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Spatial Optimization and Economies of Scale for Cellulose to Ethanol Facilities in Indiana

David Perkis, Wallace Tyner, Paul Preckel, and Sarah Brechbill[1]

Introduction

Ethanol output has grown significantly in recent years, both in Indiana and across the United States. With the desire to promote cleaner, renewable fuels, both the federal and state governments have instituted subsidies intended to increase output. In December 2007, Congress passed and the President signed the "Energy Independence and Security Act of 2007", which contains a renewable fuel standard (RFS) requiring 35 billion gallons of ethanol by 2022, of which at least 16 billion must come from cellulosic sources (U.S. Congress, 2007). Additionally, recent increases in gasoline prices compared to the historically low prices experienced in the United States likely will continue to put upward pressure on the demand for substitutes. As less expensive production technologies in ethanol manufacturing come online, ethanol substitution levels in fuel mixtures may continue to increase.

While there is much excitement about this ethanol boom and the potential for profit, there are also undesirable outcomes for participants in closely related markets. Specifically, with corn being the primary input for the ethanol production process, livestock producers dependent on corn as a feed ingredient have been negatively impacted by rising corn prices. Such factors also impact food markets as higher costs for feed are passed on to consumers of chicken, eggs, dairy, beef, and pork through higher prices. Thus, while ethanol shows great potential as a cleaner fuel that could decrease U.S. dependence on foreign oil, there are concerns about how increased ethanol output levels and the induced demand for corn will impact the affordability of certain dietary staples.

Given the potential for adverse price effects in food markets, there is a desire to develop alternative sources of the raw materials needed for ethanol production. Materials rich in cellulose show great potential as ethanol feedstocks. Not only can they be converted to the necessary precursors for ethanol production, but many cellulose sources are natural byproducts of other farming and manufacturing processes. Corn stover and wood trimmings are two common examples of byproducts of corn farming and logging respectively (Perlack *et al.*, 2005). Furthermore, some high energy sources of cellulose that would be grown as primary crops can be grown on terrains hostile to corn and other crops, thus in some cases being produced on currently uncultivated lands without having to displace food production.

Recently, the "Billion-Ton" study investigated the potential for U.S. grown biomass sources to provide enough ethanol to replace 30 percent of domestic fuel consumption (Perlack *et al.*, 2005). In short, the authors conclude this would be feasible, with cellulose based sources making up a substantial portion of the over 1.3 billion dry tons of biomass resources projected to be available for conversion to fuels.

The state of Indiana has benefited from the push for ethanol and other biomass based fuels. The large quantity of farmland dedicated to growing corn has made Indiana an attractive site for the construction of conventional corn to ethanol dry grind manufacturing facilities. With the push for alternative biomass to produce ethanol, it is useful to begin assessing how Indiana can position itself to take advantage of cellulosic materials if the Billion-Ton study projections are correct. The Billion-Ton study anticipates that 18.3 million dry tons of cellulose feedstocks would be available in Indiana given proper land utilization. As these sources are developed, and firms begin to construct facilities for conversion to ethanol, there will be many questions affecting the welfare of firms and citizens alike. For instance, where should manufacturing facilities be located and how large should they be? Which locations will best take advantage of the cellulose source materials with respect to minimizing costs? What impact will a potentially large network of facilities have on our roads and highways? What will be the impact of new manufacturing facilities and some newly cultivated land on the Indiana job market and the environment?

The intent of this paper is to begin to answer some of these questions and to provide a framework for follow-up studies.

[1] Perkis is a Ph.D. candidate; Tyner is a Professor; Preckel is a Professor; and Brechbill is a Graduate Student, all respectively, in the Department of Agricultural Economics at Purdue University, West Lafayette, Indiana.

Specifically, it seeks to determine an optimal spatial distribution of ethanol plants within the state of Indiana given the projections of biomass availability projected by the Billion-Ton study and detailed cost information for harvesting, storing, and shipping biomass products (Brechbill and Tyner, 2008). Additionally, this paper provides guidance regarding the optimal size of ethanol facilities based on economies of scale. One of the key assumptions is that conversion facilities will use all of the cellulose materials grown within Indiana, and only these materials, in the production of ethanol. This is acknowledged to be a strong assumption, but one which should not dramatically alter the findings of the study. Since crop costs grow with increased shipping distances one would expect that only crops near the borders would be shipped across state lines, and there is no reason to believe that more crops would be shipped in one direction or the other. It is therefore believed that the impact of this assumption on the conclusions should be small.

Projections of optimal plant locations have been made in the past. Notably, Nelson projected plant locations across Indiana for 40 equal output sites (Nelson, 1981). However, Nelson focused on agricultural residues without taking into account cellulose source crops which are specifically grown for conversion to ethanol. Additionally, Nelson made regional assumptions of harvest rates not required here due to the detailed county level data provided by the Billion-Ton study. Given expected residue and crop outputs in this data, a specific county level analysis can be performed by combining the yield data with inter-county distances and transportation costs. Additionally, this paper considers some of the larger throughput rates anticipated to benefit from economies of scale based on historical experience from fermentation of corn-based sugars (Dale and Tyner, 2006).

Another series of papers exemplified by English, Menard, and De La Torre Ugarte (2000) has a broader scope by investigating the impact of corn stover and other biomass output expectations on the economies of several corn-growing states including Indiana, even including output prices and other factors for sensitivity analyses. However, the authors focus on economy wide results at the state level as opposed to county level output decisions, the main focus of this paper's spatial distribution plan. Additionally, this paper utilizes the most recent county yield estimates (Billion-Ton study) and biomass cost information (Brechbill and Tyner, 2008) for Indiana.

This paper will focus on the anticipated 14.6 million dry tons per year of corn stover and switchgrass available to be processed by biochemical conversion (Perlack *et al*., 2005). This process breaks the cellulose down to simple sugars using enzyme hydrolysis, and then ferments the sugars to produce ethanol. Enzymatic hydrolysis and fermentation are currently used to convert corn to ethanol and would be conducive to the cellulose sources considered in this study. These sources are corn stover, an agricultural residue from corn production, and switchgrass, a high energy primary crop (USDOE, 2006). In addition to considering the optimal spatial distribution and size of plants given the projections of the Billion-Ton study, an additional scenario will be tested making more conservative assumptions with respect to collection rates of corn stover, as well as land utilization and biomass conversion rates for both corn stover and switchgrass.

Methodology

Focusing on biochemical conversion facilities, it is assumed producers can utilize one of two plant sizes, a large plant (100 million gallons/year) or a small plant (50 million gallons/year), in order to convert Indiana's projected corn stover and switchgrass into ethanol. It is also assumed that this conversion process will be robust enough to handle either of the two feedstocks in varying proportions within one plant. While this might assume an optimistic level of manufacturing robustness, the key components of each material which are hydrolyzed are similar. It seems feasible that enzyme mixtures, as well as technological modifications of the crops themselves, could be developed to provide such robustness. Finally, the following simplifying assumptions are made: (1) each county will have at most one manufacturing facility, (2) the construction and operating costs are identical for each plant except for the biomass raw material costs and an economy of scale factor which will be represented by an added per gallon cost for the smaller plant, and (3) cost differences exist only in the growing (switchgrass), harvesting, and transportation costs of the biomass raw material mixture which is input into the process.

The objective for firms is to maximize their profit, which is revenue less costs. Since plants of modest size are assumed, individual plants should not have an impact on the price of ethanol and unit revenues are thus assumed to be identical for each site regardless of its location. Thus, to maximize profits, firms must focus on minimizing their costs. Since construction and operating costs are assumed to be identical for each site, optimization focuses on the production, harvesting and transportation costs of biomass. Specifically, how do the relative costs for each crop impact the choice of the input mix in order to minimize costs.

This model will assume that costs are minimized over all sites, even though each site may be owned by a different enterprise. While this appears to be more of a central planning solution than one of competitive firms maximizing profits, the general results should be similar, with plants locating based on the comparative advantages relative to surrounding counties (Nelson, 1981). In reality plants will likely contract for cellulose raw materials before the plant is even constructed. The early plants will locate in least cost areas and will contract for available raw material in those areas. Since the purpose of this exercise is to determine the use of all biochemically converted cellulose sources, it is assumed that the price of ethanol is sufficiently high that all plant sites are constructed and able to make a positive profit. Otherwise, not all sites would be constructed and continue operating. As sites are constructed to convert the total supply of materials, firms acting competitively will locate in order to minimize total costs.

The amount of dry biomass shipped between counties is designated X_{ijk}, where i is the set of counties where biomass is produced, j is the set of counties where ethanol is potentially produced, and k is the set of biomass feedstocks (corn stover and switchgrass). The relevant parameters for the cost minimization model are as follows:

p_k – production cost for biomass feedstock k ($/dry ton shipped with profit)

s_k – fixed shipping cost for biomass feedstock k ($/dry ton shipped)

f – freight rate for shipping biomass ($/dry ton shipped/mile)

d_{ij} – distance from county i to county j (miles)

C^p – added plant cost for a 50 Mgal facility (reflecting diseconomies of scale)

N – total plant capacity needed (100 Mgal/year)

l – fractional storage loss of biomass feedstock

b_{ik} – amount of biomass k produced in county i (dry tons/yr)

c_k – million gallons of ethanol per dry ton of biomass

The binary (0-1) variables I_j^{50} and I_j^{100} represent the number of 50 million and 100 million gallon ethanol plants respectively in county j, and the model is optimized by minimizing the total cost C as follows:

$$\min_{x_{ijk}, I_j^{50}, I_j^{100}} C = \sum_i \sum_j \sum_k \left(p_k + s_k + fd_{ij}\right) x_{ijk} + \sum_j I_j^{50} C^p$$

$$\frac{1}{2}\sum_j I_j^{50} + \sum_j I_j^{100} = N \quad \text{subject to:} \qquad (1)$$

$$I_j^{50} + I_j^{100} \le 1 \text{ for each j} \qquad (2)$$

$$\sum_j x_{ijk} \le (1-l) b_{ik} \text{ for each k and i} \qquad (3)$$

$$\sum_i \sum_k c_k x_{ijk} \ge 50 I_j^{50} + 100 I_j^{100} \text{ for each j} \qquad (4)$$

$$x_{ijk} \ge 0 \text{ for each i, j, and k} \qquad (5)$$

$$I_j^{50} = 0,1 \text{ for each j} \qquad (6)$$

$$I_j^{100} = 0,1 \text{ for each j} \qquad (7)$$

The optimization problem has several constraints. Constraints 2, 6, and 7 imply that any county can have at most one plant of either size, 100 Mgal or 50 Mgal, and that fractional plants are not permitted. Constraint 1 requires that the total amount of ethanol produced will exactly exhaust the feedstock resource base. Finally, constraints 3, 4, and 5 require that the amount of biomass supplied by a county cannot exceed the amount available from the farms in that county after taking collection/storage losses into account, and the amount of biomass supplied to each manufacturing site must be sufficient to cover the production level. The problem is implemented using GAMS version 22.5 (Brooke *et al*, 2005).

To determine the sensitivity of the model to biomass availability and total statewide ethanol output levels, several of the strong assumptions of the Billion-Ton study are relaxed in a second application of the model, with each adjustment of assumptions resulting in lower ethanol yields for Indiana in what is considered a more conservative scenario. For instance, our base case assumes that all cropland is managed with no-till methods. When this assumption is relaxed, corn stover recovery rates drop from 70 percent to 52.5 percent (Table 1). Additionally, land utilization rates for the base case are assumed to be 100 percent whereas a rate of 75 percent in the second application recognizes that land owners may choose not to participate. Finally, conversion rates are decreased in the second application to reflect technical inefficiencies which are likely as manufacturing facilities begin to convert cellulosic biomass to ethanol for the first time (Tiffany, 2007).

Experience has shown that corn dry grind facilities are typically sized between 20 and 100 million gallons, with plants producing at or over 80 million gallons reaping most of the economies of scale associated with capital expenditures (Dale and Tyner, 2006). On a dry cellulosic biomass input basis, there is some evidence suggesting that economies of scale might be optimized when crossing over 2,000 metric tons per day, roughly equating to 65 million gallons per year (Huang *et al*., 2006). The plant sizes of 50 and 100 million gallons are chosen for simplicity. Aside from the belief that these will aptly represent the low and high economy of scale regimes, the fact that 100 is divisible by 50 provides some interpretive benefits to the model. Namely, investors deciding upon a single 100 Mgal plant or two 50 Mgal plants will have to weigh the tradeoffs between the economy of scale benefits of a larger plant and the reduced transportation costs associated with distributing production sites more broadly.

Given these plant sizes, assumed conversion rates, and the resource constraints, the maximum amount of ethanol expected to be produced in the base case is 1,050,000,000 gallons per year (Table 1). This number is very high compared to estimates developed in other papers which apply further constraints beyond the Billion-Ton study based on several present day realities. The recent work of Brechbill and Tyner (2008) is one example. Using the assumptions of the second application will allow for the effects of biomass density to be

Table 1. Indiana Ethanol Supply Capabilities from Major Cellulosic Sources				
	Billion-Ton Projection		Conservative Estimate	
	Corn Stover	Switchgrass	Corn Stover	Switchgrass
Projected Yearly Dry Tons of Biomass	9,887,958	5,348,497	6,206,723	5,348,497
Corn Stover Clearance (%)	70%	N/A	52.5%	N/A
Land-Use Rate	100%	100%	75%	75%
Adjusted Yearly Dry Tons of Biomass	9,228,761	5,348,497	3,258,530	4,011,373
Storage Losses	8.4%	8.4%	8.4%	8.4%
Ethanol Conversion (gal/dry lb biomass)	81.4	79.0	69.7	67.6
Volume Ethanol (mil gal/year)	688	387	208	248
Total Volume Ethanol (mil gal/year)	1,075		456	
Total Ethanol Assumed (mil gal/year)	1,050		450	

Sources: Projections are taken from the Billion-Ton study with no-till methods, adjusting for 70 percent corn stover harvest rate as opposed to 75 percent. Conservative estimates are taken from Billion-Ton study with current tillage methods, adjusting for 52.5 percent corn stover harvest rate as opposed to 75 percent. Ethanol conversion figures are taken from McLaughlin *et al*., 1999 and Spatari, Zhang, and Maclean, 2005 for the projects and from Tiffany, 2007 for the conservative estimate. Storage losses are calculated (see notes for Table 2).

tested, as 450,000,000 gallons are expected to be produced annually given the more conservative estimates of this scenario.

The costs being minimized are a combination of raw material costs, transportation costs, and economy of scale costs (the added cost of operating a small plant). Because corn stover is a residue, the cost of growing corn stover is only the marginal cost of additional fertilizer applied because of nutrients lost when the stover is removed. For the base case, harvesting, handling and storage costs are added, taking storage losses and a 15 percent profit premium into account, to provide a product cost of $33.68 per dry ton of shipped material (Table 2). Harvesting costs assume a corn stover clearance level of 70 percent, with 30 percent remaining on top of the soil past the harvest. Bales are net wrapped to minimize costs during handling. Fixed and variable transportation charges are applied at a rate of $2.20 per dry ton and $0.15 per dry ton-mile respectively. Miles are measured as the distance between the county of the farm and the county of the

Table 2. Raw Material and Transportation Costs for Harvested Crops and Shipped Product				
	Billion-Ton Projection		Conservative Estimate	
	Corn Stover	Switchgrass	Corn Stover	Switchgrass
Seeding & Establishment Costs ($/harvested dry ton)	0	4.51	0	4.51
Equipment Cost ($/harvested dry ton)	1.86	1.31	1.86	1.31
Fertilizer/Herbicide Costs ($/harvested dry ton)	15.63	15.41	15.63	15.41
Harvest Costs ($/harvested dry ton)	5.25	2.88	4.85	2.88
Handling Costs (net wrap) ($/harvested dry ton)	3.97	3.97	3.97	3.97
Storage ($/harvested dry ton)	0.11	0.09	0.11	0.09
Land Rent ($/harvested dry ton)	0	14.00	0	14.00
Total Raw Material Cost ($/harvested dry ton)	26.83	42.17	26.43	42.17
Storage Losses (loss %)	8.4%	8.4%	8.4%	8.4%
Profit (% of raw material cost)	15%	15%	15%	15%
p_k: Total Raw Material Cost ($/shipped dry ton w/profit)	33.68	52.95	33.18	52.95
s_k: Shipping Costs, Fixed ($/shipped dry ton)	2.1962	1.8919	2.4466	1.8919
f: Freight Costs, Variable ($/shipped dry ton-mile)	0.1498	0.1498	0.1498	0.1498

Sources: Raw material costs for corn stover and switchgrass, as well as shipping charges and storage/transportation losses, are taken from a concurrent Purdue University working paper (Brechbill and Tyner, 2008). All costs account for residence times of harvesting, storage, and transportation.

plant. This cost takes into account the round trip between the farm and the manufacturing facility. Similar estimates using the conservative assumptions of the second case can also be found in Table 2.

Switchgrass is grown as a primary crop, and therefore requires seeding and establishment costs not present for corn stover. Additionally, a land rental fee is assumed to represent the value of the land's next best alternative use. Adding these costs together with the harvest and storage costs, and assuming a 15 percent profit premium, results in a raw material cost of $52.95 per shipped ton. Shipping costs are then added in an identical manner to that of corn stover (Table 2).

Because transportation costs are based on the mileage between a farm in one county and a potential manufacturing site in another county, the distances between counties are required as part of the optimization problem. In this analysis, the distances between county seats are utilized as a proxy for transportation distances. Latitude and longitude coordinates were obtained for each county seat using arcGIS. Using these measures, the Haversine formula was implemented to determine the distance between county seats on the globe (Sinnott, 1984). Given that this method would produce no shipping charges for transit within a county, a distance of 10 miles is assumed for intra-county transportation.

As previously mentioned, a cost factor C^p is added for each facility, with the value equaling zero for a 100 Mgal plant and positive for a 50 Mgal plant. This factor represents the added cost of producing at a low output level and not taking advantage of the economies of scale. For instance, when producing ethanol from corn, the savings in capital expenditure is calculated to be on the order of $0.23 or greater when doubling the plant size from 50 to 100 million gallons (Dale and Tyner, 2006). Since C^p is included as an annual operating cost, it will have to be converted to a capital cost by implementing a financial analysis similar to those performed on corn ethanol plants. Specifically, what level of capital savings provides the same net present value (NPV) benefit as saving the added cost of C^p by operating at a larger level? Assumptions for the financial analysis are listed in Table 3.

It is expected that if C^p is set to zero for a 50 million gallon facility (i.e., no economies of scale), that only small facilities will be used in an attempt to spread production more broadly over the state and minimize shipping distances. As C^p increases, the ideal spatial distribution of facilities should include some larger plants as the benefits of running a large scale operation would outweigh the costs of longer shipping routes. Thus, the model will be optimized over various levels of C^p to determine at what level of diseconomy of size makes it preferable to utilize larger plants, either occasionally or throughout the state.

Results

The increase in capital expenditure needed to make large plant sizes economical is modest (Table 4). At a total capital investment (TCI) level just under $0.07 per gallon, at least three large plants are needed to minimize costs. Increasing TCI in very small increments results in optimized scenarios with more and more large plants until costs are minimized by operating as many large plants as possible (ten to be exact) at TCI levels of almost $0.17/gallon and higher.

Based on this cost minimization approach, a large number of counties chosen for the biochemical production of ethanol from cellulose sources (corn stover and switchgrass) are located in the top half of the state independent of the economies of scale. As Figure 1 demonstrates, when no economies of scale are assumed, all ethanol is produced using 50 million gallon plants, a majority of which are located in the northern half of Indiana, with roughly one third being located in the southern half (using Indianapolis in Marion County as an unofficial dividing line between the two halves). While the counties are spread out within regions, there are still several instances of neighboring counties having facilities, especially in the northwest region of the state. Several plant locations in the northwest tend to be the lowest cost operations in the state (Figure 1).

With respect to crop usage, there is a strong correlation between corn stover use and cost. As demonstrated by Table 5, which ranks the counties by corn stover use, the top five plants with respect to reducing costs all utilize the highest levels of corn stover. In fact, the ranking of cost reduction is almost identical to the ranking of corn stover usage, with plants incurring greater costs as they switch from corn stover to switchgrass. In fact, the highest cost plants are the three plants located in the southwest portion of the state (Figure 1)

Table 3. Assumptions for Financial Analysis to Annualize Economies of Scale[a]

Assumption	Value
Project Years	25
Start-Up Years/Operating Years	2/23
1st/2nd Year Capital Investment Split	40% / 60%
Investment Hurdle Rate (Real)	8.7%

[a]Would cover increased shipping distances associated with larger plant sizes.
Source: Assumptions taken from dry mill model (Dale and Tyner, 2006)

Table 4. Operating Cost Savings and Their Economy of Scale Equivalents[a]

Operating Costs, c_j^p ($/gal ethanol)	Economy of Scale[b] in capital Investment $/gal ethanol	Target Number of 100 Mgal Plants, High IN Output	Target Number of 100 Mgal Plants, Moderate IN Output
$0.000	$0.000	0	0
$0.003	$0.034	0	0
$0.006	$0.067	3	0
$0.009	$0.101	5	0
$0.012	$0.134	8	0
$0.015	$0.168	10	1
$0.018	$0.201	10	2
$0.021	$0.235	10	2
$0.024	$0.268	10	3
$0.027	$0.302	10	3
$0.030	$0.335	10	4
$0.033	$0.369	10	4
$0.036	$0.402	10	4

[a]Lead to the transition from 50 million gallon facilities to 100 million gallon facilities for the production of cellulose source ethanol.

[b]Economies of scale for ethanol from corn are over $0.23/gallon based on scaling up from a 50 Mgal facility to a 100 Mgal facility (Dale and Tyner, 2006).

and are the only three plants to use over 60 percent switchgrass.

This trend carries over into the larger economies of scale scenario in which as many plants as possible are of the large variety (Figure 2). In this scenario, the top four plants in corn stover use are in northwest portion of the state. The two highest cost plants are located in the southwest and utilize significant levels of switchgrass.

By relaxing some of the assumptions from the Billion-Ton study, less cellulosic biomass is produced and collected in each county, resulting in a drop of total ethanol produced in Indiana. In this case, the highest cost and lowest cost plants are located in the same regions as the base case with the low cost plants still using mostly corn stover and the high cost plants using the most switchgrass (Figures 3 and 4). However, with the lower density of cellulosic biomass materials, greater economies of scale are required to allow for large plant sizes to be produced. While economies of scale of $0.17/gallon ethanol allow for most plants to be converted to 100 Mgal facilities in the base case, this value only allows firms operating under conservative assumptions to consider such facilities in the low cost regions, with the full conversion to 100 Mgal facilities occurring at $0.33 / gallon ethanol (Table 4).

Discussion

The state of Indiana has a large potential for producing biomass sources containing cellulose, which can be biochemically converted to ethanol. This analysis optimizes the overall utilization costs of these biomass resources through the selection of optimal plant locations and sizes. However, this analysis is really a two-step optimization problem. The first step is performed by the Billion-Ton study, in which land utilization is optimized based on crop potentials and current land use. For instance, since switchgrass is not a residue but a primary crop, its production requires ground preparation, seeding, and land rental fees making it more costly to grow than corn stover which is a residue of corn. Currently it would be foolish to grow switchgrass on land capable of producing corn, as both corn and corn stover can be used to produce ethanol. Therefore, switchgrass would be chosen for lands less economically suited for producing corn. These factors are taken into account in the land utilization choices of the Billion-Ton study, which are therefore taken as a given, having already balanced the trade-offs between costs and benefits. While there are likely still arguments to be made for alternate land utilization strategies, they should not affect the general conclusions of this analysis.

From the analysis presented here, it is clear that current costs would dictate a high concentration of facilities within corn stover producing areas. There is ample corn stover in the

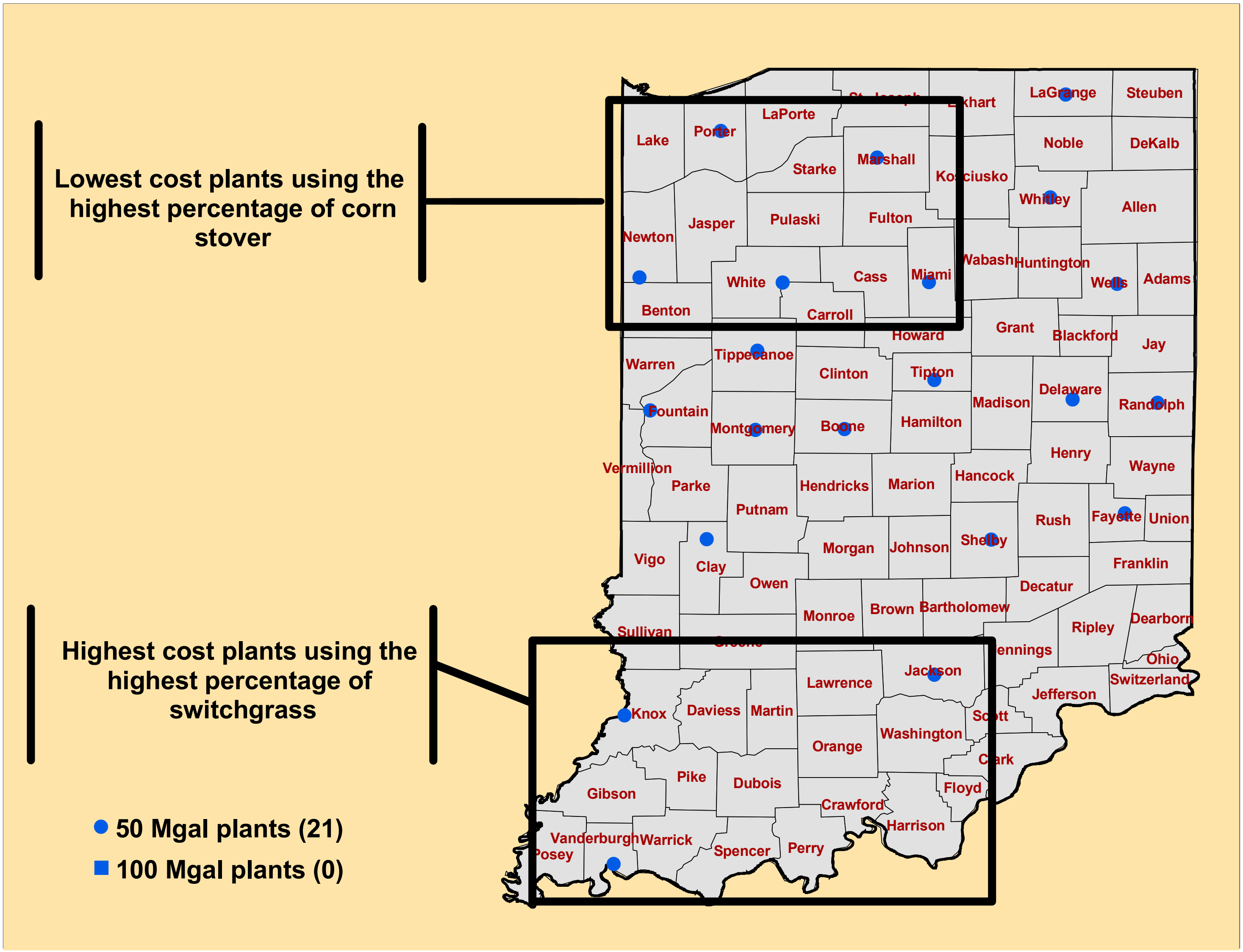

Figure 1. Optimal Counties of Manufacturing Sites for the Biochemical Conversion of Corn Stover and Switchgrass to Ethanol Based on Billion-Ton Study Projections and No Economies of Scale

northwest to support a proportionally large number of facilities, regardless of the assumptions. In areas where the land is better suited to growing switchgrass and corn stover is in short supply, raw material costs are higher due to the added costs of establishing, seeding, and renting the land. The facilities projected for two counties in the highlighted region of the southwest are prime examples, with the highest switchgrass level usage, very low corn stover farm yields, and the highest cost facilities.

If the assumed cellulosic source yields from the Billion-Ton study hold true, it is likely large plant sizes of 100 million gallons or more will minimize costs. The model predicts that economies of scale for TCI above \$0.17/gallon ethanol would provide a sufficient incentive to outweigh increased shipping costs, and economies of scale for corn are at least \$0.23 / gallon ethanol. Assuming that technological developments lead researchers to enzymes which can chemically break down cellulosic materials into fermentable sugars, the actual process differences between corn and cellulose conversion are (1) preparation of the material for the enzymatic conversion and (2) processing and use of the byproducts. If neither of these cause large differences in the cost structures for corn and cellulosic conversion, and assuming that yields are high enough to match the Billion-Ton study projections, then there likely would be more larger plants as suggested in Figure 2. However, another unknown is whether or not there will be diseconomies of scale due to the requirement for handling very large amounts of cellulosic materials. For example, a 100 million gallon plant with a yield of 70 gallons per ton operating 360 days per year 24 hours per day would need 3968 tons of raw material per day. Using 13 ton trucks, that amounts to over 300 trucks per day or 12 per hour (Popp and Hogan, 2007).

To the degree that the assumptions of the Billion-Ton study do not hold true, the results of the conservative scenario may be more applicable for predicting the spatial distribution

Table 5. Cost Ranking and Biomass Percentages for Each Plant Site Based on Cost Minimization Procedure[a]

Plant Location	Low Cost Ranking[b]	% Ethanol from Corn Stover[c]	% Ethanol from Switchgrass
Marshall	2	99%	1%
Porter	4	97%	3%
White	3	97%	3%
Newton	1	95%	5%
Miami	5	94%	6%
Shelby	6	85%	15%
Tipton	7	83%	17%
Tippecanoe	8	76%	24%
Boone	9	76%	24%
Randolph	10	64%	36%
Lagrange	11	63%	37%
Montgomery	13	61%	39%
Wells	12	59%	41%
Whitley	16	51%	49%
Delaware	15	51%	49%
Fountain	14	49%	51%
Fayette	17	48%	52%
Clay	18	41%	59%
Knox	19	38%	62%
Vanderburgh	20	24%	76%
Jackson	21	24%	76%

[a]Billion-Ton assumptions without economies of scale.
[b]1 is the lowest cost plant and 21 is the highest cost plant.
[c]While plants using close to 90 percent or higher of corn stover are likely to operate with this single input, no such restriction was placed on the model.

and size of plants. For instance, if no-till methods are not implemented or a significant proportion of land owners do not employ their land in the production and harvesting of cellulosic biomass, then economies of scale of a 100 Mgal facility may not be sufficient to cover the costs associated with the larger shipping distances which would be required to collect material. In this scenario, if economies of scale were similar to corn, it is likely that one or two large plants could be supported in the corn stover rich part of Indiana, with smaller plants filling out the rest of the state (Table 4).

An assumption was made pertaining to the robustness of manufacturing facilities and their ability to handle various proportions of the two major biomass sources. It may turn out that facilities are constructed to handle only a single biomass feedstock. However, this should not alter the main conclusions presented here. A firm wanting to convert only corn stover would most likely locate in the northwestern part of the state where corn stover supplies are ample, while a firm focusing on switchgrass conversion would likely locate in the south. All the crops should still be utilized based on the assumption that ethanol prices are high enough to yield any facility operator a positive profit, regardless of the crop type used. Producers utilizing higher cost crops would simply have lower profits.

Finally, the issue of naming specific counties as being "ideal" for ethanol production facilities could be misleading. Other than anticipated crop yields and distances between counties, no data was collected on any distinguishing characteristics of the counties such as infrastructure, local government incentives, or industrial zoning. A small change in raw material production costs or shipping charges could easily shift the ideal location for a facility into a neighboring county. The important conclusions here pertain to the quantity and spatial distribution of plants within certain regions of the state and the costs of operating in those regions more than the exact counties where sites might be located in the future. Additionally, as switchgrass and other primary cellulosic sources continue to be developed and optimized for the specific purpose of ethanol production, further shifts in ideal plant locations are likely to occur.

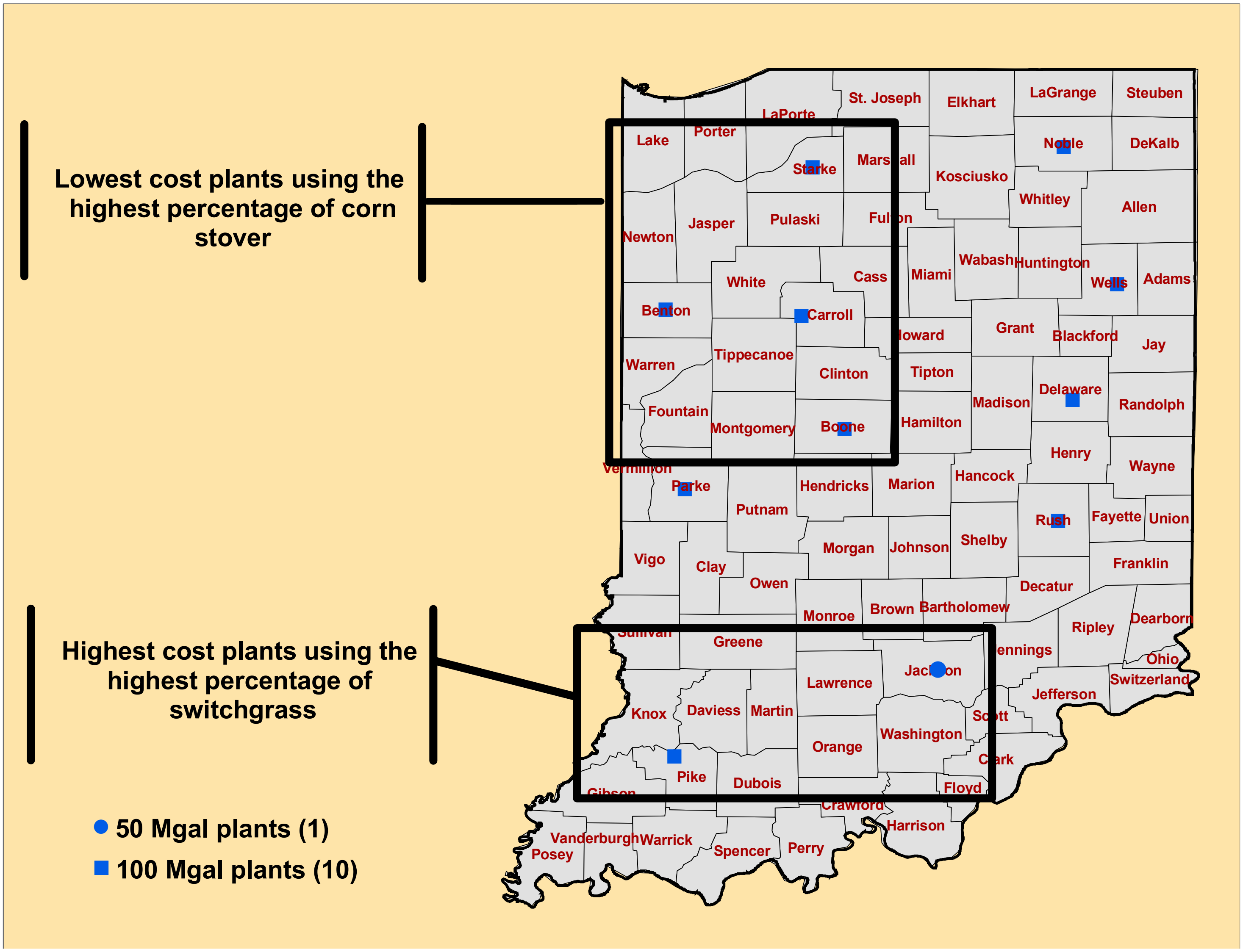

Figure 2. Optimal Counties of Manufacturing Sites for the Biochemical Conversion of Corn Stover and Switchgrass to Ethanol Based on Billion-Ton Study Projections and Economies of Scale

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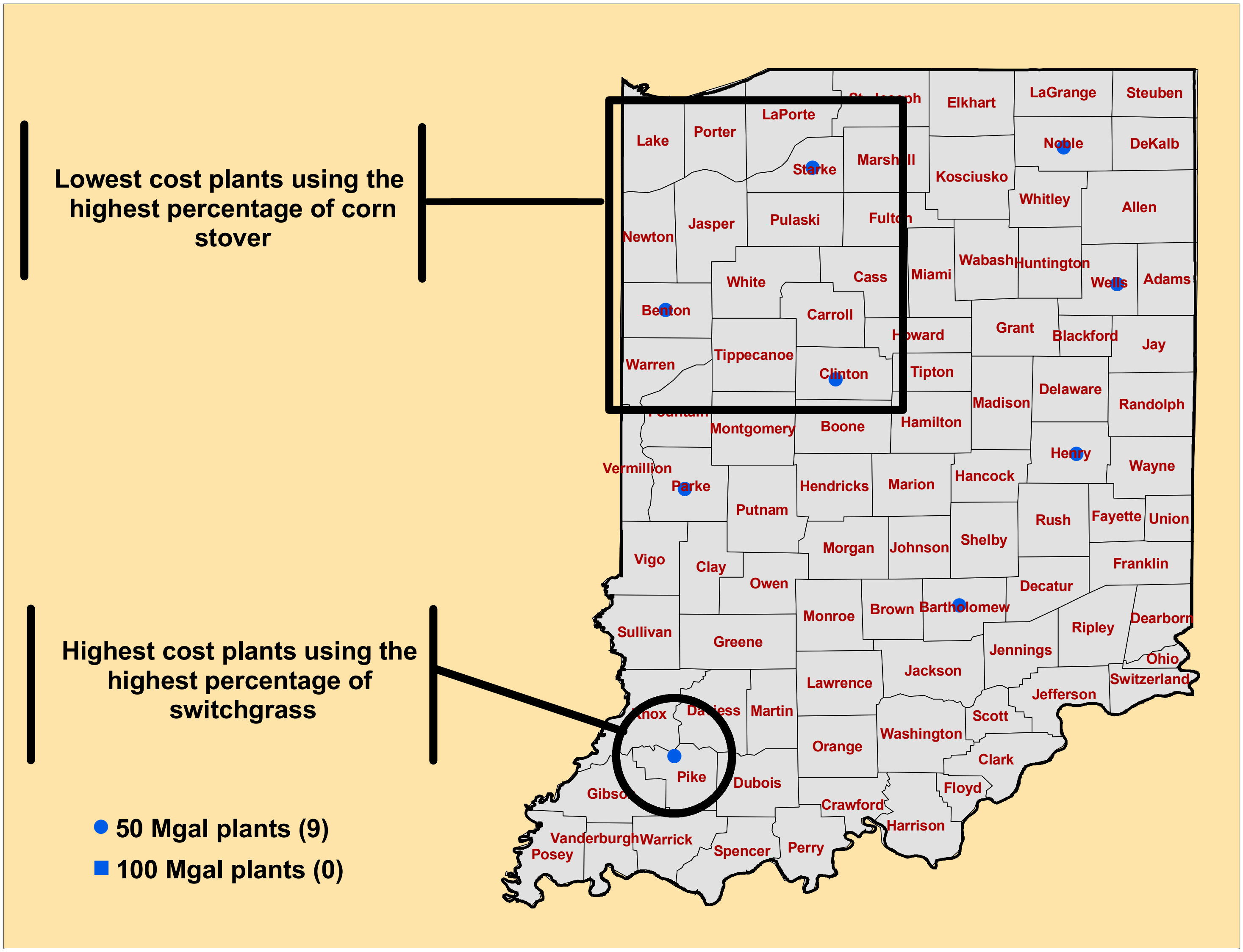

Figure 3. Optimal Counties of Manufacturing Sites for the Biochemical Conversion of Corn Stover and Switchgrass to Ethanol Based on Conservative Total Yield Estimates and No Economies of Scale

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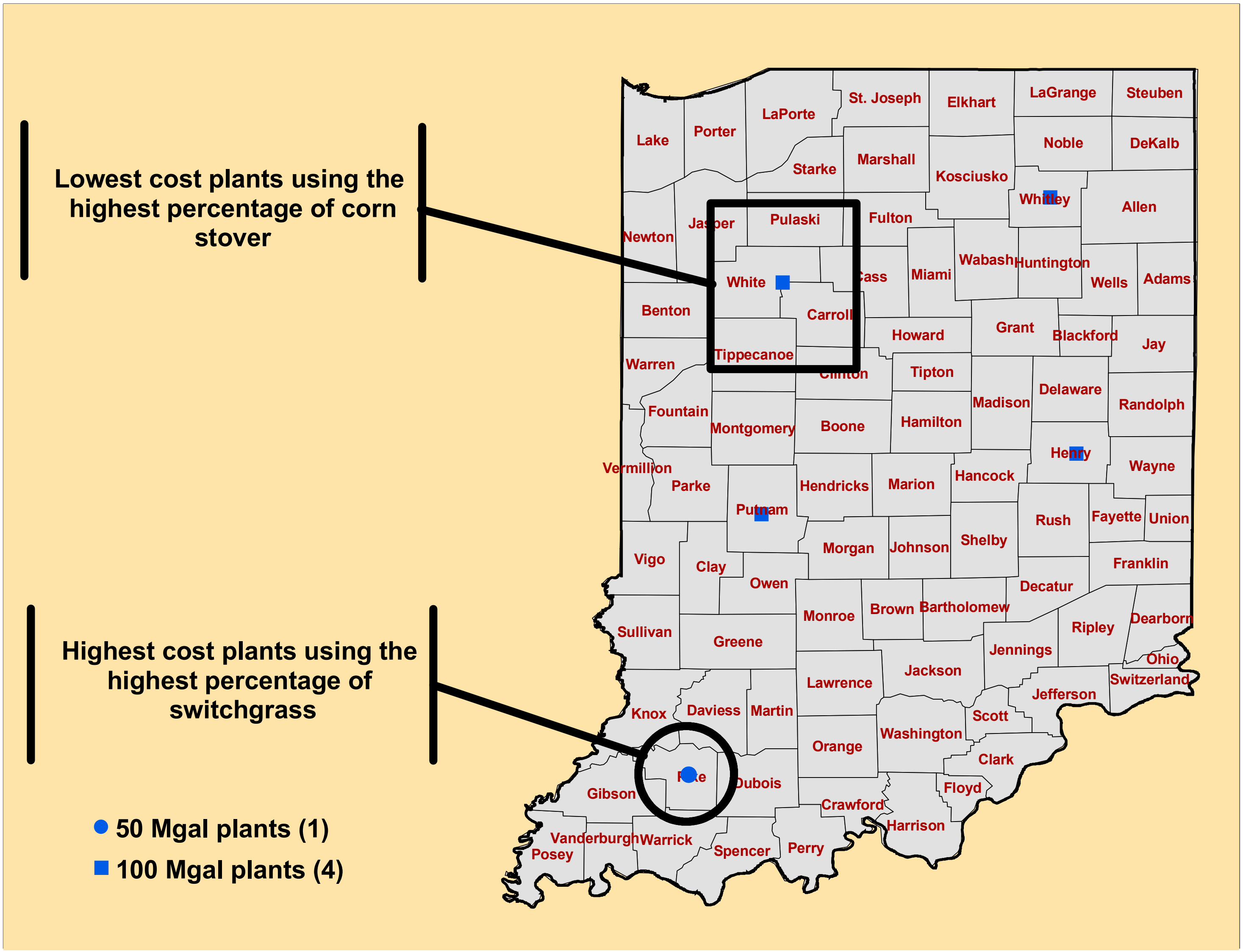

Figure 4. Optimal Counties of Manufacturing Sites for the Biochemical Conversion of Corn Stover and Switchgrass to Ethanol Based on Conservative Total Yield Estimates and Economies of Scale