COUNTY-LEVEL ANALYSIS OF CROP RESIDUES AVAILABILITY FOR FUEL ETHANOL PRODUCTION IN OHIO

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ABSTRACT. *Increasing demand of corn for ethanol production places significant pressure on the availability of corn for food and animal feed. Other feedstocks such as crop residues, energy crops, wood waste, and forest residues are being considered for cellulosic ethanol production in the near future. The availability of crop residues for cellulosic ethanol production in Ohio was analyzed in this study. Results showed that two clusters of counties, each with a collection radius of less than 80 km (50 miles), had the capability to provide feedstock for two ethanol plants with feedstock demand of 5,000 dry tons per day each. These two plants would be located in the northwestern region of Ohio to produce a total of 927 million L (245 million gal) of ethanol per year. Other counties that have low biomass availability could grow energy crops such as switchgrass and provide mixed feedstocks for a cellulosic ethanol plant.*

Keywords. *Availability, Biomass, Corn, Crop residues, Ethanol, Stover, Straw, Wheat.*

Ohio corn production for grain in 2006 was about 470 million bushels (Ohio Department of Agriculture, 2007). Currently, seven ethanol plants are under construction in Ohio, which will consume about 4.2 million dry tons (165.5 million bushels) of corn and produce 1.78 billion L (469 million gal) of ethanol per year (OCGA, 2007). This ethanol production will consume more than 30% of the corn production in Ohio, placing significant pressure on the availability of corn for animal feed and human food in Ohio. The ethanol use for blended fuel (10% ethanol blends) in Ohio was 7.25 billion L (1,916 million gal) in 2004 (RFA, 2006). The seven new ethanol plants can only meet 25% of the 2004 blend ethanol needs of Ohio. The demand for ethanol in Ohio is providing a huge opportunity for farmers and biobased industries. The availability of other low-cost feedstocks, such as agricultural and forest residue and energy crops, for the production of biofuel and biobased products needs to be studied.

Agricultural residue is a low-cost feedstock for near-term bioethanol production. Corn stover and wheat straw are the most plentiful sources of agricultural residues for bioethanol production. Crop residues play an important role in protecting the soil surface from water and wind erosion and in helping to maintain nutrient levels. Corn stover includes stalks, leaves, cobs, and husks and contains approximately 35% cellulose, 22% hemicellulose, and 18% lignin (EERE, 2007). Currently in the U.S., most of the corn stover is tilled or left undisturbed on the field. Soybean is the second major crop in Ohio, with an annual average harvest of 5.68 million dry tons (209 million bushels) (Ohio Department of Agriculture, 2007). Since soybeans generate a relatively small amount of residue, which rapidly degrades in the field, soybean residue as a feedstock for ethanol production is of limited use. Therefore, soybean residue was not considered as a potential feedstock for ethanol production in this study. Wheat is the third major crop in Ohio, with an annual average harvest of 1.69 million dry tons (62 million bushels) (Ohio Department of Agriculture, 2007). Wheat straw contains approximately 33% cellulose, 23% hemicellulose, and 17% lignin (EERE, 2007).

The amount of corn stover that can be sustainably collected is estimated to be 80 to 100 million dry tons per year in the U.S. (Kadam and McMillan, 2003). Perlack and Turhollow (2003) indicated that corn stover can be collected, stored, and transported to ethanol facilities that consume 500 to 4,000 dry tons per day for about $43 to $60 per dry ton using conventional baling equipment. Transportation, collection, baling, and farmer payments account for over 90% of the total delivery cost (Perlack and Turhollow, 2003).

Jeanty et al. (2004) studied the distribution of usable crop residues among Ohio counties. Usable amounts of wheat straw and corn stover for each Ohio county were obtained. The majority of the crop residues were located in the northwestern, western, northern, and central areas. The available amount of urban wood waste and forest residues were also obtained for Ohio counties. The majority of the forest residues were located in the southeastern area of Ohio.

In this article, the availability of major crop residues (sustainable amount per square mile) in Ohio for ethanol production at the county level was investigated. The sustainable amount of crop residue in each county was calculated based on the residue yield and collection factor. Finally, counties were clustered for the purposes of identifying potential feedstock supply areas for future bioethanol plants.

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METHODOLOGY

SUSTAINABLE CROP RESIDUE

Grain production data for Ohio were obtained from the USDA National Agricultural Statistics Service (NASS, 2007). Average values of corn and wheat production in Ohio for 2005 and 2006 were used in this study. Based on the research of Kadam and McMillan (2003) and Perlack and Turhollow (2003), grain to stover ratios of 1:1 for corn and 1:0.8 for wheat were used in this study. The amount of crop residues that can be removed sustainably depends on the quantity of residue produced, the portion of the residue that can be removed without damaging soil quality, and site accessibility. The portion of residue that can be removed without damaging soil quality depends on a variety of factors, such as weather (wind, rainfall), crop rotation practices, soil fertility, slope of the land, and tillage practices. Considering the need for adequate soil cover to control soil erosion, estimates of the crop residue that can be removed have ranged from 20% (Nelson, 2002) to 35% (McAloon et al., 2000). A collection factor (percentage of crop residue removed from the field) of 35% was used in this study.

An index of biomass availability was defined as the amount of sustainable crop residue per square kilometer (mile). It is the sustainable amount of crop residue that can be collected per square kilometer (mile). The land area of each county was obtained from the state agricultural report sources (Ohio Department of Development, 2007). Biomass availability is an important index to evaluate the collection cost of biomass for ethanol production.

BIOETHANOL PRODUCTION POTENTIAL

There is considerable variation in the literature with regard to the yield of ethanol from a given substrate. Yield is affected by the composition of the crop residues and by the ethanol production technologies. Using the online toolkit provide by the National Renewable Energy Laboratory (NREL, 2007), the theoretical ethanol yield for corn stover was calculated to be 415 L per dry ton (113 gal per dry ton) with an average corn stover composition and assuming that both hexose and pentose sugars are fermented. An estimated ethanol yield of 300 L per dry ton (79.3 gal per dry ton) was used for corn stover in this study, which is about 64% of theoretical ethanol yield. An ethanol yield of 292 L per dry ton (77.1 gal per dry ton), used by Kadam and McMillan (2003) to estimate the national ethanol potential in the U.S. from wheat straw, was used in this study to predict the ethanol potential of wheat straw. The hydrolysis technologies assumed are either dilute acid hydrolysis or enzymatic hydrolysis. The fermentation process should be able to convert hexose and some of the pentose.

RESULTS AND DISCUSSION

BIOMASS AVAILABILITY

The total sustainable amount of corn stover and wheat straw in Ohio was estimated to be 4.6 and 0.7 million dry tons per year, respectively. The majority (85%) of these crop residues are located in the northwestern and central regions of Ohio. The sustainable amount of crop residues in 43 counties in the northwestern and central region was estimated to be 4.5 million dry tons (table 1).

The biomass availability of corn stover for each county of Ohio is shown in figure 1. The total amount of crop residues (corn stover and wheat straw) is shown in figure 2. The biomass availability of each county is distinguished with a dif–

Table 1. Biomass availability and ethanol potential for the top 43 counties of Ohio.

		Land Area		Collectable Biomass Amount (t)			Biomass Availability		Ethanol Potential	
	County	(mile^2)	(km^2)	Corn Stover	Wheat Straw	Total	(t mile^{-2})	(t km^{-2})	(gal)	(L)
1	Fulton	407	1,054	136,013	18,714	154,727	380	147	10,073,087	38,126,633
2	Henry	417	1,079	117,285	31,156	148,441	356	138	9,663,871	36,577,753
3	Crawford	402	1,041	118,968	18,841	137,809	343	132	8,971,715	33,957,941
4	Mercer	463	1,200	131,830	19,775	151,605	327	126	9,869,837	37,357,333
5	Darke	600	1,553	172,484	17,480	189,964	317	122	12,367,097	46,809,461
6	Van Wert	410	1,062	109,298	19,425	128,723	314	121	8,380,185	31,719,002
7	Wood	617	1,599	145,284	43,429	188,713	306	118	12,285,678	46,501,292
8	Putnam	484	1,253	107,734	37,974	145,708	301	116	9,485,937	35,904,270
9	Hardin	470	1,218	122,026	14,701	136,727	291	112	8,901,243	33,691,204
10	Wyandot	406	1,051	97,613	19,681	117,294	289	112	7,636,127	28,902,742
11	Hancock	531	1,376	117,459	31,664	149,123	281	108	9,708,294	36,745,895
12	Auglaize	401	1,039	93,257	19,345	112,602	281	108	7,330,660	27,746,550
13	Madison	465	1,205	121,426	8,894	130,320	280	108	8,484,171	32,112,587
14	Sandusky	409	1,060	98,040	16,070	114,110	279	108	7,428,836	28,118,142
15	Preble	425	1,100	113,157	5,210	118,367	279	108	7,706,002	29,167,219
16	Shelby	409	1,060	97,489	13,326	110,816	271	105	7,214,371	27,306,393
17	Fayette	407	1,053	99,173	8,704	107,877	265	102	7,023,029	26,582,164
18	Miami	407	1,054	100,571	6,838	107,409	264	102	6,992,564	26,466,855
19	Seneca	551	1,426	114,389	30,198	144,587	263	101	9,412,963	35,628,064
20	Pickaway	502	1,300	107,669	18,061	125,729	251	97	8,185,275	30,981,267
21	Paulding	416	1,078	70,082	34,103	104,185	250	97	6,782,670	25,672,406
22	Allen	404	1,047	86,146	14,727	100,873	249	96	6,567,098	24,856,465
23	Champaign	429	1,110	101,613	4,863	106,476	248	96	6,931,831	26,236,979
24	Clinton	411	1,064	92,760	4,460	97,220	237	91	6,329,277	23,956,315
25	Clark	400	1,036	88,666	3,381	92,046	230	89	5,992,430	22,681,347

(continued)

Table 1 (cont'd). Biomass availability and ethanol potential for the top 43 counties of Ohio.

		Land Area		Collectable Biomass Amount (t)			Biomass Availability		Ethanol Potential	
	County	(mile^2)	(km^2)	Corn Stover	Wheat Straw	Total	(t mile^{-2})	(t km^{-2})	(gal)	(L)
26	Huron	493	1,276	97,161	16,240	113,401	230	89	7,382,685	27,943,463
27	Marion	404	1,046	82,422	10,219	92,641	229	89	6,031,170	22,827,980
28	Williams	422	1,092	75,949	19,466	95,415	226	87	6,211,757	23,511,501
29	Logan	458	1,187	93,897	7,860	101,757	222	86	6,624,614	25,074,163
30	Greene	415	1,075	84,574	4,123	88,697	214	83	5,774,401	21,856,109
31	Defiance	411	1,065	68,667	16,874	85,541	208	80	5,568,896	21,078,270
32	Erie	255	660	46,618	6,213	52,830	207	80	3,439,377	13,018,041
33	Union	437	1,131	72,507	10,220	82,727	189	73	5,385,711	20,384,917
34	Morrow	406	1,052	57,296	9,691	66,987	165	64	4,360,982	16,506,317
35	Ottawa	255	660	30,470	10,555	41,025	161	62	2,670,829	10,109,086
36	Fairfield	505	1,308	69,638	10,172	79,811	158	61	5,195,869	19,666,363
37	Delaware	442	1,146	52,800	8,830	61,629	139	54	4,012,226	15,186,277
38	Wayne	555	1,438	69,750	7,409	77,159	139	54	5,023,230	19,012,924
39	Knox	527	1,365	65,085	4,002	69,087	131	51	4,497,729	17,023,904
40	Lucas	340	882	36,558	5,425	41,983	123	48	2,733,203	10,345,172
41	Ashland	424	1,099	42,678	5,537	48,215	114	44	3,138,900	11,880,736
42	Montgomery	462	1,196	49,708	2,511	52,219	113	44	3,399,556	12,867,320
43	Licking	687	1,778	64,797	4,912	69,709	102	39	4,538,219	17,177,160
	Total	19,142	49,576	3,921,005	621,280	4,542,284	237	92	295,713,602	1,119,275,982

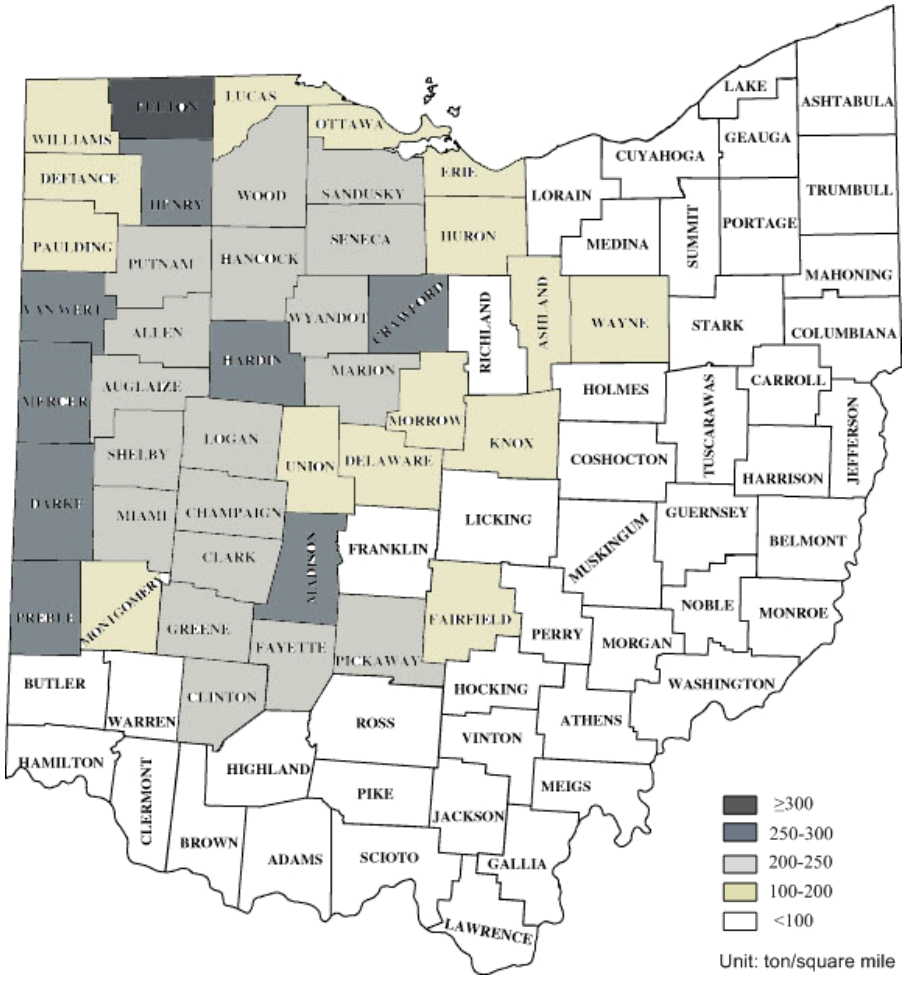

Figure 1. Availability of corn stover in Ohio on county basis.

ferent color based on the sustainable amount of crop residue per square mile. Fulton County has the highest total biomass availability at 147 dry tons km^{-2} (380 dry tons mile^{-2}). The biomass availability of eight counties (Fulton, Henry, Crawford, Mercer, Darke, Van Wert, Wood, and Putnam) falls between 115 and 155 dry ton km^{-2} (300 to 400 dry tons mile^{-2}).

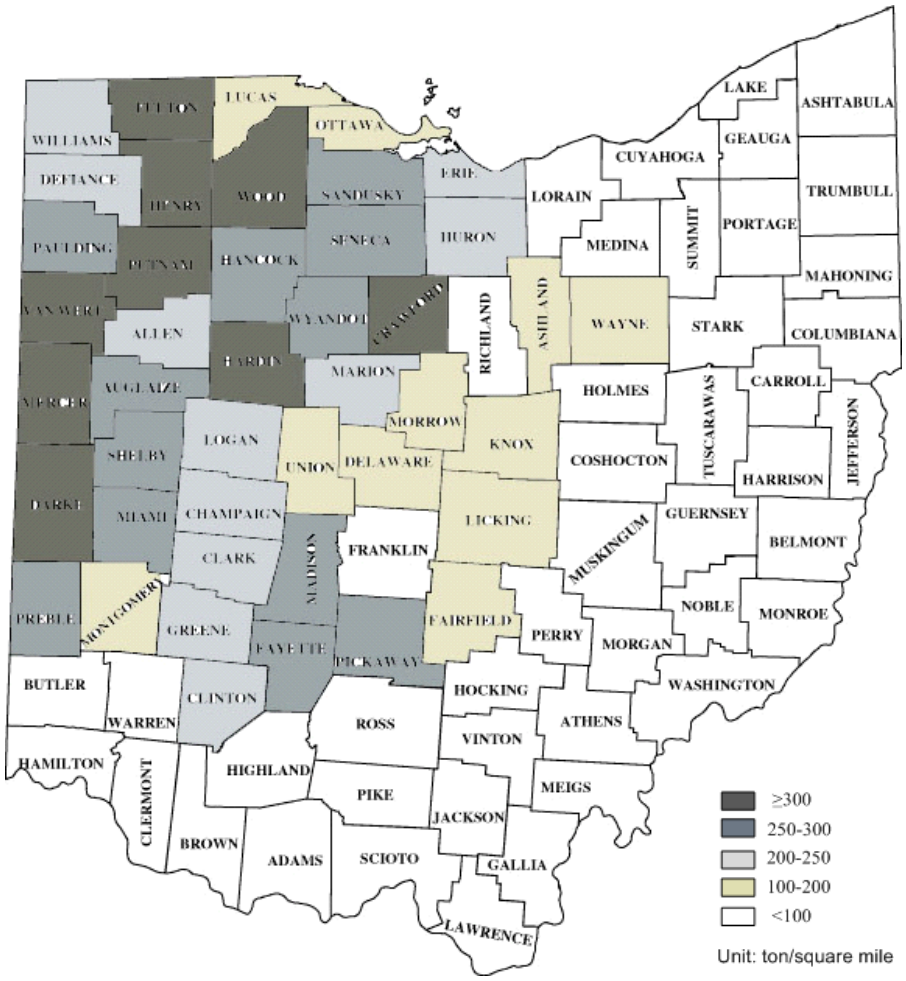

Figure 2. Availability of crop residues (corn stover and wheat straw) in Ohio on county basis.

Bioethanol Production Potential

Bioethanol potential from crop residues in Ohio was estimated to be about 1.3 billion L (343 million gal) per year. The bioethanol potential from crop residues in the 43 northwestern and central counties of Ohio was estimated to be about 1.1 billion L (295 million gal) per year, which would account for about 85% of the total ethanol potential from crop residues in Ohio.

The delivery cost of biomass is the most important factor for the bioethanol producer. Nearly one-third of the biomass ethanol cost can be attributed to the cost of feedstock (Perlack and Turhollow, 2003). The total feedstock cost includes handling costs and any payments to the landowner. The cost of delivery of feedstock from the farm to an ethanol plant is mainly a function of the transportation distance. The scale of the bioethanol conversion facilities is relatively significant for the economy of bioethanol production. Generally, capital costs for ethanol plants increase by 60% to 70% for each doubling of output capacity (Perlack and Turhollow, 2003). As plants increase in capacity, the cost saving from economies of scale can be offset somewhat by increased transportation costs associated with hauling feedstock greater distances. Consequently, the ideal location of an ethanol plant involves striking a balance between larger handling capacities and higher feedstock costs.

Based on considerations of economies of scale and biomass availability, the optimal locations of potential ethanol plants in Ohio were studied. Feedstock transportation cost was assumed to have a fixed component of \$5.50 per dry ton and a variable component of \$0.55 km^{-1} (\$0.88 mile^{-1}) (Kerstetter and Lyons, 2001). The transportation cost can be calculated with equation 1 according to the collection radius:

$$C = \frac{\int_0^{r_0} (5.50 + 0.55r) \cdot 2\pi r \cdot \overline{B_a}\, dr}{\pi r_0^{\,2} \cdot \overline{B_a}} = 5.50 + 0.367 r_0 \quad (1)$$

where C is the transportation cost (\$ t^{-1}), r_0 is the collection radius (km), r is radius (km), and $\overline{B_a}$ is the average biomass availability of the region (t km^{-2}).

Based on the amounts of crop residue and land area of each county, counties with high biomass availability were clustered to provide two ethanol plants with feedstock demands of 6,783 and 5,743 dry tons per day, respectively (fig. 3).

Cluster 1 consists of seventeen counties including: Crawford, Fulton, Henry, Van Wert, Wood, Putnam, Hardin, Wyandot, Hancock, Sandusky, Seneca, Paulding, Allen, Williams, Defiance, Ottawa, and Lucas (fig. 3). These seventeen counties can sustainably produce 6,783 dry tons of residues per day, which can supply an ethanol plant with a capacity of 503 million L (133 million gal) ethanol per year. The equivalent collection radius for this ethanol plant was estimated to be 77 km (48 miles). The equivalent collection ra–

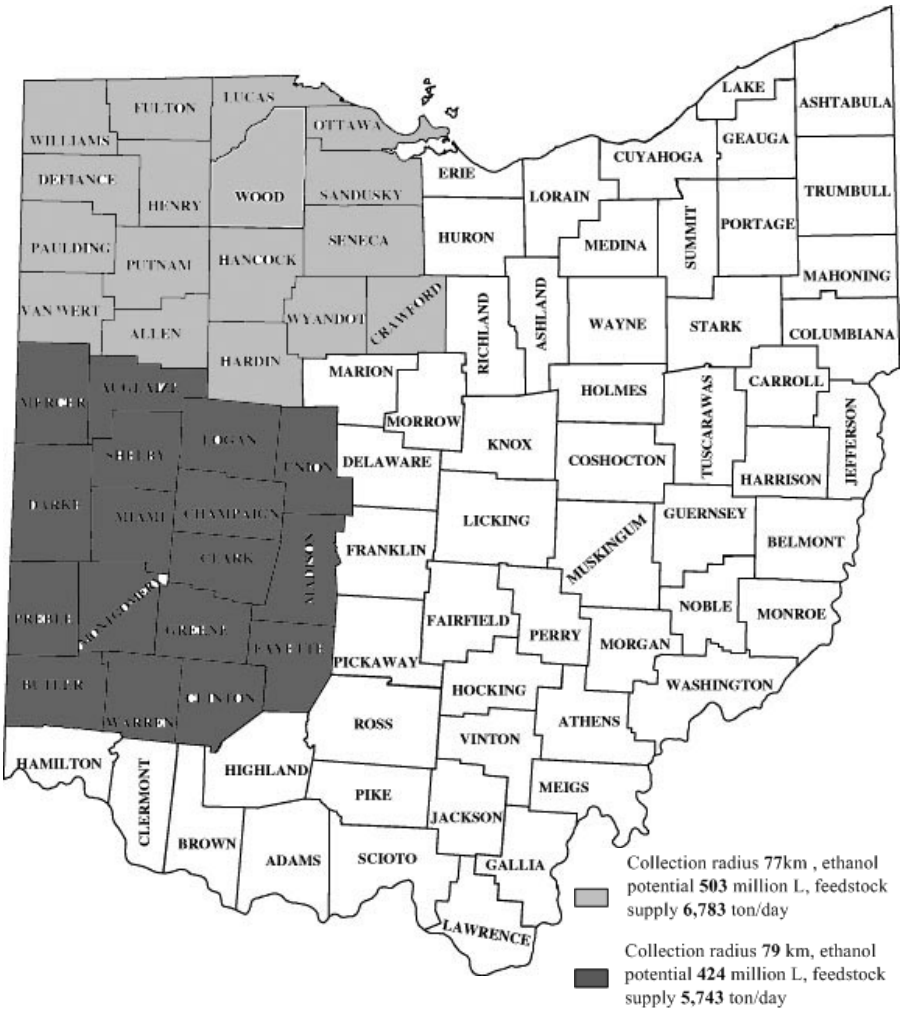

Figure 3. Clusters of counties for ethanol production in Ohio.

dius was calculated based on the total area of the counties in the cluster. The transportation cost for this cluster was estimated to be about \$33.76 ton^{-1} based on equation 1.

Cluster 2 consists of seventeen counties including: Mercer, Darke, Auglaize, Madison, Preble, Shelby, Fayette, Miami, Warren, Champaign, Clinton, Clark, Logan, Greene, Union, Montgomery, and Butler (fig. 3). These seventeen counties can sustainably produce 5,743 dry tons of residues per day, which can supply an ethanol plant with a capacity of 424 million L (112 million gal) ethanol per year. The equivalent collection radius for this cluster was estimated to be 79 km (49 miles). The transportation cost for this cluster was estimated to be about \$34.49 ton^{-1} based on equation 1.

These clusters of counties are just selected examples of how to combine counties to provide feedstock for a potential ethanol plant within a minimum collection radius. The location of any future ethanol plant would be determined using the biomass availability of each county. This methodology could also be used to analyze the ethanol potential and best location of a potential ethanol plant in other states.

Counties with less supply of crop residues generally might have other cellulosic biomass such as wood waste or municipal solid waste (MSW) in suburban areas. It is possible to provide mixed feedstock for a cellulosic ethanol plant in those areas.

Conclusion

- Crop residues of corn stover and wheat straw were considered in this study. More than 85% of the crop residues in Ohio are located in the northwestern and central regions.
- Corn stover and wheat straw in the 43 counties in the northwestern and central regions of Ohio can be utilized to produce about 1.1 billion L (295 million gal) of ethanol per year.
- The best location for bioethanol production in Ohio is in the northwestern region. Two clusters of counties have the capability to provide more than 5,000 dry tons of feedstock per day for each ethanol plant with a collection radius of less than 80 km (50 miles).
- Other feedstocks, such as wood waste, MSW, and energy crops, should be further studied in the future.

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REFERENCES

EERE. 2007. Biomass feedstock composition and property database. Washington, D.C.: U.S. Department of Energy. Available at: www1.eere.energy.gov/biomass/feedstock_databases.html. Accessed 20 November 2007.

Jeanty, P. M., D. Warren, and F. Hitzhusen. 2004. Assessing Ohio's biomass resources for energy potential using GIS. Report to the Ohio Department of Development.

Kadam, K. L., and J. D. McMillan. 2003. Availability of corn stover as a sustainable feedstock for bioethanol production. *Bioresour. Tech.* 88(1): 17-25.

Kerstetter, J. D., and J. K. Lyons. 2001, Logging and agricultural residue supply curves for the Pacific Northwest. Report prepared for the U.S. Department of Energy. Available at: www.energy.wsu.edu/documents/renewables/SupplyCurveReport.pdf. Accessed 17 June 2008.

McAloon, A., F. Taylor, W. Yee, K. Ibsen, and R. Wooley. 2000. Determining the cost of producing ethanol from cornstarch and lignocellulosic feedstocks. Tech. Rep. NREL/TP-580-28893. Golden, Colo.: National Renewable Energy Laboratory.

NASS. 2007. Agricultural statistics data base: U.S. and state data. Washington, D.C.: USDA National Agricultural Statistics Service. Available at: www.nass.usda.gov/Data_and_Statistics/Quick_Stats/. Accessed 13 November 2007.

Nelson, R. G. 2002. Resource assessment and removal analysis for corn stover and wheat straw in the eastern and midwestern United States: Rainfall and wind-induced soil erosion methodology. *Biomass Bioenergy* 22(5): 349-363.

NREL. 2007. Theoretical ethanol yield calculator. Washington, D.C.: U.S. Department of Energy. Available at: www.eere.energy.gov/biomass/ethanol_yield_calculatorhtml. Accessed 31 November 2007.

OCGA. 2007. Ohio ethanol plants. Marion, Ohio: Ohio Corn Growers Association. Available at: www.ohiocorn.org/Ethanolstills.pdf.

Ohio Department of Agriculture. 2007. 2006 annual report. Washington, D.C.: USDA National Agricultural Statistics Service, Ohio Field Office.

Ohio Department of Development. 2007. Ohio county profiles. Columbus, Ohio: Ohio Department of Development. Available at: www.odod.state.oh.us/research/files/s0.htm. Accessed 10 November 2007.

Perlack, R. D., and A. F. Turhollow. 2003. Feedstock cost analysis of corn stover residues for further processing. *Energy* 28(14): 1395-1403.

RFA. 2006. From niche to nation: Ethanol industry outlook 2006. Washington, D.C.: Renewable Fuels Association. Available at: www.ethanolrfa.org/objects/pdf/outlook/outlook_2006.pdf. Accessed 3 December 2007.