when considering forest biomass only. The Ferndale location has the highest transportation costs for both cumulative and separate feedstock utilization scenarios.

CONCLUSIONS

Ethanol processing plant optimal location decisions depend on many factors, including costs associated with feedstock transportation and ethanol distribution. As an initial step for future necessary multi-factor analysis, this paper has investigated the least-cost locations in the state of Washington pertaining to the feedstock transportation at different levels of ethanol processing. In further steps, an investigation of distribution costs in terms of market proximity to processing plants will be integrated. In such an analysis, the distribution costs can be derived by extending the GIS-model employed in this paper to account for ethanol blending terminals and fueling stations in relation to the processing plants.

Because of the spatially variable distribution of the feedstock resources and increasing transportation costs for longer destinations, all of the feedstock deposits cannot be utilized at the same expense. Additionally, it was demonstrated that for different processing capacities, optimal plant locations vary according to the type of the feedstock. The GIS approach proposed in this paper allowed spatial manipulation of data considering multiple geographic locations in the study area, which provides more accurate evaluation of available feedstock resources within specified distances from processing plants. Finally, the flexibility of the model enables its application to any geographic area.

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