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Optimizing Ethanol Production in North Dakota

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ABSTRACT

A spatial equilibrium model based on a non-linear mathematical programming algorithm was developed to determine the optimal number, location, and size of cellulose ethanol plants for North Dakota. The objective function of the model is to minimize processing cost of biomass for ethanol and the transportation cost of shipping biomass to processing plants and ethanol to blending facilities. A heuristic approach, combined with a spatial equilibrium model, was used to determine the optimal number, location and size of biomass processing plants.

Keywords: Cellulosic ethanol, biomass, mathematical programming, heuristic, production costs.

HIGHLIGHTS

The Energy Security and Independence Act requires the production of 36 billion gallons of ethanol by 2022. Corn-based ethanol production will level out at about 11 billion gallons, indicating that the remaining 25 billion gallons of ethanol should be produced from biomass, including corn stover, wheat straw, grasses from CRP land, and dedicated energy crops. Currently, biomass-based ethanol has several problems. First, biomass ethanol is more expensive to produce than corn-based ethanol. Secondly, biomass is difficult to handle and expensive to transport. Third, biomass ethanol production requires 75% more water than corn-based ethanol production.

Three scenarios were developed to determine the location, size, and number of biomass-based ethanol plants required to process biomass produced in North Dakota. The levels of biomass were 80%, 65%, and 50% of total wheat straw, corn stover, and CRP grasses produced in North Dakota. A maximum of 12 plants were chosen for the base model. A heuristic approach, combined with a spatial equilibrium model determined the optimal number, location and size of processing plants in North Dakota.

Under all three scenarios, the same 10 processing plants are determined in the solution. They were Grafton, Grand Forks, Fargo, Wahpeton, Valley City, Devils Lake, Minot, Williston, Bismarck, and Dickinson. As the availability of biomass increased from 50% to 80%, the size of biomass plants increased. For the 50% scenario, the average size of the biomass plants is 75 million gallons per year. The average size of the processing plants in the 65% scenario is 89 million gallons per year and the average size of the processing plant for the 80% scenario was 110 million gallons per year.

In addition to being larger, the plants were more efficient as the availability of biomass increased. The average total cost of production for the plants under the 50% scenario was $1.95 per gallon of ethanol compared to $1.28 per gallon for the 80% scenario.

Plant location is important under all scenarios. The total cost of production for the least efficient set of 10 production plants is higher than the most efficient set of 10 production plants by 82% to 141%. Biomass ethanol production plants need to be located near an adequate source of biomass to limit transportation costs.

Optimizing Cellulose Ethanol Production in North Dakota

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INTRODUCTION

Ethanol production in the United States has grown from 2.8 billion gallons in 2003 to 9 billion gallons in 2008. Almost all of the production is corn-based ethanol. The Energy Security and Independence Act (ESIA) of 2007 require 36 billion gallons of ethanol to be blended into the U.S. gasoline supply by 2022. To accomplish this, about 25 billion gallons of biomass-based ethanol should to be produced in the United States. Currently, about 36% of the U.S. corn supply is converted into ethanol, which seems to be about the maximum amount considering the recent price response to the growing ethanol demands for corn. Biomass ethanol will have to provide a substantial portion in the future since corn based ethanol is limited.

There are three major problems concerning the production of biomass ethanol. First, the current cost of production for biomass-based ethanol is substantially higher than corn-based ethanol. Second, biomass is bulky, generally light weight, and is difficult and expensive to transport even moderate distances. Finally, biomass ethanol requires seven gallons of water per gallon of ethanol compared to four gallons of water per gallon of corn-based ethanol. A 100 million gallon cellulose ethanol plant would require almost 2 million gallons of water per day.

Various cost estimates have been made for the production of cellulose ethanol. They range from $2.50 per gallon to $4.00 per gallon. That compares with about $1.73 per gallon for corn-based ethanol at current corn prices (EPA).

Cellulose ethanol can be produced from almost any type of plant or animal material. That includes crop and forestry residue, materials from dedicated biomass crops, by-products from agricultural food processing and organic materials from landfills. However, the processing plant location is important since this material cannot be transported long distances because of high freight costs. Another relevant question is what would be the size of the plant under increasing returns to scale. A firm can reduce its total production costs as the size of a plant increases.

Ethanol, whether corn-based or biomass-based, is shipped from the processing plants to refineries for blending with gasoline. Locations of refineries are another important determinant in optimizing the production and distribution of ethanol.

The objective of this study is to determine the optimal biomass processing locations and number in North Dakota subject to water requirements, the concentration of biomass produced, and the location of gasoline blenders. It is assumed that the processing plants experience increasing returns of scale.

The basic algorithm used in this study is similar to one developed by Stollsteimer (1963) to determine the optimal number, size, and location of plants when transportation costs from origins to plants and transportation costs from plants to destination are relevant. Ladd and Lifferth extended the Stollsteimer model to determine the optimal number, size and location of plants using a heuristic approach. The method used for this study is a heuristic approach combined with a mathematical optimization model to determine the optimal size, number, and location of processing plants when processing plants in a region experience increasing returns to scale and transportation costs of biomass from producing regions to plants and transportation costs of ethanol from plants of refineries are relevant. The mathematical programming model optimizes flows of biomass from producing regions to processing plants and ethanol from processing plants to blending facilities conditional to given number and location of plants in a region. Unlike the previous studies, this study is capable of including all the necessary constraints which are important in processing cellulose ethanol. Some of those are availability of biomass and water required for processing. Then the optimal number, size and location of plants in a region are determined using a heuristic approach subject to the optimization of the mathematical programming algorithm.

DEVELOPMENT OF AN EMPIRICAL MODEL

An empirical model is developed to determine the optimal number, location, and size of cellulose ethanol plant in North Dakota to maximize the use of biomass produced in the state. The criteria is to minimize average processing costs of biomass for ethanol production, average transportation costs of biomass from producing regions to processing plants, and transportation costs of ethanol from processing plants to blending facilities.

Under economies of scale in processing biomass as the number of plant increases, the size of each plant decreases and average total processing cost (ATPC) increases. Thus, with the given amount of biomass for ethanol production in North Dakota, ATPC and the number of plants have a positive functional relationship as shown in Figure 1. However, average total transportation cost (ATTC) decreases as the number of plant increases in a region mainly because more plants result in shorter travel distances of biomass and ethanol (Figure 1).

The optimal number of plants is determined at the point where ATC curve is at the minimum. Other costs in processing ethanol are the price of biomass produced in producing regions and the price of water at processing plants. However, these costs are fixed on a per ton or per gallon basis. They are assumed to be the same in all regions in North Dakota.

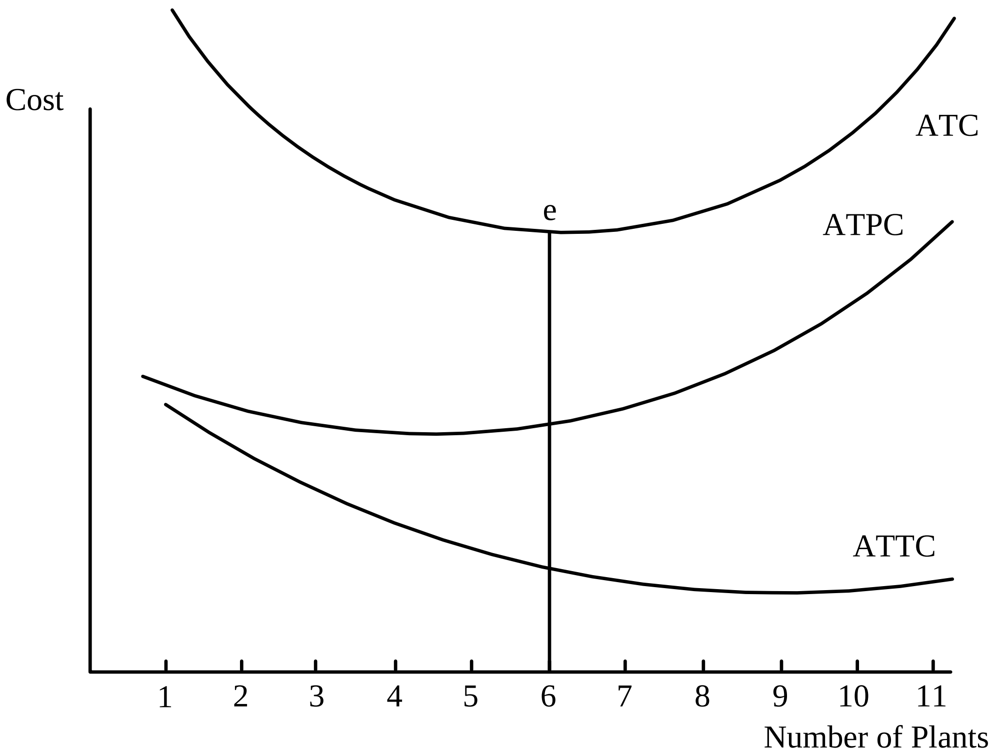

Figure 1. Average Total Transportation, Average Total Production, and Average Total Costs for Various Number of Biomass Ethanol Processing Plants

It is assumed that biomass is shipped by semi-truck from biomass producing regions to processing plant and ethanol produced at plants is moved to blending facilities by rail. The base model has 64 biomass producing regions and 12 pre-determined processing plants. Each county in North Dakota is identified as a producing region along with 11 counties in western Minnesota. All possible processing plants are identified based on the availability of water, density of biomass and the accessibility of rural highways and rail roads.

Specification of a Mathematical Programming Model

The model developed for this study is a spatial equilibrium model based on a non-linear mathematical programming algorithm. The objective function of the model is to minimize processing costs of biomass for ethanol and transportation costs of biomass and ethanol.

The objective function of the model is specified as

(1) $$Z = \sum_j ATPC(Q_j^{\,e})Q_j^{\,e} + \sum_i \sum_j t^b{}_{ij} Q^b{}_{ij} + \sum_j \sum_n t^e{}_{jn} Q^e{}_{jn}$$

Where ATPC(Q^e_j) represents average total processing cost which is a nonlinear decreasing function of the amount of ethanol processed in plant j, t^b_{ij} is transportation cost of biomass (\$/ton), and t^e_{jn} is transportation cost of ethanol (\$/gallon). Q^b_{ij} and Q^e_{jn} are quantities of biomass shipped from producing region i to consuming region j and ethanol shipped from the processing plant j to blending location n, respectively.

This objective function is minimized subject to the following constraints

(2) $\sum_j Q^b_{ij} = B_i$ i = 1,2,.........64

(3) $\sum_i Q^b_{ij} * \lambda = Q^e_j$ j = 1,2,........12

(4) $Q^e_j * \gamma \le W_j$ j = 1,2,........12

(5) $\sum_{j=1} Q^e_{jn} \le D^e_n$ n = 1,2,.......13

(6) $\sum_{j=1}\sum_{n=1} Q^e_{jn}{}^{\mathbf{e}} = \sum_{j=1} Q^e_j$ i = 1,2,........64 j=1,2,.........12 n=1,2,......13

where B_i = total amount of biomass available in producing region i

λ = conversion ratio from biomass to ethanol (gallons/ton)

γ = water requirement to produce a gallon of ethanol (water/1000 gallons ethanol)

W_j = total amount of water available for ethanol production at plant j (1000 gallons)

D^e_n = amount of ethanol needed at blending facilities (1000 gallons)

Equation 2 represents that the total amount of biomass shipped from producing region i to processing plant j should be equal to the total amount of biomass available in the producing region i. This indicates that the total amount of biomass produced in each producing region is used to produce ethanol in the processing plants, meaning that biomass produced in producing region is not allowed to be stored in the region. Equation 3 indicates that the total amount of biomass received by plant j should be processed for ethanol. This implies that processing plants are not allowed to store biomass or ethanol at their locations. Equation 4 represents that the total water used in plant j should be smaller than water available in area where the plant in located. Equation 5 indicates that the amount of ethanol produced in plants should be shipped to blending location n based on the blending requirement. Equation 6 indicates that the total amount of ethanol produced in the region should be equal to total amount of ethanol shipped out for blending.

A Heuristic Approach to Determine the Optimal Number, Location and Size of Plants

The base model includes all possible pre-determined locations of ethanol plants in North Dakota based on density of CRP and cropland, availability of water needed for processing, accessibility to railroads, highways and availability of other resources (e.g., labor). The number of processing plants in the model is 12. In addition the model contains 64 biomass producing regions which include 11 counties in western Minnesota and 13 blending locations in North Dakota, Minnesota, Montana, Wyoming, and Illinois where ethanol produced in processing plants can be shipped.

Since the number of pre-determined processing plants is 12 in the state, that is also the maximum number of processing plants in the base model. The mathematical programming model optimizes the size of each processing plant, optimal flow of biomass to the processing plants, and optimal flow of ethanol from processing plants to blending locations under an assumption that the number of plants is 12. The model determines the size of plant in each location conditional to the given member and location of the plant and average total cost (ATPC+ATTC) in the region.

Iterative simulation starts with one less plant, 11 in the state and finds the optimal location and size, which minimizes ATC. In this case, the total number of combinations of all possible locations is ${}_{12}C_{11}=12$. The mathematical programming model is run for each combination of the 11 plants and calculates the ATC. One combination from all the 12 possible combinations is chosen on the basis of the minimum ATC. For p number of plants in a state, the total combinations of all possible locations of p plants is ${}_{12}C_{p}$. The mathematical programming model is run for all possible combinations of p plants. One combination which gives the lowest ATC is chosen. This process will continue until $ATC_p<ATC_{p-1}$. In this case, the optimal number of processing plants is p.

The step-by-step process is as follows:

1. Run the mathematical model with 12 pre-determined processing plants, 64 producing regions and 13 blending locations and calculate the ATC_{12} ($ATPC_{12}$ + $ATTC_{12}$).

2. The next iteration starts with one less plant in the state. The total combinations of 11 plants in the region are 12, (${}_{12}C_{11}$,). Run the mathematical programming model for each of the 12 combinations and calculate the ATC_{11} for each combination. Choose one combination of 11 plants which provide for the minimum ATC. If ATC_{11} is smaller than ATC_{12}, continue to step 3.

3. Eliminate two plants; the combinations of 10 plants in the region are ${}_{12}C_{10}$. Run the mathematical programming model for each of the possible combinations of 10 plants and calculate ATC_{10} ($ATPC_{10}$+ $ATTC_{10}$) for each combination of 10 plants. Choose one combination which minimizes ATC. If $ATC_{10} < ATC_{11}$, continue this iteration for 9 plants. This iterative process continues until $ATC_{p-1}>ATC_{p.}$ In this case, p is the optimal number of plants in a region. The mathematical programming model with p plants provides the optimal location, number, and size of each plant in the state.

The iterative procedure is conducted for 3 different levels of biomass to be used for ethanol production, 80%, 65%, and 50% of all biomass available in the region. The total amount of biomass available in a region is different from the quantity of biomass used for ethanol production mainly because some producers would not be interested in collecting wheat straw, corn stover and other biomass from their fields.

DATA

This study evaluates biomass ethanol production from CRP grasses, wheat straw, and corn stover. Other biomass sources, such as land fill materials and agricultural processing waste are not considered. To determine the potential biomass supplies, corn and wheat production in North Dakota was divided into the 53 counties along with county CRP acres in the counties. Eleven northwestern Minnesota counties were included in the model. Seven years of wheat and corn yields along with harvested acres were obtained from National Agricultural Statistics Service (Table 1). CRP acres were obtained from Farm Service Agency. It was assumed that CRP grass produces 3 tons per acre per year realizing that CRP in the eastern half of North Dakota would have higher yields than the western half of North Dakota. Twelve locations of processing plant were pre-determined across on the basis of availability of biomass, water requirements, accessibility to highway, and existing locations of blending facilities (Figure 2). Thirteen refineries were identified for consumption of ethanol produced in North Dakota.

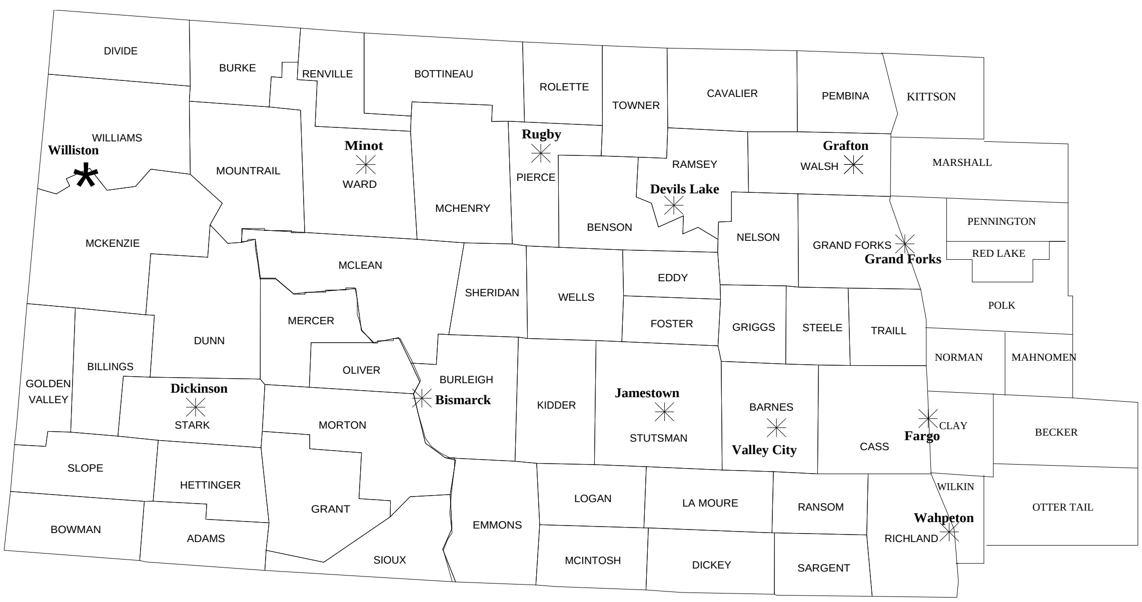

Figure 2. Possible Locations for Bio-mass Ethanol Processing Plants

Biomass Available for Processing

The biomass production (tons/acre) from corn is estimated on the basis of a procedure developed by Illinois State University as follows:

(7) Stover production = [(Yield * test weight)/2000]*0.8.

Research shows between 30% and 60% of the stover can be economically harvested. For this study, it is assumed that 50% of the available stover left after harvest is collected and available for transport to ethanol processing facilities.

Table 1 shows corn and corn stover production in North Dakota, and northwestern Minnesota counties. Corn production is concentrated in southeast North Dakota and western Minnesota. The largest producer of corn in North Dakota is Richland County followed by Cass and Dickey Counties. The largest corn producing county in northwestern Minnesota is Otter Tail followed by Wilkin.

Table 2 shows wheat production in North Dakota and northwestern Minnesota counties. Unlike corn, wheat production is not concentrated in a few locations. The largest wheat producing counties are Ward, Cavalier, McLean, Williams, Walsh, Cass, and Pembina. They plant 26% of the state's wheat acres in North Dakota and harvest 28% of the wheat production. The state plants 8.5 million acres and harvests 296.7 million bushels of wheat per year. The northwestern Minnesota counties produce 70.6 million bushels of wheat on 1.3 million acres.

The biomass production (lbs/acre) for wheat is estimated on the basis of a formula developed by Washington State University:

(8) Straw production = [1067.7+69.76*(yield)].

Research shows that about 70% of the wheat straw can be economically harvested for biomass and transported to ethanol processing facilities.

Table 3 shows the CRP acres and biomass production in North Dakota and northwestern Minnesota. Stutsman, Walsh, Nelson, Bottineau, McHenry, Burleigh, and Kidder counties have the largest CRP acreage. They produce about 22% of the state's CRP biomass production. The state has a little more than 3 million acres of CRP land and produces 9.1 million tons of biomass. The northwestern Minnesota counties have 786 thousand acres of CRP land. It is assumed that CRP produces 3 tons per acre per year and is harvested every other year (NDSU Soil and Range Science).

Table 1. North Dakota and Western Minnesota Corn Acres, Yield, and Corn Stover by County, 2000-2007

County	Harvested Area	Yield	Corn Stover	County	Harvested Area	Yield	Corn Stover
County	Acres	Bu/acre	1000 tons		Acres	Bu/acre	1000 tons
Adams	2,675	42.20	1,468	McLean	13,875	86.45	15,593
Barnes	84,500	115.93	127,344	Mercer	3,025	88.58	3,483
Benson	25,925	89.08	30,021	Morton	6,625	82.80	7,131
Billings	1,300	54.13	915	Mountrail	725	58.05	547
Bottineau	3,475	63.85	2,884	Nelson	12,850	84.18	14,061
Bowman	3,525	50.35	2,307	Oliver	6,075	90.03	7,110
Burke	700	45.70	416	Pembina	14,925	92.50	17,947
Burleigh	15,475	76.35	15,360	Pierce	9,550	75.00	9,311
Cass	152,125	126.20	249,576	Ramsey	38,650	82.85	41,628
Cavalier	1,175	86.25	1,317	Ransom	66,700	131.53	114,045
Dickey	113,250	130.43	192,018	Renville	2,475	71.00	2,284
Divide	1,400	64.20	1,168	Richland	236,000	129.55	397,459
Dunn	5,875	49.13	3,752	Rolette	3,625	66.93	3,154
Eddy	7,250	101.53	9,569	Sargent	90,500	131.45	154,641
Emmons	32,725	75.03	31,918	Sheridan	5,050	94.73	6,219
Foster	22,475	95.58	27,925	Sioux	2,500	108.60	3,530
Golden Valley	4,250	60.93	3,366	Slope	1,525	54.75	1,085
Grand Forks	39,925	98.35	51,046	Stark	5,550	57.25	4,131
Grant	7,567	74.63	7,341	Steele	49,375	111.13	71,328
Griggs	18,875	110.33	27,071	Stutsman	81,625	107.60	114,177
Hettinger	8,475	50.03	5,512	Towner	6,625	84.65	7,290
Kidder	10,000	123.68	16,078	Traill	101,375	117.48	154,817
La Moure	106,875	128.40	178,396	Walsh	15,400	102.58	20,536
Logan	14,775	86.38	16,500	Ward	5,950	79.65	6,161
McHenry	15,950	80.70	16,733	Wells	32,125	92.75	38,735
McIntosh	16,150	89.65	18,822	Williams	1,500	83.90	1,636
McKenzie	2,000	73.58	1,913	Norman	51,020	123.24	81,739
Becker	20,175	113.65	29,807	Otter Tail	118,740	127.80	197,273
Clay	60,840	131.87	104,296	Pennington	3,467	105.05	4,734
Kittson	2,733	106.59	3,787	Polk	32,400	104.27	43,921
Mahnomen	22,025	111.62	31,960	Red Lake	6,060	106.28	8,373
Marshall	7,500	106.42	10,379	Wilkin	64,780	130.59	109,978

Source: NASS

Table 2. North Dakota and Western Minnesota Wheat Acres, Yield, and Wheat Straw by County, 2000-2007

County	Harvested Area	Yield	Wheat Straw	County	Harvested Area	Yield	Wheat Straw
	Acres	Bu/acre	1000 tons		Acres	Bu/acre	1000 tons
Adams	160,800	21.90	171,825	McLean	366,875	34.73	506,910
Barnes	180,850	46.28	300,880	Mercer	90,350	28.53	111,159
Benson	154,950	34.70	213,999	Morton	203,600	24.73	231,602
Billings	22,800	22.55	24,725	Mountrail	283,525	28.05	345,537
Bottineau	245,850	37.15	354,246	Nelson	110,850	38.73	163,987
Bowman	128,775	26.05	150,652	Oliver	61,350	31.13	79,375
Burke	207,550	29.88	262,193	Pembina	227,650	44.03	366,235
Burleigh	109,775	31.45	142,898	Pierce	123,425	34.80	170,762
Cass	239,575	43.35	381,471	Ramsey	127,075	38.65	187,757
Cavalier	345,250	39.20	514,753	Ransom	70,400	48.55	121,035
Dickey	57,850	42.35	90,701	Renville	184,600	37.30	266,667
Divide	268,400	28.00	326,776	Richland	144,625	47.40	244,585
Dunn	159,000	27.45	191,447	Rolette	91,950	39.75	138,328
Eddy	47,950	38.30	70,438	Sargent	74,300	45.15	121,572
Emmons	129,525	28.63	159,673	Sheridan	95,775	32.73	127,655
Foster	83,350	35.43	116,589	Sioux	25,050	16.50	23,465
Golden Valley	66,250	28.63	81,670	Slope	125,575	24.13	141,006
Grand Forks	217,600	44.35	351,794	Stark	260,925	29.50	327,232
Grant	129,025	19.20	129,365	Steele	120,775	41.58	187,074
Griggs	76,525	40.20	115,964	Stutsman	171,650	40.23	260,219
Hettinger	335,625	30.35	427,880	Towner	197,450	37.25	284,989
Kidder	50,200	32.00	66,021	Traill	106,550	48.00	181,755
La Moure	121,675	37.15	175,322	Walsh	243,175	42.95	384,829
Logan	77,450	34.20	106,020	Ward	374,400	38.10	548,159
McHenry	165,775	32.33	219,336	Wells	204,650	40.38	310,996
McIntosh	81,175	32.03	106,808	Williams	392,950	29.50	492,807
McKenzie	184,550	26.43	217,592	Norman	140,800	52.48	255,573
Becker	55,433	49.73	96,906	Otter Tail	61,150	46.07	101,432
Clay	129,933	53.49	239,054	Pennington	71,025	49.17	123,188
Kittson	144,475	48.42	247,931	Polk	293,033	56.63	561,616
Mahnomen	28,933	49.48	50,400	Red Lake	55,600	51.33	99,364
Marshall	210,225	47.53	356,179	Wilkin	128,833	50.23	226,770

Source: NASS

Table 3. CRP Acres and Production of Biomass for North Dakota and Western Minnesota Counties, 2007

County	CRP acres	Biomass, tons	County	CRP acres	Biomass, tons
Adams	65,209	163,023	McLean	74,528	186,320
Barnes	91,109	227,773	Mercer	18,168	45,420
Benson	56,586	141,465	Morton	38,688	96,720
Billings	16,137	40,343	Mountrail	57,223	143,058
Bottineau	109,290	273,225	Nelson	111,748	279,370
Bowman	61,225	153,063	Oliver	5,361	13,403
Burke	52,056	130,140	Pembina	30,527	76,318
Burleigh	102,648	256,620	Pierce	72,676	181,690
Cass	36,186	90,465	Ramsey	76,258	190,645
Cavalier	42,300	105,750	Ransom	68,937	172,343
Dickey	51,748	129,370	Renville	15,255	38,138
Divide	66,275	165,688	Richland	30,608	76,520
Dunn	20,158	50,395	Rolette	66,357	165,893
Eddy	63,206	158,015	Sargent	38,639	96,598
Emmons	52,922	132,305	Sheridan	58,970	147,425
Foster	35,624	89,060	Sioux	7,971	19,928
Golden Valley	23,372	58,430	Slope	21,139	52,848
Grand forks	80,603	201,508	Stark	79,587	198,968
Grant	46,392	115,980	Steele	21,962	54,905
Griggs	73,477	183,693	Stutsman	164,637	411,593
Hettinger	84,120	210,300	Towner	59,480	148,700
Kidder	94,230	235,575	Traill	7,224	18,060
La Moure	66,911	167,278	Walsh	121,454	303,635
Logan	61,786	154,465	Ward	39,310	98,275
McHenry	104,686	261,715	Wells	64,580	161,450
McIntosh	55,753	139,383	Williams	58,397	145,993
McKenzie	19,746	49,365	Norman	49,649	123,626
Becker	32,710	81,448	Otter Tail	72,581	180,727
Clay	35,814	89,177	Pennington	72,545	180,637
Kittson	107,578	267,869	Polk	145,713	362,825
Mahnomen	18,924	47,121	Red Lake	45,022	112,105
Marshall	193,197	481,061	Wilkin	15,028	37,420

Source: FAS

Mileage Matrix

A mileage matrix was developed for distance between the major city in each county and predetermined location of the ethanol plant using the mileage chart in "Discover the Spirit: North Dakota Official Highway Map, 1992-93". It is assumed that the biomass would be transported from production locations to processing plant by double trailer semi-truck. Each load consists of about 26 tons. Likewise a mileage matrix was developed for distance between each ethanol processing plant and each oil refinery using mileage chart in the "Road Atlas" by Rand McNally. Transportation of ethanol would be by rail from processing plant to refinery. Transportation costs were calculated in early 2009 when diesel prices were $2.30 per gallon.

Refineries

Table 4 shows the location of the oil refineries used for this study. Thirteen refineries were identified for blending the ethanol produced in North Dakota plants which will operate at about 95% capacity. They include one in North Dakota, four in Montana, two in Minnesota, three in Illinois, two in Wyoming, and one in Wisconsin.

Table 4. U.S. Oil Refineries For Blending Cellulosic Ethanol Produced In North Dakota

Location	Capacity	Gasoline/day	Ethanol/day	Ethanol/Year
	Bls/day	---------------gallons-------------		1,000 gallons
St. Paul MN	288,150	5,618,925	561,893	205,091
St. Paul MN	74,000	1,443,000	144,300	52,669
Billings MT	60,000	1,170,000	117,000	42,705
Laurel MT	59,600	1,162,200	116,220	42,420
Billings MT	58,000	1,131,000	113,100	41,282
Mandan ND	58,000	1,131,000	113,100	41,282
Great Falls MT	9,500	185,250	18,525	6,761
Superior WI	34,300	668,850	66,885	24,413
Joliet IL	238,600	4,652,700	465,270	169,823
St. Louis IL	306,000	5,967,000	596,700	217,765
Lemont IL	167,000	3,256,500	325,650	118,862
New Castle WY	14,000	273,000	27,300	9,964
Evansville WY	24,500	477,750	47,775	17,437
Total	1,391,650	27,137,175	2,713,718	990,507

Source: EIA

Water Requirement

A 100 million gallon biomass ethanol plant requires about 700 million gallons of water per year or about 2 million gallons of water per day. Table 5 shows volume of water available annually at the processing plant locations. Ground water is from aquifers while surface water is from rivers. The ground water data are from nd.water.usgs/wateruse/county_2005.html and surface water data are from ndwater.usgs.gov/data/basinmap.html. Seasonal breakdowns are not available. Water from aquifers is more consistent than river flows. The flows of many rivers in North Dakota almost stop during the dry months of the summer. Because of current water usage, it is assumed that 20% of the ground water and 10% of the surface water would be available for biomass ethanol production.

Production Cost of Ethanol

Biomass ethanol production costs were estimated using a spreadsheet developed by Oklahoma State University. The spreadsheet was developed in 2008. The spreadsheet was adapted to estimate production costs of ethanol plants from 20 million gallons to 130 million gallons. Those production costs are specified as a function of volume of ethanol production in a non-linear functual form as:

(9) $PC_j = a + b*E_j + c*E_j^{\ 2}$

Where PC_j = ethanol production costs in plant j ($/1000 gallons)
E_j = ethanol production in plant j (1000 gallons)
a = intercept term
b and c = regression coefficients.

The estimated equation is
$PC = 255.44 - 2.46x10^{-2}\ E_j + 1.33\ x\ 10^{-7}\ E_j^{\ 2}$
(-7.84) (5.69)
$R^2 = 0.947$

The first and second derivatives of the cost equations are

$$\partial PC_j / \partial PE_j = -2.46x10^{-2} + 2.66x10^{-7} E_j$$
$$\partial^2 PC_j / \partial E_j^2 = 2.66x10^{-7}$$

Setting the first derivative equal to zero and solving for E_j give the optimal size of plant as 92.5 million gallons annually.

Table 5. Total Annual Water Availability

	Ground Water*	Surface Water*
	------million gallons per year-----	
Grafton	1,825	20,705
Grand Forks	1,825	766,961
Fargo	5,475	341,173
Wahpeton	1,825	236,893
Valley City	1,825	46,771
Jamestown	1,825	26,117
Bismarck	5,475	3,934,907
Dickinson	365	11,344
Devils Lake	1,825	11,000
Rugby	365	0
Minot	5,475	13,771
Williston	1,825	4,617,733

*Source: USGS

RESULTS

Three different levels of biomass availability were evaluated; 80%, 65%, and 50% of the biomass available in North Dakota. Table 6 shows the average total transportation cost, average total production cost and the average total cost of ethanol production. The costs are listed as dollars per gallon of ethanol.

Table 6 shows, under the three scenarios, transportation costs increase and production costs decrease as the number of ethanol plants is reduced. ATPC includes a producer payment of $40[1] per ton of biomass. As the number of processing plants decreases in North Dakota, the required biomass for processing travels longer distances, resulting in increased transportation costs. However, the production costs decrease as the plants become larger under increasing returns of scale. The ACT is minimum with 10 plants in North Dakota under the three scenarios. The ACT is lower when more biomass is available for processing due mainly to economies of scale in producing ethanol.

1 The level of producer payments would not impact the size or number of plants as the payment is constant and is paid on every ton of biomass. The level would impact the production cost of ethanol.

Table 6. Average Total Transportation Costs, Average Total Processing Costs and Average Total Costs for the Production of Ethanol Under Alternative Amounts of Biomass Availability

Number of plants	80%			65%			50%		
	ATTC	ATPC	ATC	ATTC	ATPC	ATC	ATTC	ATPC	ATC
	--------------------------dollar per gallon of ethanol----------------------------------								
Base (12)	0.49	1.05	1.54	0.49	1.36	1.86	0.49	2.03	2.52
11	0.50	0.84	1.34	0.50	1.11	1.61	0.50	1.69	2.19
10	0.52	0.76	1.28	0.51	0.95	1.46	0.51	1.43	1.95
9	0.62	0.74	1.37	0.62	0.91	1.53	0.61	1.39	2.00

Figure 3 shows the location of the 12 processing plants in North Dakota and optimal flows of biomass from producing counties to the processing plants under the 80% scenario. The ATC is $1.54 per gallon of ethanol with ATTC of $0.49 per gallon and ATPC of $1.05 per gallon. The ATC decreases and reaches the minimum when the number of plants is 10 in North Dakota. The ATC increases as the number of plants decrease further to nine. The locations of those 10 plants are Grafton, Grand Forks, Fargo, Wahpeton, Valley City, Devils Lake, Minot, Williston, Bismarck, and Dickinson. Each plant produces between 100 and 127 million gallons of ethanol with an average of 121 million gallons per year under the scenario. The ATC is $1.28 per gallon with 10 plants, a 17% decrease in ATC compared to the ATC with 12 plants (Figure 4). The ATTC increases to $0.52 per gallon while the ATPC decreases to $0.76 per gallon. The ATPC is based on the production cost analysis developed by Oklahoma State University in 2008. Thus, the ATPC does not include recent changes in all the cost components occurred through advanced processing technology since 2008.

Under the 65% scenario, transportation costs also increase since biomass is shipped to plants from longer distances. Under this scenario, the optimal number of plants is 10 which include the same locations as those under the 80% scenario. The ATC is $1.46 per gallon, which is about 32% lower than the ATC in the base model with 12 plants, but 14% higher than that under the 80% scenario. The size of the plants range between 78.0 million gallons and 108.7 million gallons with an average size of 97.9 million gallons.

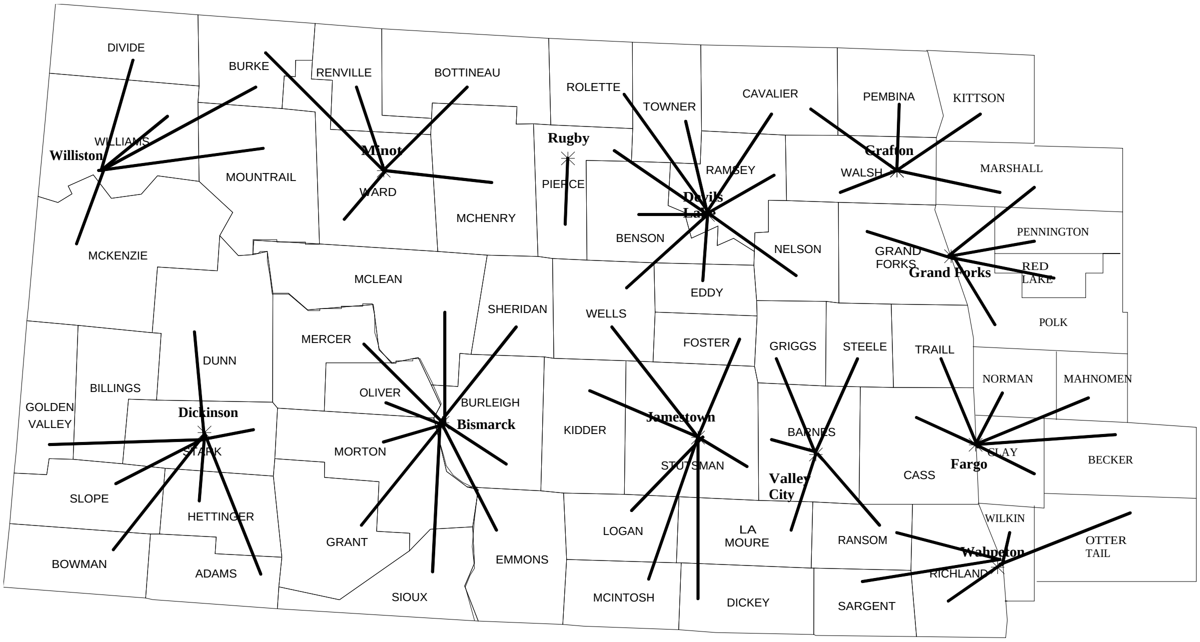

Figure 3. Sources of Biomass For Each Ethanol Production Plant, 12 Plants, the 80% Biomass Scenario

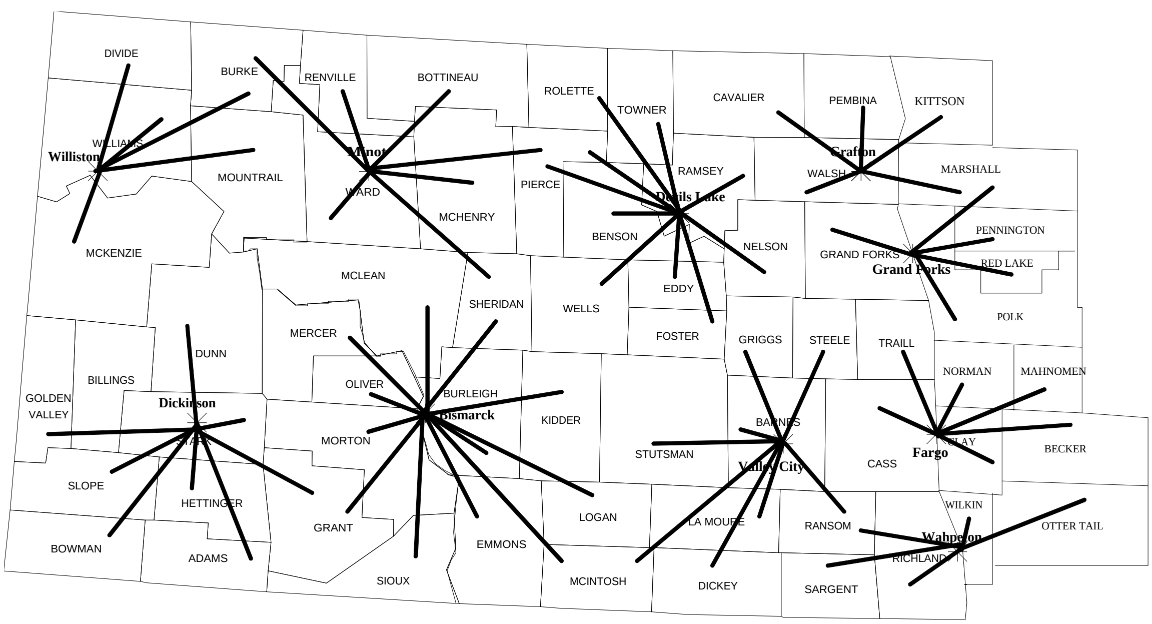

Figure 4. Sources of Biomass For Each Ethanol Production Plant, 10 Plants, the 80% Biomass Scenario

Under the 50% scenario, the least cost solution is also 10 plants. The ATC decreases from $2.52 per gallon with 12 plants to $1.95 per gallon with 10 plants. However, the ATC is about 54% higher than that under the 80% scenario. Under this scenario, the optimal locations of the plants are the same as those under the 80% scenario. ATTC increases 2% while ATPC decreases about 30% compared to the base scenario with 12 plants. The size of plant ranges between 57 million gallons per year and 85 million gallons per year with an average of 73 million gallons.

Figure 5 shows the range of ATC for nine to twelve plants in North Dakota under the 80%, 65% and 50% scenarios. Under the three scenarios, the minimum total production costs are obtained when 10 plants are chosen in North Dakota. The optimal locations of the plants are identical under the three scenarios. However, the size of each plant decreases and the ATC increases as biomass availability decreases in North Dakota.

The ATCs with 10 plants range from $3.09 per gallon to $1.28 per gallon under the 80% scenario, depending upon the location of the 10 plants, indicating that the ATC is affected by not only the number of plants in a region, but also the location of the plants. The difference of $1.81 per gallon is a 59% decrease in costs between the least efficient and most efficient combinations of plant locations. The ATC with 10 plants ranges between $3.52 and $1.46 per gallon under the 65% scenario. The ATC ranges between $3.55 and $1.95 under the 50% scenario.

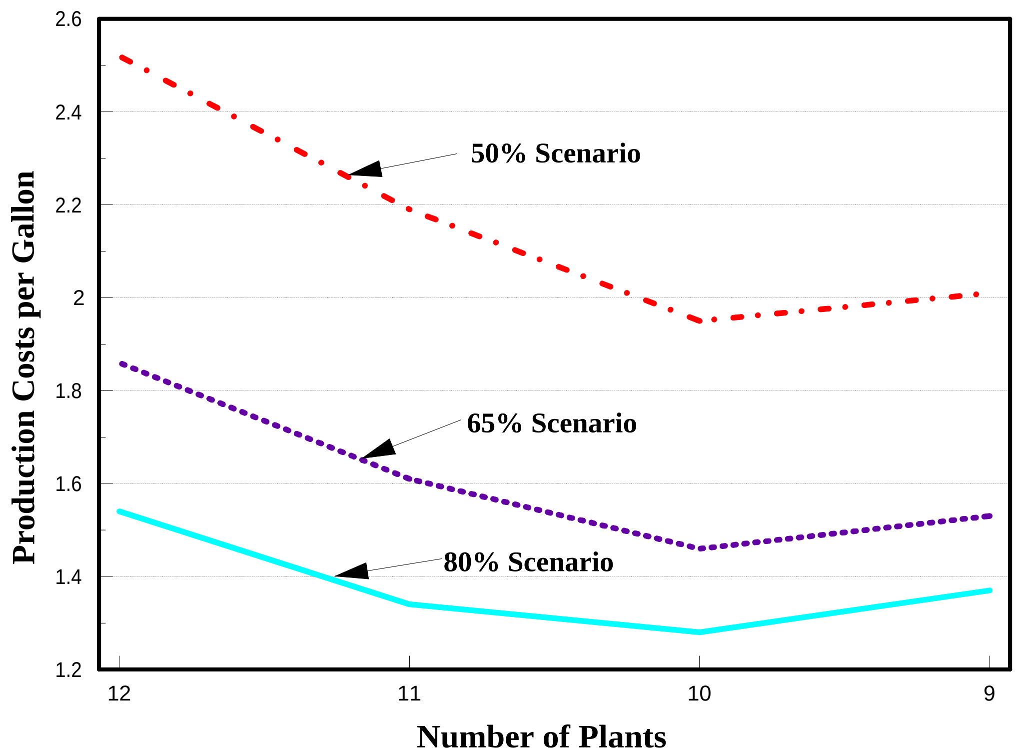

Figure 5. Minimum Production Costs for Biomass Ethanol Plants, Various Number of Plants Under the 80%, 65% and 50% Scenarios

Water availability does not seem to be a constraint in biomass ethanol production. Annual data does not show the seasonality that occurs in water availability in North Dakota. Further research would be needed utilizing monthly data to determine water constraints.

Transportation is a major cost in the production of biomass ethanol. For example with the 80% scenario, the average shipping distance is 22 miles with 12 plants, 24 miles with 10 plants and 27 miles with 9 plants. With the 65% availability scenario, shipping distance is 23 miles with 12 plants, 25 miles with 10 plants and 30 miles with 9 plants. With the 50% availability scenario, shipping distance is 22 miles with 12 plants, 23 miles with 10 plants and 29 miles with 9 plants. When biomass is limited, transportation costs increase rapidly. The transportation distance for the 50% scenario is less than the other scenarios because the plants are much smaller than the other scenarios.

Table 7 shows the average size of ethanol plants under the various scenarios. The ethanol plants are larger with higher levels of biomass availability. Average plant size of the least cost solution under the 80% scenario is 110 million gallons per year. With the 65% scenario, plant size of the least cost averages 89 million gallons per year and under the 50% scenario plant size of the least cost averages 75 million gallons per year.

Table 7. Average Ethanol Production Plant Size, Various Scenarios

	Base-12	10 plants
	--------------1000 gallons---------------	
80% Scenario	100,454	109,586
65% Scenario	81,619	89,039
50% Scenario	62,784	75,340

CONCLUSION

A heuristic approach combined with a spatial optimization model was developed to optimize the number, location and size of biomass ethanol plants in order to process alternative amounts of biomass in North Dakota. The biomass included in this study is wheat straw, corn stover, and CRP grasses. Water requirements were also included to determine which locations may have water shortages.

Three scenarios were analyzed under various assumptions of the availability of biomass. The first was that 80% of available biomass is used for ethanol production. The second assumption was that 65% of available biomass is used for ethanol production and finally, 50% of available biomass is used for ethanol production. These assumptions were made because it is highly unlikely that all biomass available in the region is collected and shipped to processing plants. Producer willingness to collect biomass would depend mainly upon the price of biomass. The relationship between biomass collected and price could be positive.

The results indicate that average total production costs are minimized when 10 plants produce ethanol in North Dakota under the three scenarios. The average total cost would be lower when more biomass is available for processing due mainly to economies of scale in producing ethanol. The lowest ATC under the 80% scenario is 14% lower than that under the 65% scenario and 52% lower than that under the 50% scenario. The optimal size of the plant which minimizes the average total cost is production capacity of over 100 million gallons of ethanol per year. Under the 65% and 50% scenarios, the size of each plant is much smaller, resulting in higher processing costs. Another important element in developing the biomass ethanol industry is the location for the processing plants to minimize the transportation cost of biomass and ethanol.

Oil prices are an important factor affecting the ethanol industry. Higher oil prices would increase transportation costs which would tend to increase the number of plants in a region, resulting in a smaller size of ethanol plant. At the same time, higher oil costs could increase ethanol prices which would tend to increase average plant size. However, the aspect of changes in oil price is not analyzed in this study. Government policy decisions are also important in determining the optimal number and size of biomass ethanol plants. Programs which subsidize production of biomass ethanol could have significant impact on the size, number and location of biomass processing plants in a region. Another important variable is biomass processing costs which are based on the production cost of cellulose ethanol from Oklahoma State University. Changes in the cost structure could cause different results regarding the size, number and location of the processing plants.

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