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

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Cellulose Supply Expectations

“Energy Independence and Security Act of 2007”
Calls for 16 billion gallons ethanol per year to be produced from cellulose sources by 2022.

The “Billion Ton Study”
Projects over 1.3 billion tons of biomass available for conversion to energy sources and other products, with over 0.9 billion tons from agricultural residues.

Cellulose Supply Impacts

How will increased supplies impact local economies?

- Business risks
- Labor markets
- Federal and municipal tax incentives
- Transportation infrastructure
- Environmental risks
- Trade

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Cellulose Supply Analysis of Impacts

Objective

- Based on mandates and raw supply, determine the likely distribution and scale of cellulose to ethanol facilities within a region to assist state and local decision makers in managing the market, risk, and infrastructure issues expected due to supply increases.

Cellulose Supply: Crops

Corn Stover	Switchgrass
	
Secondary crop from corn	Primary grass crop

Cellulose Supply

Analysis Approach

Example: Indiana

Crops: Corn Stover and Switchgrass

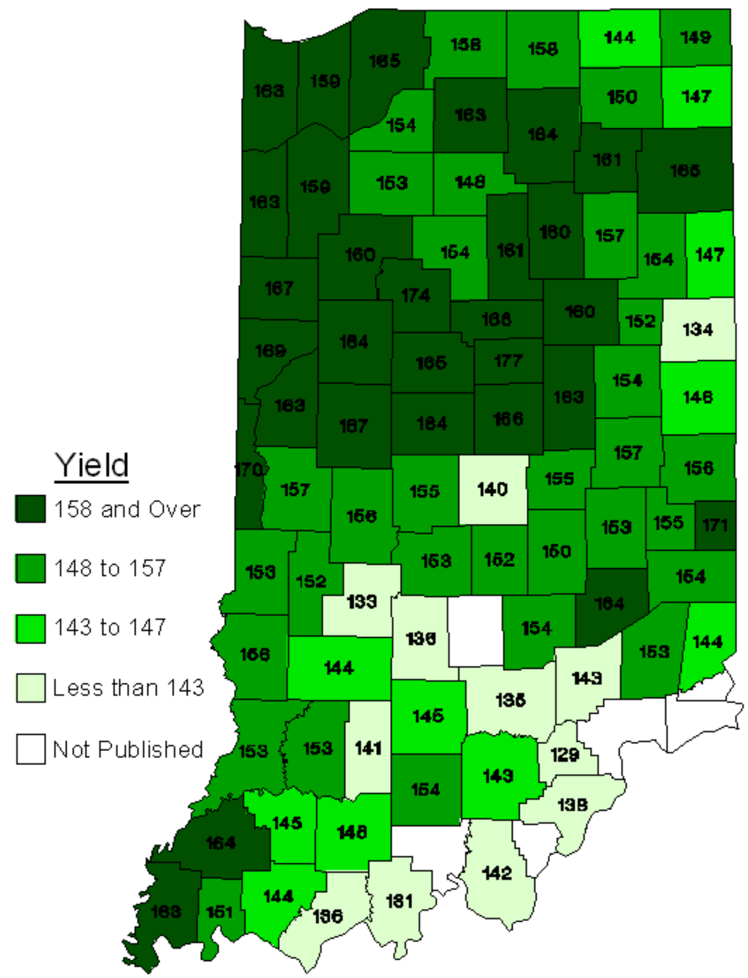
Supply data: Billion Ton Study (Perlack, et al., 2005)

-Corn Stover harvested heavily in corn rich areas

-Switchgrass grown and harvested heavily in various areas (uncorrelated to corn)

Cost data: Brechbill & Tyner (2008)

2006 CORN YIELDS



Source: USDA, NASS, Indiana Field Office

Cellulose Supply

Economic Impact: Past Work

Nelson (1981)

- Agricultural residues in Indiana using equal output sites
- No primary crops, no scale considerations

English, Menard, De La Torre Ugarte (2000)

- Economic impact (output, employment, value-added) of corn stover to ethanol conversion for several midwestern states, including Indiana.
- Sensitivity analysis of ethanol and corn stover prices, plant size, start-up phase.
- Main unit of analysis is sub-region (9 in Indiana for 92 counties) with a focus on state level aggregate economic impacts.

Cellulose to Ethanol Model

Strategy

- Maximize profits across Indiana

  Assuming constant revenue and operating costs per gallon, this is equivalent to the following:

- Minimize input and diseconomy costs
  - Harvest costs
  - Storage costs
  - Transport costs
  - Economy of scale savings

Cellulose to Ethanol:
Model Scenarios

Yield Estimate		High	Low
Tillage Methods		No Till	Current
Corn Stover Clearance %		70.0%	52.5%
Land Use Rate		100%	75%
Storage Losses (net wrap)		8.4%	8.4%
Million Dry Tons:	Corn Stover	> 9.2	> 3.2
	Switchgrass	> 5.3	> 4.0
Ethanol: (gal/dry ton biomass)	Corn Stover	81.4	69.7
	Switchgrass	79.0	67.6
Ethanol (Mgal/yr):	Corn Stover	688	208
	Switchgrass	387	249
Total Ethanol (gal/yr)		1.05 billion	0.45 billion

Model Assumptions

- Cost is minimized by adjusting the location and size of facilities, as well as the amounts of biomass shipped.
- Any county can have either one 100 million gallon plant, one 50 million gallon plant, or no plant.
- Plants can process any combination of corn stover and switchgrass which yields the target plant volume.
- County seats act as proxies to determine shipping distances
- Economies of scale are annualized over 23 years of a 25 year plant (equal NPV)

Graphic produced by the U.S. Department of Energy Office of Science.

Model Objective

- Minimize total cost, C, where x_{ijk} is the amount of dry biomass k, shipped from a farm in county i to a plant in county j, or:

$$\min_{x_{ijk}, I_j^{50}, I_j^{100}} C = \sum_{i}\sum_{j}\sum_{k}\left(p_k + s_k + fd_{ij}\right)x_{ijk} + \sum_{j} I_j^{50} C^p$$

and:

$I_j^{50} \equiv$ the number of 50 million gallon ethanol plants in county j

$I_j^{100} \equiv$ the number of 100 million gallon ethanol plants in county j

$p_k \equiv$ production cost for biomass feedstock k ($/dry ton shipped)

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

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

$d_{ij} \equiv$ distance from county i to county j (miles)

$C^p \equiv$ added plant cost for a 50 Mgal facility (diseconomies of scale)

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Model Objective:

Input Costs

- Rental costs are higher for switchgrass due to land rental fees not incurred by corn stover.
- Freight costs are similar on a dry ton basis due to similar moisture levels.

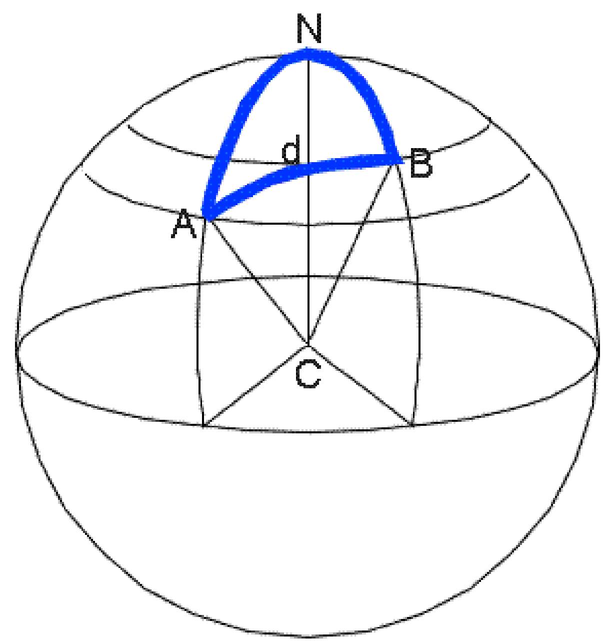
Crop	Corn Stover	Switchgrass
Production cost ($/dry ton harvested)	26.43 – 26.83	42.17
(p_k) Production cost ($/dry ton shipped)	33.18 – 33.68	52.95
(s_k) Fixed shipping cost ($/dry ton shipped)	2.20 – 2.45	1.89
(f) Freight charges ($/dry ton shipped/mile)	0.15	0.15

Data from Brechbill and Tyner, 2008 based on net wrap storage

Model Objective:

Distance

- Material shipped from a farm in county i to a plant in county j is assumed to travel the distance (d_{ij}) between the two county seats.
- The Haversine formula calculates the distance using latitudes/longitudes to account for earth's curvature.
- More relevance for regions larger than Indiana



Model Objective:
Diseconomy Costs

- C_p is the annualized diseconomy of running a small plant (50 Mgal), and is capitalized on an equal NPV basis assuming:

Project years	25
Capital purchased in 1st year	40%
Capital purchased in 2nd year	60%
Operating years for annualized costs	3 through 25
Investment hurdle rate (real)	8.7%

Model Constraints

- Crop shipments are limited by the amounts grown and harvested in the county:

$$\sum_{j} x_{ijk} \leq (1 - l) b_{ik} \qquad \text{for each k and i}$$

Additional Variables:
$l \equiv$ fractional storage loss of biomass feedstock
$b_{ik} \equiv$ amount of biomass k produced in county i (dry tons/yr)

Model Constraints

- All potential biomass is shipped to the plants and converted to ethanol.

$$\sum_i \sum_k c_k x_{ijk} \geq 50 I_j^{50} + 100 I_j^{100}; \quad x_{ijk} \geq 0$$

for each i, j, and k

$$\frac{1}{2} \sum_j I_j^{50} + \sum_j I_j^{100} = N$$

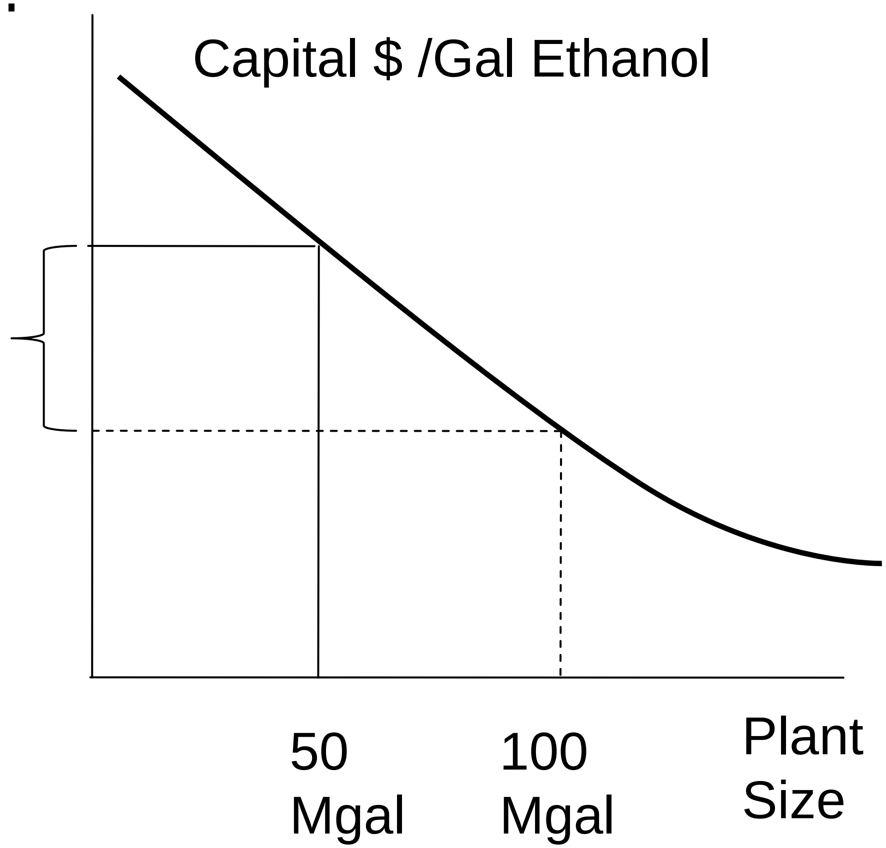
Additional Variables:

$c_k \equiv$ million gallons ethanol per dry ton of biomass

$N \equiv$ total plant capacity needed (100 Mgal/year)

Model Execution

- Minimize cost, C, using a mixed integer linear programming model in GAMS, version 22.5.
- Adjust C_p to determine the levels of diseconomy which result in the switch from small facilities (50 Mgal) to large facilities (100 Mgal).
- Run model for both high and low yield scenarios



Results

Economies of Scale

\# 100 Mgal plants

- None
- Mixed
- Maximum

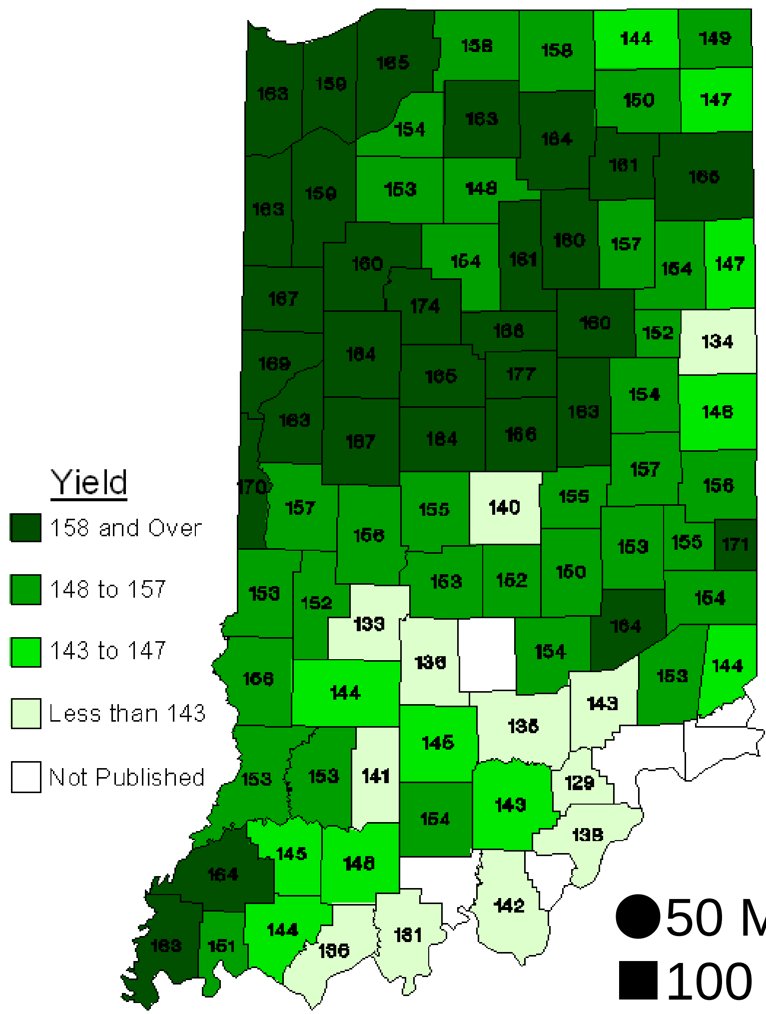
Corn Economy of Scale ($0.23)

Economy of scale in capital investment ($/gal ethanol)	Target number of 100 Mgal plants, high yield	Target number of 100 Mgal plants, low yield
$0.000	0	0
$0.034	0	0
$0.067	3	0
$0.101	5	0
$0.134	8	0
$0.168	10	1
$0.201	10	2
$0.235	10	2
$0.268	10	3
$0.302	10	3
$0.335	10	4
$0.369	10	4
Maximum 100 Mgal plants	10	4

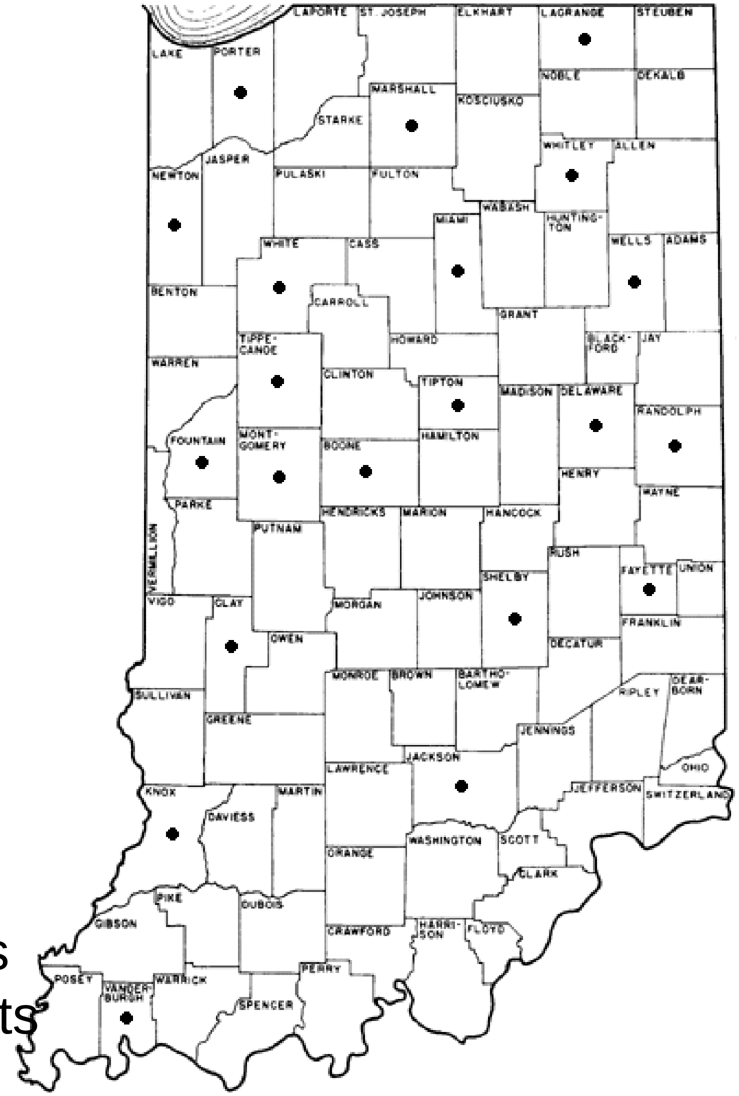
Results, Location

High Yield, Low Economies of Scale ❏

2006 CORN YIELDS



Source: USDA, NASS, Indiana Field Office



●50 Mgal plants

■100 Mgal plants

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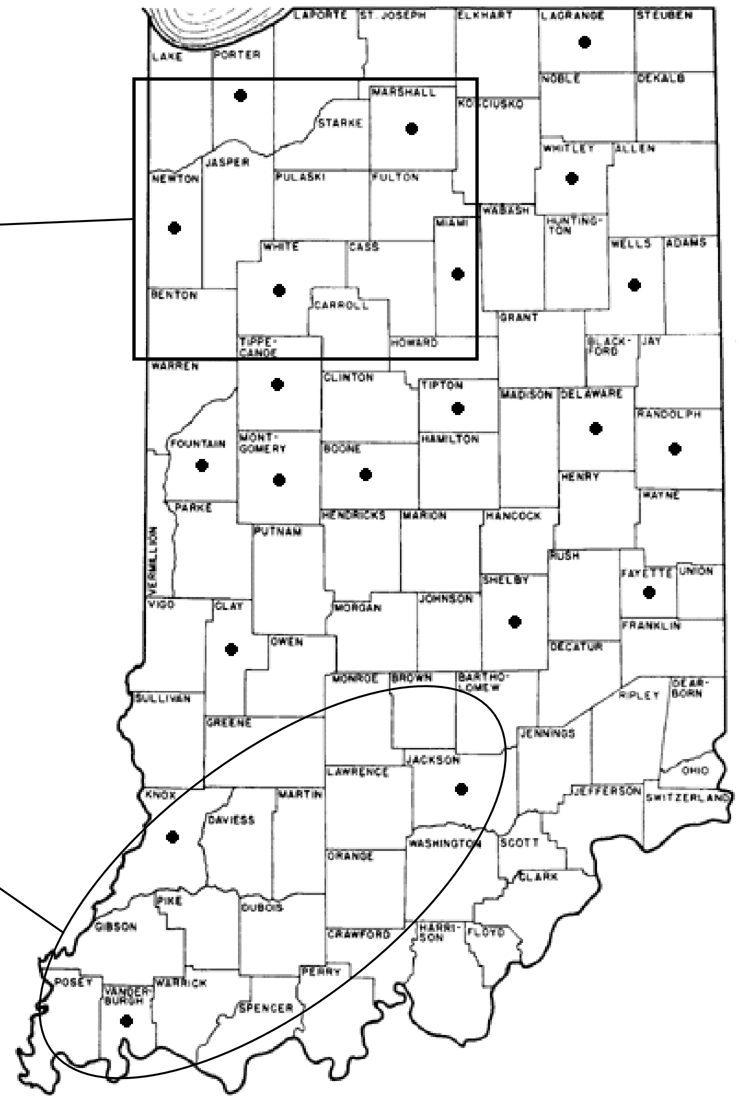
Results, Cost

High Yield, Low Economies of Scale ❑

Lowest cost plants using the highest percentage of corn stover

Highest cost plants using the highest percentage of switchgrass



● 50 Mgal plants

■ 100 Mgal plants

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Results, Location/Cost

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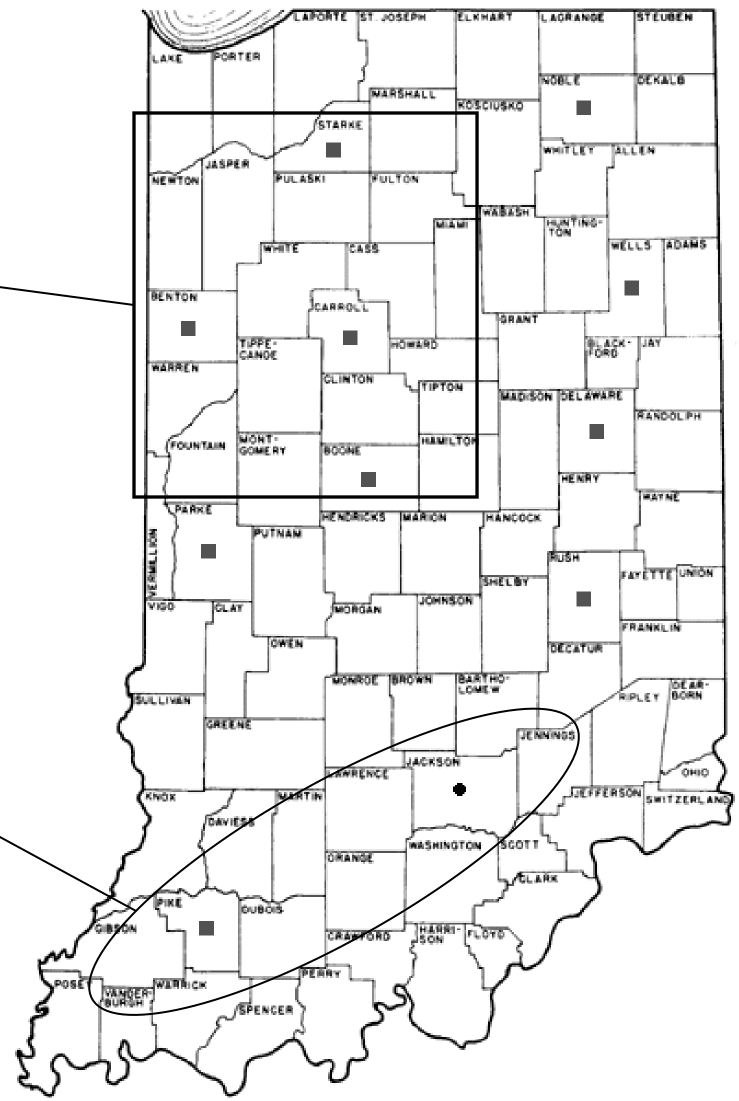


● 50 Mgal plants
■ 100 Mgal plants

Results, Cost

High Yield, High Economies of Scale

Plant location (county)	Low cost ranking*	% ethanol from corn stover#	% ethanol from switchgrass
Starke	1	98%	2%
Benton	2	88%	12%
Carroll	3	84%	16%
Boone	4	69%	31%
Rush	5	66%	34%
Delaware	6	64%	36%
Wells	7	63%	37%
Noble	8	63%	37%
Parke	9	50%	50%
Pike	10	31%	69%
Jackson	11	23%	77%

* 1 is the lowest cost plant and 11 is the highest cost plant.

Conclusions

High Yield

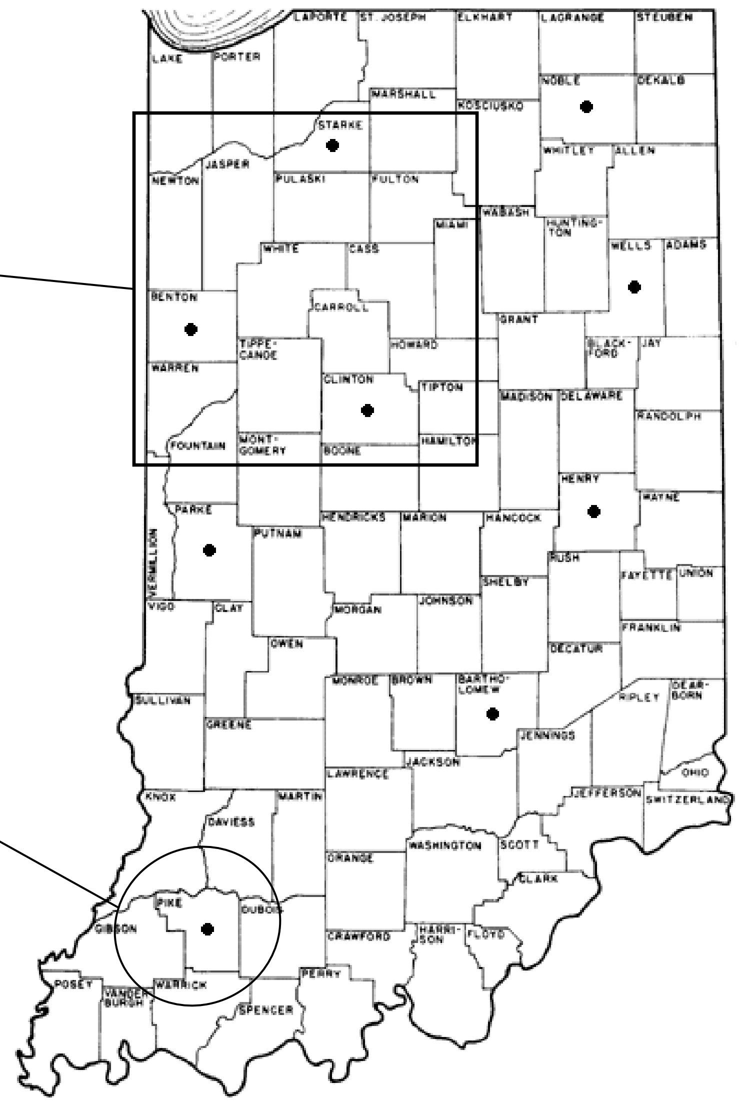
- Location is driven by total biomass concentration, with corn stover dominating in the high yield scenario.
- Costs are driven by land rents, with plants specializing in corn stover, a by-product of corn production, saving the land rent incurred when producing switchgrass.
- In the absence of uncertainty, economies of scale similar to corn would provide the economic incentive for large plant sizes to be utilized almost exclusively.

Results, Location/Cost

Low Yield, Low Economies of Scale ❑

Lowest cost plants using the highest percentage of corn stover

Highest cost plant using the highest percentage of switchgrass



● 50 Mgal plants
■ 100 Mgal plants

Results, Cost

Low Yield, Low Economies of Scale ❑

Plant location (county)	Low cost ranking*	% ethanol from corn stover#	% ethanol from switchgrass
Starke	1	97%	3%
Benton	2	78%	22%
Clinton	3	65%	35%
Noble	4	52%	48%
Henry	5	39%	61%
Wells	6	38%	62%
Bartholomew	8	22%	78%
Parke	7	17%	83%
Pike	9	8%	92%

* 1 is the lowest cost plant and 9 is the highest cost plant.

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Results, Location/Cost

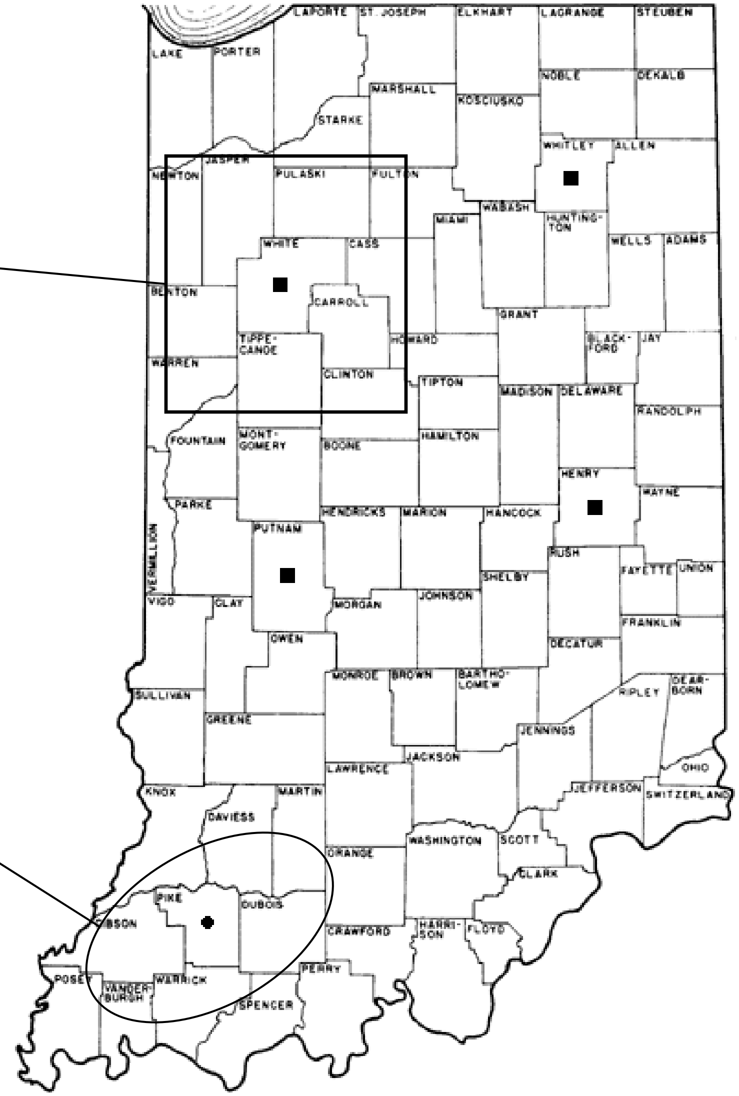
Low Yield, High Economies of Scale

Lowest cost plant using the highest percentage of corn stover

Highest cost plant using the highest percentage of switchgrass

● 50 Mgal plants

■ 100 Mgal plants



Conclusions

Low Yield

- Location is driven by total biomass concentration, with both corn stover and switchgrass playing a role.
- Lower corn stover concentrations → transportation costs prohibit extensive corn stover specialization.
- Economies of scale similar to corn would only provide incentives for one or two large plants, assuming absolutely no uncertainty.

Conclusions

- The method provides a state or region with a strategy for the spatial distribution of sites at the county level, thus providing key information for other policy decisions affecting local employment, business, transportation, environmental, and other issues.

Conclusions

- Given expected market risks, low yield assumptions, and modest economies of scale, initial sites in Indiana would likely be small and close to the corn stover regions of the northwest part of the state.

Thank You