TRANSITION TO A BIO ECONOMY

# Environmental and Rural Development Impacts

Proceedings of the October 15 and 16, 2008 Conference,
St. Louis, Missouri

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The conference was a collaboration of Farm Foundation, USDA Office of Energy Policy and New Uses, USDA Economic Research Service, USDA Rural Development, USDA Natural Resources Conservation Service, and the U.S. Forest Service.

# Optimal Biorefinery Locations and Transportation Network for the Future Biofuels Industry in Illinois

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**Abstract:** This article addresses development of the Illinois ethanol industry through the period 2007-2022, responding to the ethanol production mandates of the Renewable Fuel Standard by the U.S. Environmental Protection Agency. The planning for corn-based and cellulosic ethanol production requires integrated decisions on transportation, plant location, and capacity. The objective is to minimize the total system costs for transportation and processing of biomass, transportation of ethanol from refineries to the blending terminals and demand destinations, capital investment in refineries, and by-product credits. A multi-year transshipment and facility location model is presented to determine the optimal size and time to build each plant in the system, the amount of raw material processed by individual plants, and the distribution of bioenergy crops and ethanol.

Currently corn ethanol is the major type of renewable fuel that is extensively used as an additive in the United States. Ethanol is now sold across the country and is blended in 50% of the nation’s gasoline at varying percentages between 10% and 85%, and its usage continues to increase. Ethanol blends at higher volumes, such as 85% (E85), are available especially in Midwestern states for use in flex-fuel vehicles. Given such demand, the ethanol production facilities and capacity expansion projects are booming. U.S. ethanol production increased from about 1.6 billion gallons in 2000 to 6.5 billion gallons in 2007. In January 2007 the number of ethanol plants was 110; by November 21, 2008 there were 180 operating biorefineries, with a total production capacity of 11 billion gallons per year. Twenty-one additional refineries are currently under construction, which will further expand the total capacity by 1.6 billion gallons each year (RFA 2008). In the long-run the existence and competitiveness of the ethanol industry depend on economic and strategic plans for facility location, transportation infrastructure, and logistics.

In order to achieve a sustainable supply of transportation fuels through renewable energy sources, particularly from ethanol, the Renewable Fuel Standard (RFS) established by the U.S. Environmental Protection Agency mandates production targets for both corn-based and cellulosic ethanol. The RFS requires increasing the use of renewable fuels every year through 2022. By 2012, at least 7.5 billion gallons of renewable fuel must be blended into motor-vehicle fuel (EPA, 2008). The program targets producing 36 billion gallons of biofuels by 2022, including 15 billion gallons of corn ethanol and 21 billion gallons of advance biofuels derived

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from renewable sources other than corn (which comprises 16 billion gallons of cellulosic ethanol derived from corn, stover, perennial grasses, and woody biomass, and 5 billion gallons of biofuels from undifferentiated sources). This raises complex issues regarding the production and processing of raw materials, logistics and facility location, and the distribution of a substantial amount of biofuel in the entire U.S.

In preparation for an extensive and comprehensive analysis, this article describes the basic methodology and presents some preliminary results of an ongoing research effort. A mathematical programming framework is developed to determine the optimal transportation and processing of raw materials, delivery of the end product, selection of the biorefinery types, and capacity and location decisions to meet the mandated ethanol targets throughout the 2007-2022 planning horizon.

In this exploratory study, our analysis on transportation logistics and refinery location focuses on the State of Illinois as a test bed. This is because of three reasons. First, Illinois is a major corn producing state, producing nearly 20% of the corn grain used for ethanol production. Second, Illinois is also a major ethanol consumption region, including some of the largest metropolitan areas such as Chicago. Finally, Illinois is one of the major hubs for various modes of freight transportation such as rail and highway, and the transportation of raw materials and end products constitutes a crucial component of cost in the bioenergy industry.

## 2. The Corn and Biomass Transportation and Biorefinery Location Problem

Transportation of corn and cellulosic biomass feedstocks to biorefineries is an important cost factor in the integrated regional biofuel assessment. Field harvested corn and cellulosic biomass has a low energy density in comparison with solid fossil fuel sources such as coal, requiring large amounts of feedstock to be transported. To address the problem, Sokhansanj et al. (2006) developed a logistics model for an integrated supply analysis that simulates the collection, storage, and transportation of corn and cellulosic biomass supply to a biorefinery. Using time dependent discrete event simulation and queuing analysis that represent the entire network of material flow from the field to a biorefinery, they predicted the number and size of equipment needed to meet the biorefinery demand for feedstock. Mapemba (2006) and Mapemba et al. (2007) estimated the cost to deliver feedstock to a biorefinery as a function of the biorefinery size, the number of harvest days, and the harvest frequency. The results showed that increasing the biorefinery capacity would require larger transportation distances, thus increasing the expected delivery cost.

Kumar et al. (2006) provided a ranking of biomass collection systems based on the cost of delivered biomass, quality of biomass supplied, emissions during collection, energy input, and maturity of supply system technologies. For a given capacity, rail transport of biomass was shown to be the best option, followed by truck transport and pipeline transport, the latter of which is not appropriate for ethanol transport due to water contamination. Rail transshipment may also be preferable in cases where road congestion precludes truck delivery. Mahmudi and Flynn (2006) suggested that a combined truck-and-train transport system would be more economical than truck delivery only. There is a minimum shipping distance for rail transport above which lower costs per mile offset incremental fixed costs.

Location models of ethanol plants and biorefineries incorporate and integrate factors such as land use, transportation and optimal plant size. The problem is to locate the processing facilities so as to minimize the total transportation cost adjusted by the returns from by-product sales, such as corn distillers dried grains with solubles (DDGS). This type of facility-location problem has typically been solved using integer-programming (Daskin, 1995, Drezner, 1995) which searches for an optimal network configuration (Fuller et al., 1976; Hilger et al., 1977), selecting biorefinery locations from a set of candidates, according to some specified criteria such as water availability or distance to the transportation network (Peluso et al., 1998). Kaylen et al. (2000) built a mathematical programming model to analyze the economic feasibility of producing ethanol from lignocellulosic feedstocks at minimal cost, distinguishing between capital cost, operating cost, feedstock cost, and transportation cost. As plant size increases marginal operating cost declines with plant capacity due to economies of scale but transportation cost increases because feedstock will have to be shipped from greater distances. Under these conditions, improved feedstock logistics is essential (Hess et al., 2007).

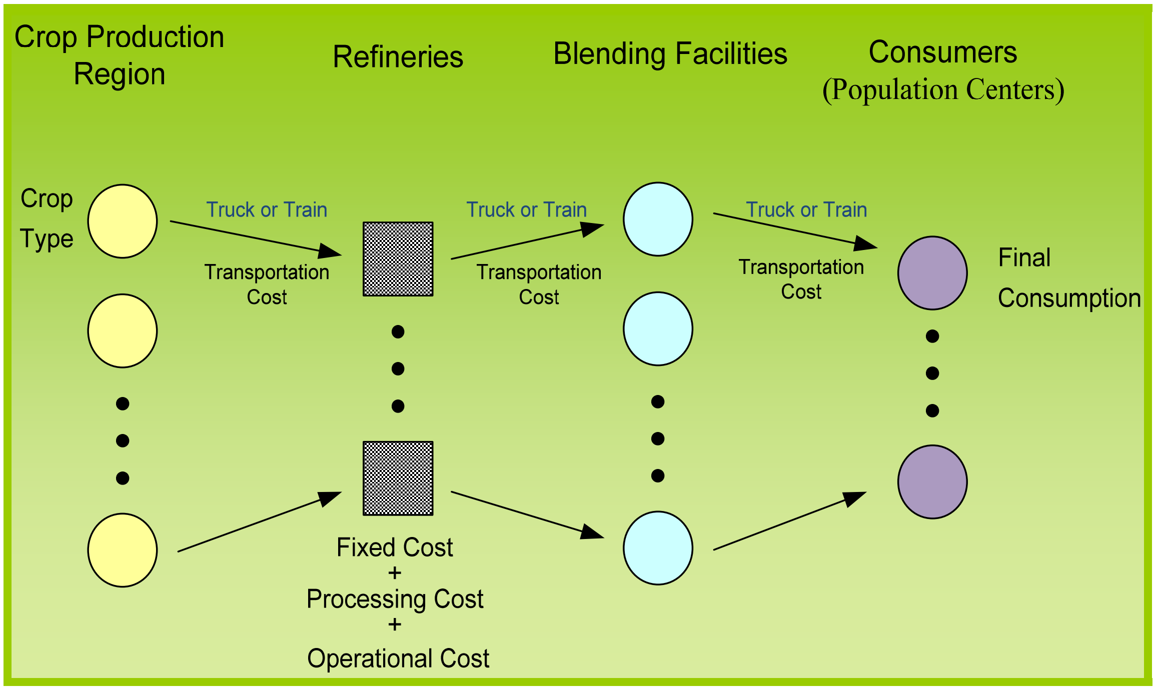
Ethanol becomes more competitive if DDGS and higher valued chemicals are produced as co-products. Several competing conversion technologies that enable the use of lignocellulosic biomass as biorefinery feedstock are under development, including gasification, pyrolysis, liquefaction, hydrolysis, fermentation, and anaerobic digestion. Finding the best mix can lead to significant cost reductions for the future biorefinery (Wright and Brown, 2007).

The challenge is to develop integrated models that incorporate the selection of the feedstock, farm, biorefinery site, size, and technology under market conditions as an instrument of decision-making. For instance, Eathington and Swenson (2007) have developed a GIS-based decision tool for the selection of optimal site, size, and technology of ethanol plants to assess different policy and economic scenarios, including biofuels-related job impacts, local demand, and growth of the industry. Building on our research on biofuels and land use in Illinois (Khanna et al., 2008a; Scheffran and Bendor, 2008) we are expanding this analysis by including modeling of optimal feedstock transportation and biorefinery location.

## 3. An Overview of the Model

The development of the future ethanol industry, including both production and distribution, involves several integrated decision layers that must be addressed simultaneously. These include: i) the type of processing facilities, their capacities, years in which they are built, and locations; ii) amount of raw materials (corn, stover, and perennial grasses) transported from production regions to biorefineries; and iii) amount of ethanol deliveries to blending facilities and then to final demand destinations. This is a typical transshipment problem with network flows including yes/no type facility location selection decisions (Dantzig and Thapa, 2003). We formulated the problem as a linear mixed-integer programming model where the transportation decisions are defined as non-negative variables while the decision to build a biorefinery in a given year and at a given location is defined as a binary variable. The capacity of each biorefinery is also defined as a nonnegative variable. A schematic representation of the problem is shown in Figure 1.

**Figure 1. A schematic representation of ethanol production and distribution**



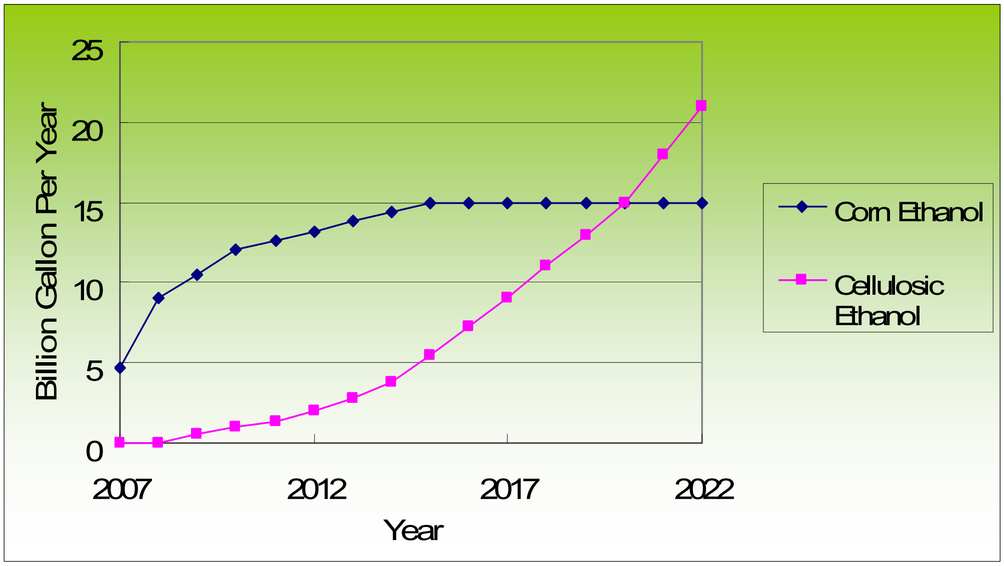
The objective of the model is to minimize the total cost of all operations, including the transportation costs of raw materials and the end product (ethanol), costs of processing, and fixed investment costs associated with building refineries, minus byproduct credits (namely the values of DDGS produced as a byproduct of corn ethanol processing and electricity generated by burning wastes of cellulosic biomass).

A supply constraint in the model, defined for each production region and each year, ensures that the amount of corn and biomass shipped from any given region to all biorefineries in the system cannot exceed the available supply in that region. An in/out constraint, defined for each processing facility and each year, restricts the amount of ethanol produced and shipped out by any biorefinery to the corresponding amount of raw inputs coming into that facility. The amount of ethanol produced by any facility is also restricted by the processing capacity of that plant specified at the time of construction, which is also determined by the model as a decision variable. The model allows expanding the capacity of a previously built biorefinery over time, but this may occur at additional investment costs. We assume that once a biorefinery is built at a given location and in a given year, then it remains operational in the following years throughout the planning horizon (i.e. closing and reopening the plant in a later year is not allowed). The capacity of any plant at construction time cannot fall below a minimum and cannot exceed a maximum capacity, both of which are specified a priori (based on the sizes of existing processing plants and capacities of the plants currently being built). We also restrict the capacity utilization in any processing facility to a specified minimum percentage of the construction capacity (if that facility is included in the system). The ethanol produced by all refineries (both corn-based and cellulosic) is delivered first to blending facilities (terminals) and then to final demand destinations after blending with gasoline. An in/out constraint balances the incoming and outgoing amount of ethanol to each blending facility. Finally, a demand constraint ensures that the ethanol demand of each demand location (specified a priori) is met.

The facility location component of the model identifies the optimal locations of both corn-based and cellulosic ethanol plants based on the transportation costs, fixed and variable costs associated with building and operating biorefineries. If a location is selected for a particular type of processing facility, then processing (up to the construction capacity) can occur at that location, otherwise no input/output can be delivered to/from that location. This is reflected in the model by a technical constraint relating the processing capacity variables to the location selection variables for individual plants.

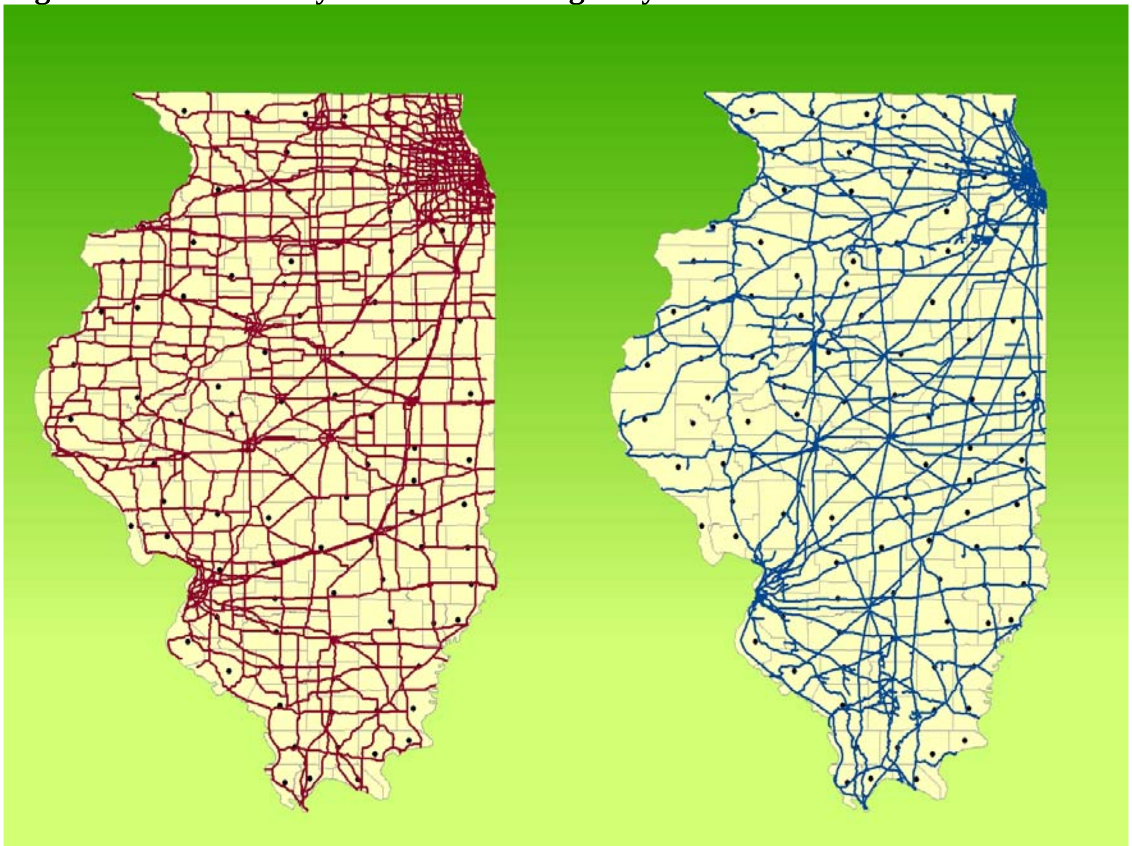
The model described above requires several sets of input data. The amounts of energy crops supplied by each production region are specified exogenously for each year of the planning horizon. These are pre-determined by use of the supply response model by Khanna et al. (2008b). Since the fermentation processes of cellulose and glucose vary significantly from each other, we consider corn-based and cellulosic ethanol plants separately with varying fixed costs, processing costs and other operational costs. We assume that the ethanol produced by all biorefineries is delivered to the existing terminals in Illinois where it is blended to gasoline. We used the centroids of the counties where existing terminals are located as ethanol transshipment points. Finally, based on the population shares of Illinois counties and the aggregate ethanol consumption target for the State, the ethanol demand of each county is specified for each year of the planning horizon. Therefore, in parallel to the growth of national ethanol production targets (Figure 2), the annual ethanol demands of individual counties also exhibit an increasing pattern throughout the planning horizon.

**Figure 2. Ethanol production mandates of the Renewable Fuel Standard**



The transportation costs between production regions and potential refinery locations, between refineries and blenders, and between blending facilities and final demand destinations (county centroids) are determined based on the minimum costs of delivery via available transportation modes (highway or railway, see Figure 3) through the multimodal transportation network, including any costs incurred from transshipment, loading/unloading and handling operations. The transportation costs are generated by shortest-path algorithms with shipping cost functions.

**Figure 3. Illinois county centroids with highway and railroad network**



Highway Railroad

The cost components at the biorefinery level include annualized fixed investment costs, processing costs, and other operational costs. The procedures and assumptions used for obtaining these cost figures will be discussed in the following section. The by-product credits are based on the current market price of DDGS and the value of electricity generated by burning processed biomass. Fixed conversion factors determine the amount of ethanol produced by each facility processing and converting corn and/or biomass into ethanol.

## 4. Model Implementation and Data

The model described above is applied to the State of Illinois for the period of 2007-2022, which is consistent with the time frame considered in the RFS program. Each of the 102 counties in Illinois is considered as a producer region that can supply one or more of the bioenergy crops. Each county centroid is assumed to be a candidate plant location where a corn-based biorefinery, or a cellulosic biorefinery, or both, can be built in any given year. Seventeen existing blending terminals in Illinois are considered, assuming that all ethanol produced in Illinois will be processed by those facilities. We also assume that 19% of the nation's ethanol targets, for both corn-based and cellulosic ethanol, would be produced and consumed in the State (based on the current share of Illinois in the total corn-based ethanol supply).

Several data sets are needed as model input, including the supplies of bioenergy crops, costs of transportation from production regions to plant locations and then to blending facilities and demand locations, and the costs for different types of ethanol plants. The procedures used to generate these data are explained below.

### *Supply of Bioenergy Inputs*

A key data set needed in the facility location model involves the spatial and temporal distribution of bioenergy input supplies, i.e., the amounts of corn and cellulosic biomass supplied by each county in each year of the planning horizon. We generated these by using the supply response component of the *Agricultural Policy Analysis Model (APAM*), a spatial and temporal resource allocation model for U.S. agriculture developed in the Department of Agricultural and Consumer Economics at the University of Illinois. In the present study we modified the model according to the particular purposes of this research and restricted its coverage to Illinois only. For the methodological and algebraic details of this model see Khanna et al. (2008).

### *The Multimodal Transportation Network and Cost Matrix*

The main criteria for qualifying candidate locations of biorefineries include accessibility to the transportation mode and sufficient water resources (necessary for ethanol processing). Most counties in Illinois have access to railroad and highways within county boundaries, and water is also widely available from major surface waters and aquifers. Hence, all counties are assumed to be a candidate site for future biorefineries. As an approximation we treat the centroid of each county both as an origin and destination of all types of freight.

Transportation costs for corn, biomass and ethanol are calculated based on the highway and railroad network provided by the Bureau of Transportation Statistics National Transportation Atlas Database. Using centroid connectors linking the centroids to their nearest node of the highway and railroad networks, the Dijkstra’s shortest path algorithm (Dijkstra, 1959) is used to determine the minimum network distance for each pair of centroids.

Railroad transportation has significantly lower per-mile variable cost, but transshipment through railroad usually incurs a higher fixed cost (Mahmudi et al., 2006) because of extra handling of the load (e.g., hauling, storage and unloading within the railroad terminal, for transshipment between truck and railcars). Initial fixed cost for railroad transportation is assumed such that the breakeven point of highway and railroad transportation is 200 km. The per-bushel-mile delivery costs of corn and cellulosic biomass are calculated for both truck and rail transportation, based on Sokhansanj et al. (2006). Similarly, we calculated the ethanol transportation costs per gallon-mile as suggested by Morrow et al. (2006).

### *Cost Data of Biorefineries*

Corn-based and cellulosic ethanol plants are associated with different cost structures. Refinery costs for each type of plant are divided into three main components: i) annualized fixed cost, which includes the cost of land allocated to the refinery physical structure (based on farmland prices and the size of required land), and the costs of construction and machinery investment; ii) processing cost, which is proportional to the capacity utilized (i.e. the amount of corn or cellulosic feedstock processed); and iii) other costs related to operational expenses, such as labor and administrative expenses, which are linked not to the utilization level, but to the capacity of the refinery. The cost parameters for corn based refineries are generated by the 'Dry Mill Simulator' component of Farm Analysis and Solution Tools (FAST) developed by Ellinger (2008) at the University of Illinois. These costs are based on the simulated performance of a 100 million gallon capacity corn ethanol plant. As the costs of cellulosic biorefineries we use the estimates by Wallace et al. (2005) for a 25 million gallon capacity plant.

### *Ethanol Demand*

The planning horizon of our analysis is 2007-2022. The mandated target for corn ethanol increases monotonically in the first half of this period and then remains constant, whereas the cellulosic ethanol demand constantly increases throughout the planning horizon. As mentioned earlier, we assumed that the State will produce and blend 19% of the national ethanol target. For simplicity, we assume that this share is the same for both corn-based and cellulosic ethanol and the biofuels from undifferentiated sources in the RFS mandates (5 billion gallons) will also come from cellulosic sources.

## 5. Model Results

Illinois is investigated in our case study as a pilot project because of the readily available input data and the State's important role in renewable energy production. The results presented below are of preliminary nature and should not be taken literally. This is the first step of a comprehensive modeling effort, which aims to address similar policy issues and prospects for the entire U.S. ethanol industry. Although being rather narrow in scope, the present application may have significant practical implications not only for Illinois but also for other major ethanol producer states.

Figure 4 shows the projected regional production of corn, corn stover, and miscanthus in the year 2022, which is used as exogenous input data by the transshipment-site selection model. A similar regional production data set is generated a priori by the supply response model (described in Section 4) for each year of the planning horizon. The model results presented below as well as the results obtained for the remaining years are driven mainly by these data. For space reasons here we present the results for 2022 only.

The optimum refinery locations that are consistent with the given input supplies are shown in Figures 5a and 5b for corn-based and cellulosic ethanol plants, respectively, along with the locations of the existing blending facilities and the top 10 major demand areas. Figure 5a reveals quite an expected result, namely corn-based biorefineries are located in those counties that are close to the major demand locations and also corn for ethanol is available at greater amounts. The situation for cellulosic biorefineries is similar. Although most of the large scale cellulosic refineries were located in southern Illinois, where much of the cellulosic biomass is produced, several biorefineries were built in the northcentral region, surrounding the greater Chicago area, supplying relatively large amount of corn stover. Besides the regional input availabilities, exact locations and sizes of the biorefineries are driven by the trade-off between costs of transportation of corn and cellulosic biomass from production regions to processing plants and transportation of ethanol from refineries to the major demand centers.

According to the model solutions, within the first three years of the planning horizon the number of corn-based biorefineries would grow from 11 in 2007 to 14 in 2009. (The number of refineries is actually the number of counties having at least one refinery. Some counties have multiple refineries, such as Peoria and Tazewell. The refinery capacity for those counties is the total capacity of all refineries located in the county.) After 2009, only one additional corn-based refinery is built (in 2015, see Figure 6). Six of the existing refineries increase their capacities (shown by the concentric circles in Figure 5a), which are in general small refineries. The three largest refineries (located in Central Illinois, namely in Macon, Peoria, and Tazewell counties) maintain their processing capacity. In order to satisfy the rising demand in the northern and northeastern counties, several new refineries have to be built in that region (Ford, Iroquois, Kane, and La Salle counties, all near the greater Chicago metropolitan area) while one large corn-based refinery is built in the southwest (Macopin county, near St. Louis). Two of those new northern refineries have the maximum capacity that we specified exogenously, namely 300 million gallons per year (this limit is based on the actual sizes of the existing plants; the largest corn ethanol plant in 2007 has the annual capacity of 274 million gallons, the ADM plant in Macon county). The average corn-based refinery capacity thus rises from 121.1 million gallons in 2007 to 200.0 million gallons in 2022.

In contrast, the number of cellulosic biorefineries increases steadily from zero (no plant exists in 2007) to a total of 18 plants in 2022 (Figures 5b and 6). This is also an expected result because of the increasing trend in the RFS targets for cellulosic ethanol production (Figure 2). The smallest cellulosic plant has an annual production capacity of 111.9 million gallons while the average plant size is 233.3 million gallons, higher than the average corn-based ethanol plant size. Five of those plants, all located in southern counties (Bond, Jefferson, Perry, Richland, and Washington), hit the maximum capacity limit (300 million gallons per year), while in the north two large scale cellulosic plants are built at near maximum capacity (in La Salle and Livingston counties, with 292.3 and 262.9 million gallons, respectively).

Table 1 displays some summary statistics for the minimum, average, and maximum sizes of the corn-based and cellulosic biorefineries in 2022. According to the model results there is no observable difference between the average distances corn and biomass are transported from production regions to processing plants. The procurement areas of individual corn-based and cellulosic biorefineries are shown in Figures 7a and 7b, respectively. There is no apparent relationship between the size of the procurement area and the plant size. This relationship depends on the amount of corn and biomass input availability in the areas surrounding a given plant. For instance, some large corn ethanol plants in central counties have relatively smaller procurement areas compared to the plants located in southern counties because the relatively abundant availability of corn for ethanol in those areas.

**Figure 4: Spatial distribution of projected (2022) biofuel feedstocks production in Illinois**

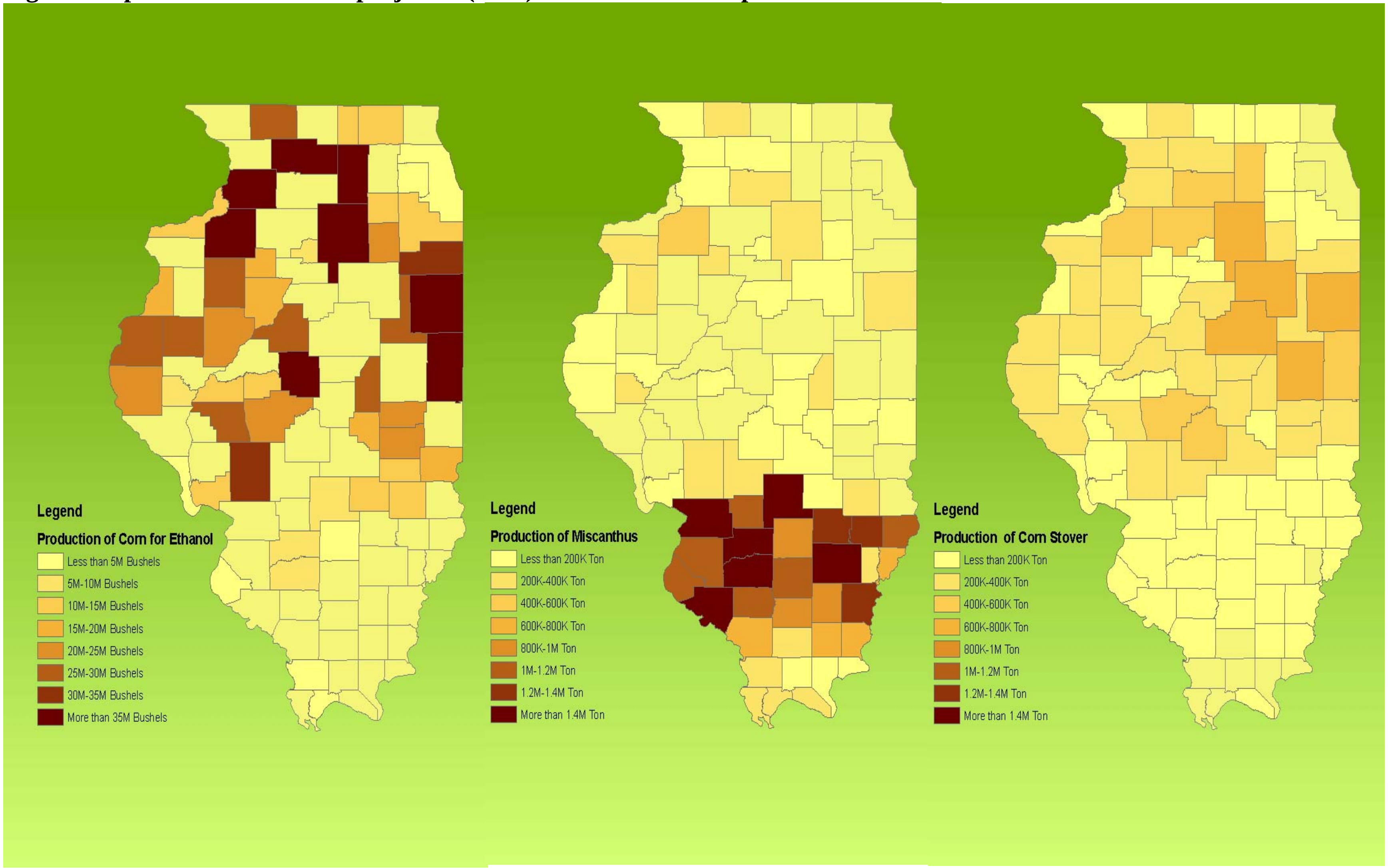


**Figure 5a. Optimal location of corn-based ethanol refineries in 2022**

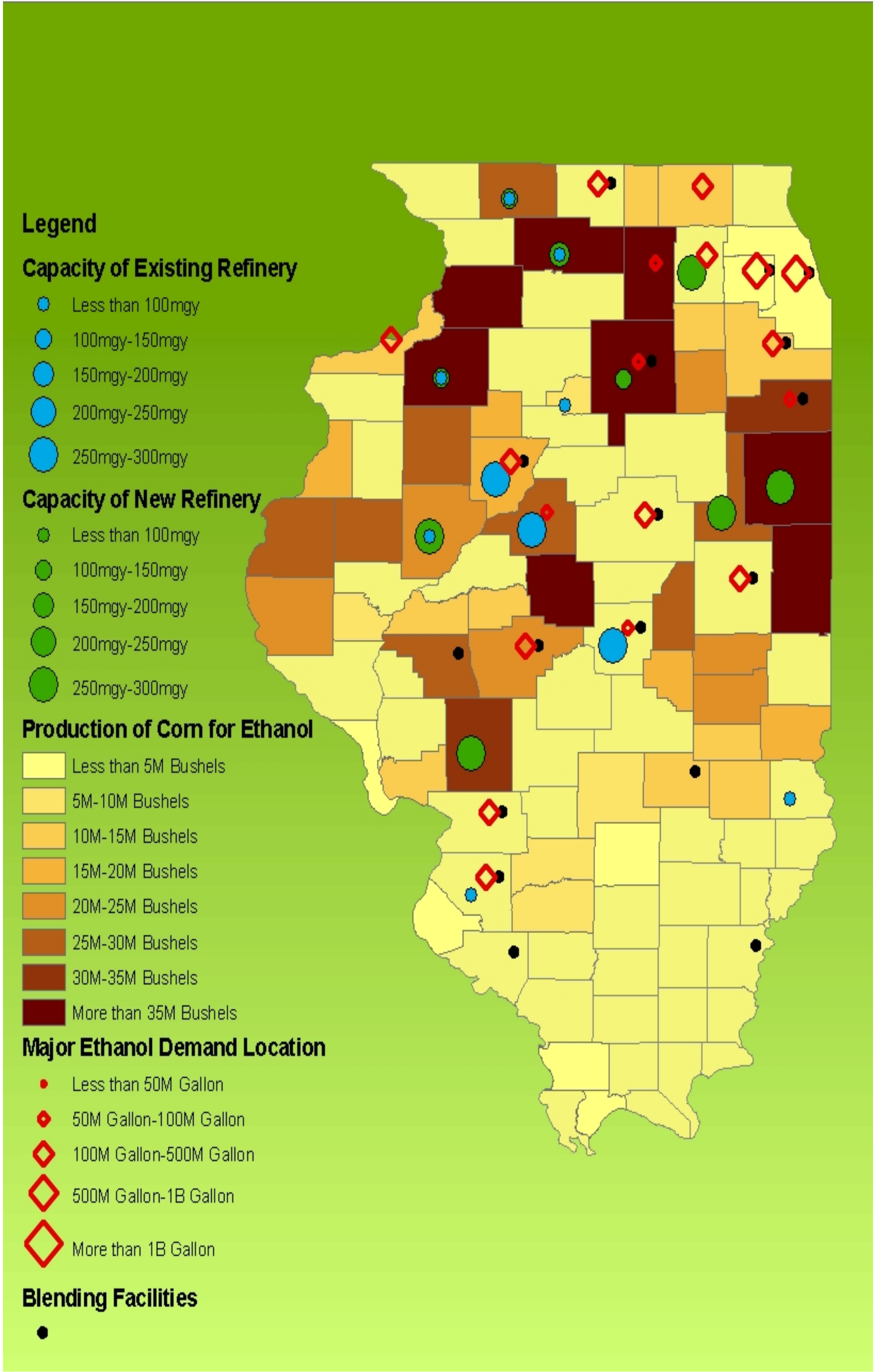


Figure 5b. Optimal location of cellulosic ethanol refineries in 2022

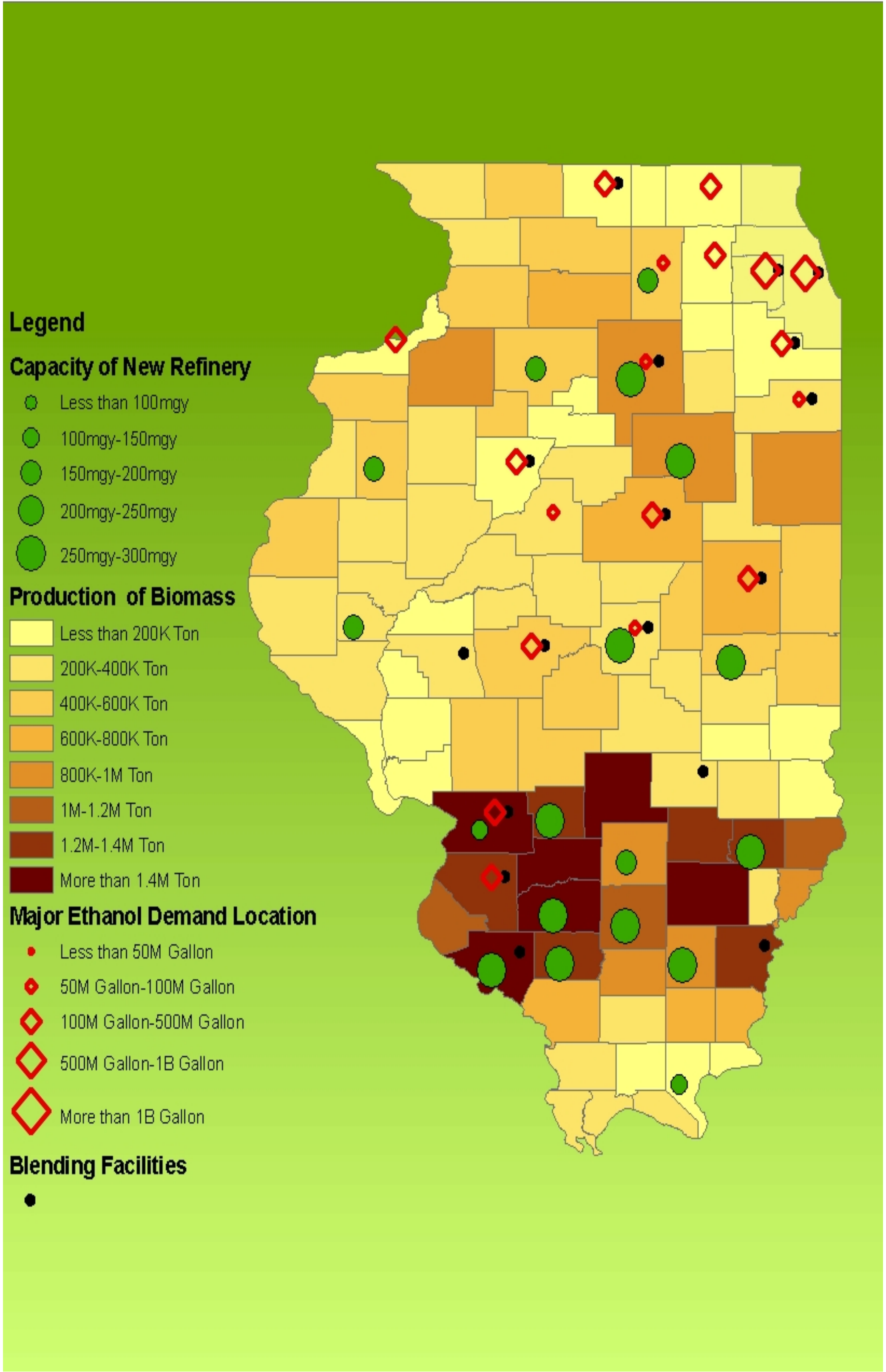


**Figure 6. Projected growth of Illinois ethanol industry during 2007-2022.**

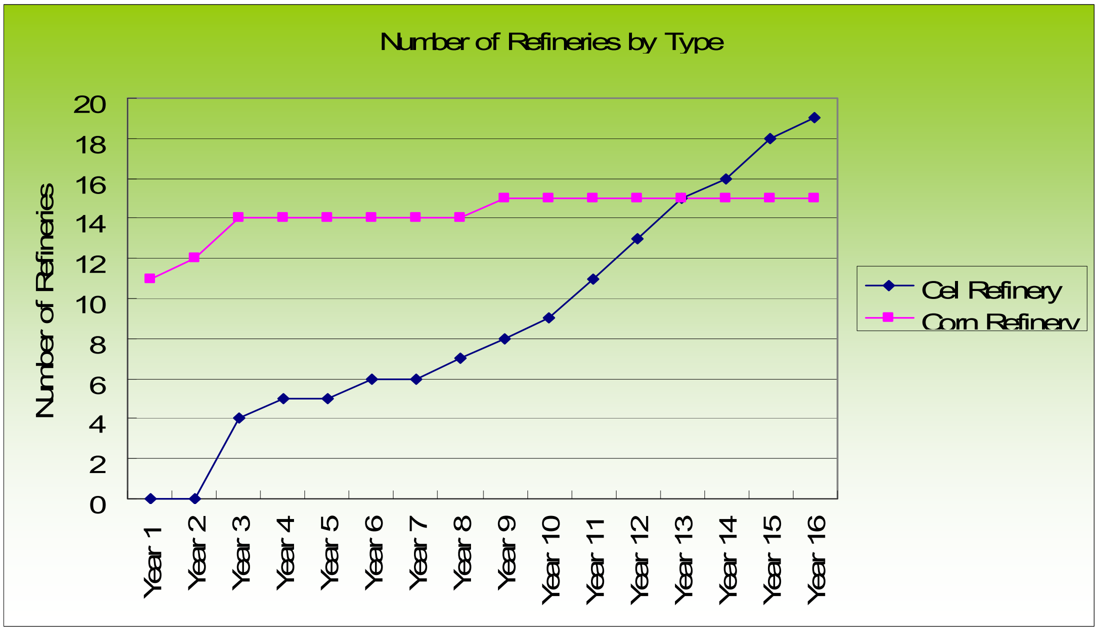


**Table 1. Summary statistics for biorefinery capacities and delivery distances**

| | Min | Average | Max |
|---|---|---|---|
| Capacity of Corn Refinery (mgy) | 78 | 200 | 300 |
| Capacity of Cel. Refinery (mgy) | 112 | 233 | 300 |
| Transportation Distance of Corn (km) | 9.6 | 61.2 | 200.1 |
| Transportation Distance of Biomass (km) | 12.3 | 57.3 | 193.4 |

**Figure 7a. Procurement areas for corn-based biorefineries (2022)**

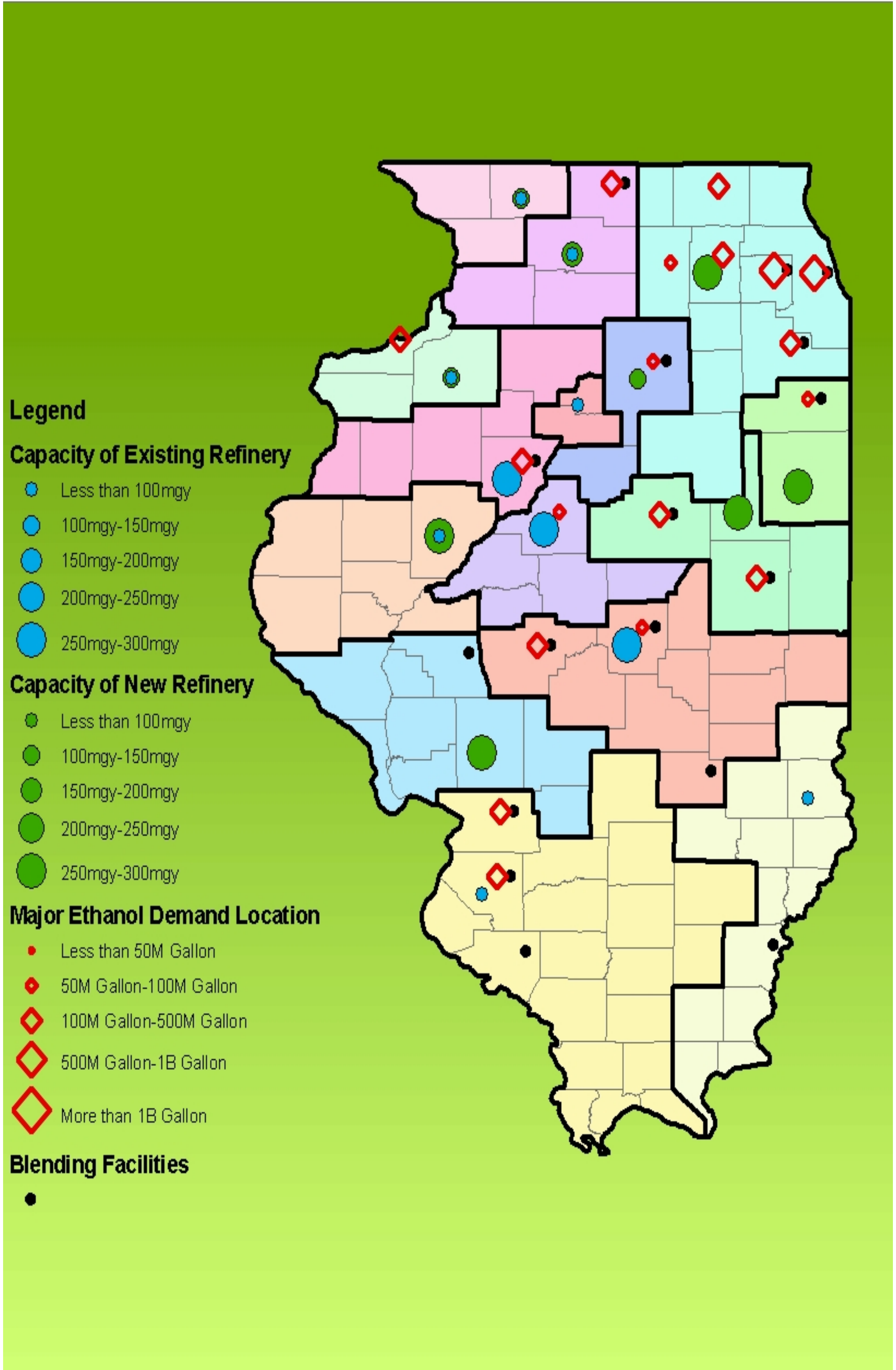
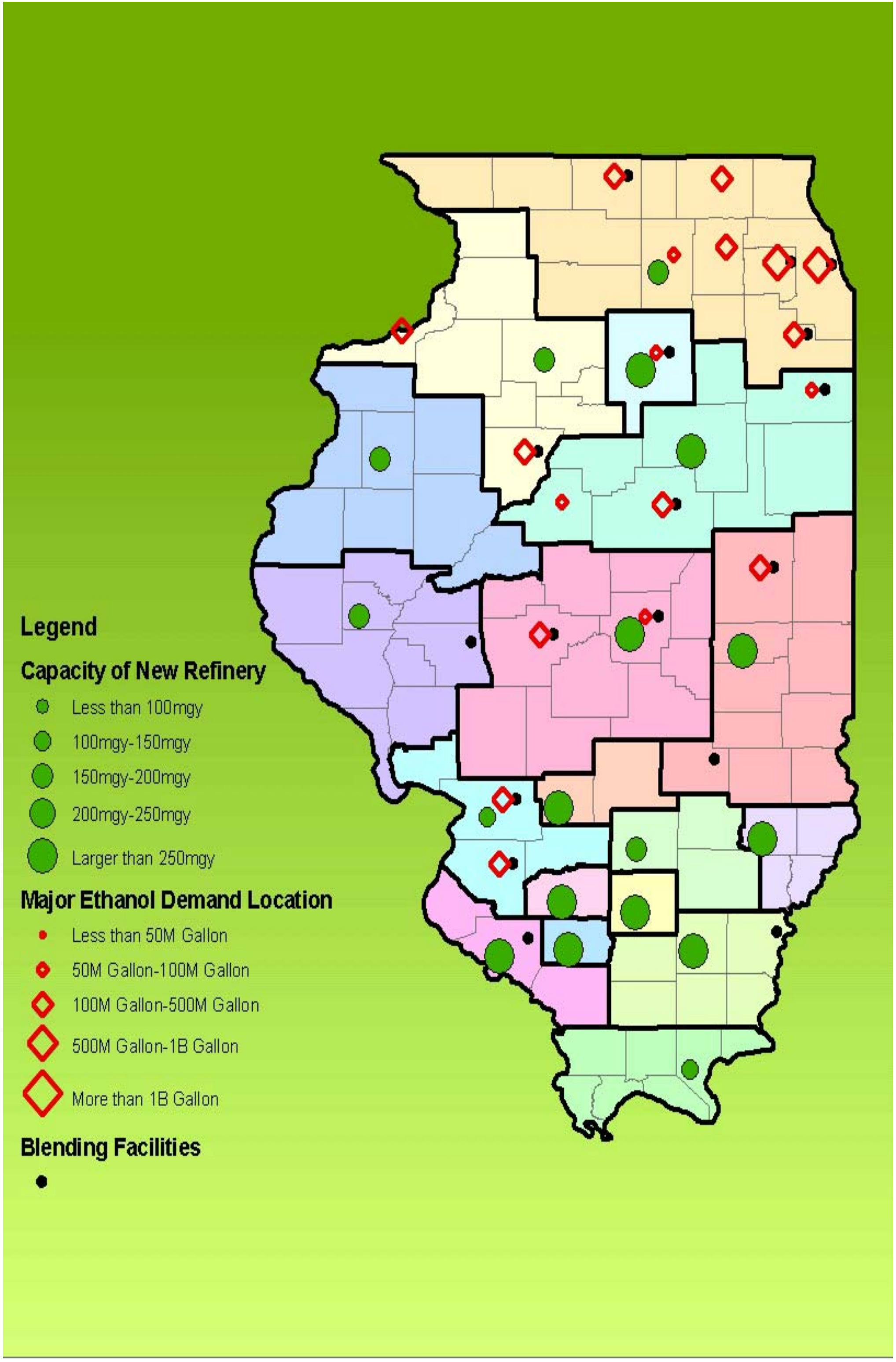


**Figure 7b. Procurement areas for cellulosic biorefineries (2022)**



## 6. Summary and Conclusions

In this article we presented the preliminary results of a mathematical programming model which aims to determine optimal locations of biorefineries in Illinois, delivery of bioenergy crops to biorefineries, and processing and distribution of ethanol produced in those facilities.

Our results show that four new and large scale corn ethanol refineries would be built in Illinois by the year 2022 and some of the existing plants would be expanded, increasing the average plant size nearly 50%. Most of the new and expanded plants are in the northern and northeastern counties, where the major demand centers are located and the increase in ethanol demand is relatively large. In contrast, 18 cellulosic ethanol refineries would be built by 2022. These refineries have generally larger capacities, with an average size of 233 million gallons per year, and they are located throughout the southern and northeastern counties where cellulosic biomass (miscanthus and corn stover) is supplied at larger amounts.

The model and application presented in this article is the first step of a comprehensive study that will address similar issues for the entire U.S. renewable biofuel industry. In the next step of our analysis the current coverage will be expanded to the Midwest region and later to a total of 28 states that are likely to supply corn and cellulosic biomass to the U.S. ethanol industry.

It would be ideal to solve the regional supply of bioenergy crops and optimal location of processing facilities simultaneously. However, the supply response model that provides input to the transhipment and facility location model used in the present study is already a very large-scale mathematical programming model. The model used in this study is also a very large-scale mixed integer programming model (including over 19,000 equations and 150,000 variables, 3,000 of which are binary variables). Solving mixed integer programs of this size is in general difficult (in this particular application solving the model took nearly six hours of processing time). Thus solving the two problems simultaneously would require a much larger-scale mixed-integer program which may be computationally intractable. This may be considered as a drawback of the present analysis. A remedy to this deficiency is to incorporate the optimal locations of biorefineries (obtained in the second stage) in the supply response model and solve it again with known refinery locations. This may lead to a near-optimal solution, if not exact optimal. We are in the process of employing this approach. Alternatively, instead of solving the model for each and every year of the planning horizon, the model can be solved only for a few benchmark years. This approach may result in an approximately optimal solution and may provide an equally valuable insight to policy makers as well as the future investors in the bioenergy industry.

## Acknowledgements

This article is based on the preliminary results of an ongoing project entitled “Economic and Environmental Impacts of Biofuels: Implications for Land Use and Policy,” under the sponsorship of the Energy Biosciences Institute and funded by BP Technology Ventures Inc. We would like to thank Drs. Madhu Khanna and Paul Ellinger, both in the Department of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign, for providing crop budgets and refinery investment and processing costs used here. The contents of

this report reflect the view of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of BP. This report does not constitute a standard, specification, or regulation.

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