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Introduction to the Proceedings of the Twenty-Seventh Symposium on Biotechnology for Fuels and Chemicals

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The Twenty-Seventh Symposium on Biotechnology for Fuels and Chemicals was held May 1–4, 2005 in Denver, Colorado. Continuing to foster a highly interdisciplinary focus on bioprocessing, this symposium remains the preeminent forum for bringing together active participants and organizations to exchange technical information and update current trends in the development and application of biotechnology for sustainable production of fuels and chemicals. This annual symposium emphasizes advances in biotechnology to produce high-volume, low-price products from renewable resources, as well as to improve the environment. Topical foci include advanced feedstock production and processing, enzymatic and microbial biocatalysis, bioprocess research and development, opportunities in biorefineries, commercialization of biobased products, as well as other special topics.

Advances in commercialization of bioproducts continued apace this year, and the level of interest and excitement in expanding the use of renewable feedstocks continued to grow. Nonetheless, significant techno-economic challenges must be overcome to achieve widespread commercialization of biotechnological fuels and chemicals production, particularly to move the feedstock base beyond primarily sugar crops and cereal grains (starch) to include holocellulose (cellulose and hemicellulose) from fibrous lignocellulosic plant materials.

Participants from academic, industrial, and government venues gathered to discuss the latest research breakthroughs and results in biotechnology to improve the economics of producing fuels and chemicals. The total of 459 attendees represented an all-time conference high; this is almost a 33% increase over the 2004 conference attendance in Chattanooga. Of this total, approximately 45% of attendees were from academia (about half of this, more than 21% of the total attendees, were students), 31% were from industry, and 22% were from government. A total of 71 oral presentations (including Special Topic presentations) and 329 poster presentations were delivered. The high number of poster submissions required splitting the poster session into two evening sessions. (Conference details are posted at http://www.eere.energy.gov/biomass/biotech_symposium/.)

Almost 35% of the attendees were international, showing the strong and building worldwide interest in this area. Nations represented included Australia, Austria, Belgium, Brazil, Canada, Central African Republic, China, Denmark, Finland, France, Gambia, Germany, Hungary, India, Indonesia, Italy, Japan, Mexico, The Netherlands, New Zealand, Portugal, South Africa, South Korea, Spain, Sweden, Thailand, Turkey, United Kingdom, and Venezuela, as well as the United States.

One of the focus areas for bioconversion of renewable resources into fuels is conversion of lignocellulose into sugars and the conversion of sugars into fuels and other products. This focus is continuing to expand toward the more encompassing concept of the integrated multiproduct biorefinery—where the production of multiple fuel, chemical, and energy products occurs at one site using a combination of biochemical and thermochemical conversion technologies. The biorefinery concept continues to grow as a unifying framework and vision, and the biorefinery theme featured prominently in many talks and presentations. However, another emerging theme was the importance of examining and optimizing the entire biorefining process rather than just its bioconversion-related elements.

The conference continued to include two Special Topics sessions devoted to discussing areas of particular interest. This year the two topics were international biofuels developments and the evolving attitudes about biomass as a sustainable feedstock for fuels, chemicals and energy production. The first Special Topic session was entitled "International Energy Agency (IEA) Task #39–Liquid Biofuels." This session focused on recent international progress on production of liquid biofuels and was chaired by Jack Saddler of the University of British Columbia. The second Special Topic session was entitled, "'Outside of a Small Circle of Friends': Changing Attitudes about Biomass as a Sustainable Energy Supply," and was chaired by John Sheehan of NREL. This session focused on the evolving perceptions within the agricultural producer and environmental and energy efficiency advocacy communities that biomass has the potential to be a large volume renewable resource for sustainable production of a variety of fuel, chemical, and energy products.

The Charles D. Scott award for Distinguished Contributions in the field of Biotechnology for Fuels and Chemicals was created to honor Symposium founder Dr. Charles D. Scott who chaired this Symposium for its first ten years. This year, the Charles D. Scott award was presented to Lee R. Lynd. Dr. Lynd is a Professor of Engineering and an Adjunct Professor of Biology at Dartmouth College, as well as a Professor Extraordinary of Microbiology at the University of Stellenbosch, South Africa. He has made many pioneering contributions to bioenergy and biomass conversion. Most impressively, his activities and accomplishments span the science, technology and policy domains. Highlights include improving our fundamental understanding of microbial cellulose utilization, advancing the design and evaluation of biomass conversion processes and providing a variety of critical analyses and inputs to policy makers in support of bioenergy. An active consultant and frequently invited presenter on technical and strategic aspects of biomass energy, Dr. Lynd has twice testified before the US Senate. He recently co-led a large multi-institutional project entitled *The Role of Biomass in America's Energy Future*. The author of more than sixty peer-reviewed papers and several comprehensive reviews, and the holder of five patents, the field of biotechnology for fuels and chemicals would not be the same were it not for Dr. Lynd's tireless and inspired efforts.

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Chairs: Joel R. Cherry, *Novozymes, Inc., Davis, CA*
Kevin Gray, *Diversa Corporation, San Diego, CA*

Session 2: Today's Biorefineries
Chairs: Robert Benson, *Tembec Chemical Products Group, North Bay, Ontario, Canada*
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Chairs: Wilfred Vermerris, *Purdue University, West Lafayette, IN*
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Session 3B: Biomass Pretreatment and Hydrolysis
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Session 4: Industrial Biobased Products
Chairs: Ray Miller, *E. I. DuPont de Nemours and Co., Inc., Wilmington, DE*
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Session 5: Microbial Catalysis and Metabolic Engineering
Chairs: Lisbeth Olsson, *BioCentrum–DTU, Technical University of Denmark, Lyngby, Denmark*
Aristos Aristidou, *Natureworks LLC, Minnetonka, MN*

Session 6: Bioprocess Research and Development
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5. "Proceedings of the Fifth Symposium on Biotechnology for Fuels and Chemicals" (1983), *Biotechnol. Bioeng. Symp.* **13.**
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20. "Proceedings of the Twentieth Symposium on Biotechnology for Fuels and Chemicals" (1999), *Appl. Biochem. Biotechnol.* **77–79.**
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25. "Proceedings of the Twenty-Fifth Symposium on Biotechnology for Fuels and Chemicals" (2004), *Appl. Biochem. Biotechnol.* **113–116.**
26. "Proceedings of the Twenty-Sixth Symposium on Biotechnology for Fuels and Chemicals" (2005), *Appl. Biochem. Biotechnol.* **121–124.**

This symposium has been held annually since 1978. We are pleased to have the proceedings of the Twenty-Seventh Symposium currently published in this special issue to continue the tradition of providing a record of the contributions made.

The Twenty-Eighth Symposium will be April 30–May 3, 2006 in Nashville, Tennessee. More information on the 27th and 28th Symposia is available at the following websites: [http://www.eere.energy.gov/biomass/biotech_symposium/] and [http://www.simhq.org/html/meetings/]. We encourage comments or discussions relevant to the format or content of the meeting.

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SESSION 1A
Feedstock Supply and Logistics

Introduction to Session 1A

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Using biomass as a source of energy and chemicals presents challenges in sourcing, moving and processing the biomass, and in using the products. Session 1A of the *27th Symposium on Biotechnology for Fuels and Chemicals* illustrates the range of research across this broad spectrum.

Three articles from this session address biomass availability: is there enough biomass to make a meaningful impact in a new energy economy? Haq and Easterly look at the availability of agricultural residues across the United States, and Shahbazi and Li focus more narrowly on whether there is a sustainable source of crop residues to support bioethanol in the State of North Carolina. Mabee and his coworkers report on biomass reserves in Canada, including both agricultural and woody biomass. In general, we can extrapolate that availability is not a limiting factor: there are abundant residues that can feed biomass processes.

Transportation of biomass is a critical cost factor because biomass has both a lower energy density (MJ/kg) than fossil fuels and a lower bulk density (kg/cubic meter). One article from this session by Mahmudi and Flynn takes a detailed look at the relative economics of rail vs truck transport, and in particular, focuses on the extra cost incurred when biomass is unloaded from a truck and trans-shipped by rail. A second article by Kumar, Sokhansanj, and Flynn develops a methodology to rank the relative merits of alternatives to collect and transport biomass when multiple criteria form the basis of selection, for example cost and environmental or community impact.

Separation and characterization of fractions of biomass and it processed products is another area of active research. Akin and his coworkers have studied corn stover fractions in detail, characterizing their chemical composition and structure. Phenols are a troublesome byproduct in many biomass processing schemes, and das Neves and his coworkers report on the removal of phenolic residues by biofiltration methods.

Three process-oriented articles came from this session. Olsson and her coworkers report on separate enzymatic hydrolysis and fermentation of wheat hemicellulose and compare it with combining these steps simultaneously. Mabee and his coworkers report on developments in converting softwood biomass, e.g., from pine and spruce, into ethanol, overcoming problems of more refractory composition of the biomass. And, Raffelt and his coworkers report on a two-step processing of biomass in which a pyrolysed slurry is produced in distributed centers and the slurry is then transported to a central large gasifier. These articles illustrate the broad range of processes under active consideration by researchers.

Finally, Jeong and Park look at the emissions profile from using rapeseed methyl esters, i.e., bio-oil, as a diesel fuel.

Together, this session's articles reflect the broad range of technical research issues that arise from sourcing, transporting and processing biomass to energy and chemicals.

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Agricultural Residue Availability in the United States

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Abstract

The National Energy Modeling System (NEMS) is used by the Energy Information Administration (EIA) to forecast US energy production, consumption, and price trends for a 25-yr-time horizon. Biomass is one of the technologies within NEMS, which plays a key role in several scenarios. An endogenously determined biomass supply schedule is used to derive the price–quantity relationship of biomass. There are four components to the NEMS biomass supply schedule including: agricultural residues, energy crops, forestry residues, and urban wood waste/mill residues. The EIA's *Annual Energy Outlook 2005* includes updated estimates of the agricultural residue portion of the biomass supply schedule. The changes from previous agricultural residue supply estimates include: revised assumptions concerning corn stover and wheat straw residue availabilities, inclusion of non-corn and non-wheat agricultural residues (such as barley, rice straw, and sugarcane bagasse), and the implementation of assumptions concerning increases in no-till farming. This article will discuss the impact of these changes on the supply schedule.

Index Entries: Agricultural residues; corn stover; wheat straw; feedstock cost; biomass supply.

Introduction

The Energy Information Administration (EIA) estimates that there is 491 million dry tons (t) (445 million dry metric tons [mt]) of biomass available in the United States on an annual basis. EIA has compiled available biomass resource estimates from Oak Ridge National Laboratory (ORNL) *(1)*, Antares Group, Inc. *(2)*, and the US Department of Agriculture (USDA) *(3)*. This article discusses how these data are used for forecasting purposes by the National Energy Modeling System (NEMS). One of the key determinants for the growth of biomass is the price–quantity relationship of biomass feedstocks. The raw data for the supply curves are available at the state or county level and these are aggregated to form regional supply schedules. Supply data are available for four fuel types: agricultural residues, energy crops, forestry residues, and urban wood waste/mill residues.

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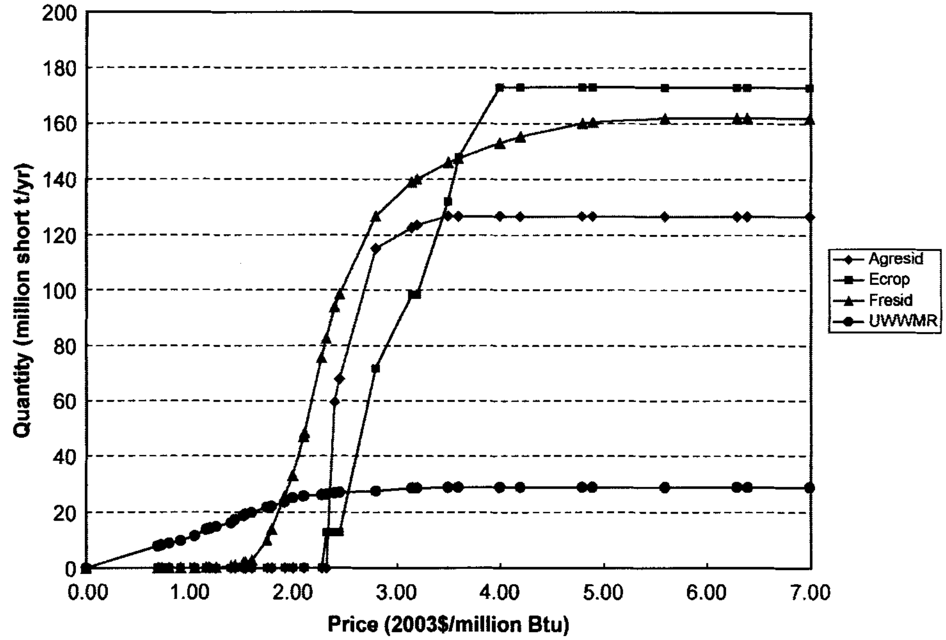

Fig. 1. Biomass resource availability, 2025.

Figure 1 shows the variation in biomass resource as a function of price. A relatively small portion of biomass supply is available at $1.50/million Btu ($1.42/GJ) or less. As a point of comparison, EIA's *Annual Energy Outlook 2005 (AEO2005) (4)* projects coal prices to remain relatively stable (compared with natural gas prices) at $1.28/million Btu ($1.21/GJ) in 2003 to $1.31/million Btu ($1.24/GJ) (in real 2003$) by 2025. Feedstock cost is a major factor that limits biomass growth under AEO2005 reference case assumptions. The available low-cost feedstock (at less than $1.50/million Btu [$1.42/GJ]) is almost exclusively urban wood waste/mill residue. This category of biomass continues to be the only significant resource available at prices up to approx $2/million Btu ($1.90/GJ). At $2/million Btu ($1.90/GJ) and higher, agricultural residues become viable as a second source of biomass. Energy crops and forestry residues begin to make significant contributions at prices around $2.30/million Btu ($2.18/GJ) or higher.

Agricultural Residues

The underlying assumption behind the agricultural residue supply curve is that after each harvesting cycle of agricultural crops, a portion of the stalks can be collected and used for energy production. Agricultural residues cannot be completely extracted, because some of them have to remain on the soil to maintain soil quality (i.e., for erosion control, carbon content, and long-term productivity). The Department of Energy (DOE)

Biomass Program is currently focusing on agricultural residues as the primary (and most likely) source of biomass feedstock supplies for the growing bioenergy industry over the next 10–15 yr. Given the importance of agricultural residues with respect to bioenergy commercialization, EIA decided to update the agricultural residue component of their biomass supply curve in modeling projected energy supplies for AEO2005 and other service requests. Specifically, three aspects of the agricultural residue supply were revised: updated corn stover availability, inclusion of residues other than corn stover and wheat straw, and incorporation of assumptions regarding no-till farming practices in the United States.

Over the last few years a substantial amount of effort has been devoted to developing new county-level estimates of potential corn stover residues, taking into account environmental considerations regarding the amount of corn stover that can be harvested when soil erosion constraints are considered. New estimates have also been made regarding the potential increase in corn stover resources that could be available if no-till cultivation practices were to be more widely adopted (currently 20% of US corn grain is produced using no-till cultivation *[5]*). No-till farming generally allows for a greater portion of the corn stover to be removed because erosion problems and constraints are substantially reduced. Since 1990, the number of acres of farmland using no-till cultivation has increased by about 1%/yr on average. The Conservation Technology Information Center (CTIC) notes that "50% of cropland acres are suitable for some form of conservation tillage to mitigate soil loss" *(6)*.

Corn Stover Revisions

ORNL recently completed new county-level estimates of available and sustainably removable corn stover for the United States. *(7)*. These estimates include projected costs for the stover at the "farm gate."* These costs include nutrient replacement costs (estimated at $6.50/dry t [$7.17/dry mt] of stover removed), as well as fixed and variable collection costs for producing and delivering round bales of corn stover (stems/leaves/cobs) wrapped with twine and left at the edge of the field. Payments for a farmer premium/profit, as well as transportation costs from the farm-gate to a conversion facility, were treated as separate additional costs. Supply has been constrained by equipment harvest efficiency (75% of gross) and the need to leave residues to limit rain and wind erosion to tolerable losses and to maintain soil moisture in rain-limited regions.

Two sets of new corn stover availability estimates were obtained from ORNL: (1) A base-case assuming corn is produced with the current mix of agricultural tillage and crop rotation practices and; (2) upper-bound case assuming all corn grain would be produced using no-till practices. There

*These costs do not include transportation and handling costs for delivering the stover from the farms to a conversion facility.

are various farm-specific soil and crop rotation constraints that limit the maximum percent of overall no-till acres that can be adopted in the United States. The all no-till scenario provides a useful upper-level benchmark in estimating potential future stover supplies. As noted earlier *(6)*, approx 50% of US farms could use conservation tillage practices such as no-till, thus we viewed 50% no-till as the practical upper limit for this cultivation approach. In our analysis we assumed that no-till corn production would reach a level of 30% by the year 2025; this would be a 10% increase in no-till cultivation practices as compared with current practices in which about 20% of corn production is via no-till. A continuation in the trend toward increased no-till farming practices is considered likely owing to soil conservation requirements under US Farm Bill programs, and growth of markets for the production of biofuels and bioproducts from cellulosic feedstocks such as corn stover.

Base-case estimates for corn stover are shown in Table 1. The total amount of corn stover available with current tillage practices is about 64 million dry t/yr (58 million dry mt/yr) (30% of the gross amount, after taking into account the need to leave some of the residue for erosion protection and other soil quality concerns). For the all no-till scenario, Table 1 shows an estimated 111 million dry t/yr (101 million dry mt/yr) of sustainably removable corn stover (51.5% of the gross amount, taking into account the fact that less corn stover would need to be left in the field with no-till practices) this amount of sustainably removable corn stover is shown in the column labeled "total available supply" in Table 1 (note that most, but not all of this amount is estimated to be available at less than $40/dry t [$44/dry mt]; a small fraction of the total is estimated to cost more than $40/dry t [$44/dry mt]).

The base-case numbers from the prior ORNL year 2000 estimate of corn stover availability *(1)* indicated that a maximum of 119 million dry t/yr (108 million dry mt/yr) of corn stover was available. The new ORNL base-case numbers reflect a significant reduction in anticipated corn stover availability, now that in-depth county-level considerations regarding erosion constraints have been addressed. For the new EIA biomass supply curve, the old maximum of 119 million dry t (108 million dry mt) of stover has been replaced with the new estimate of 62.7 million dry t (56.9 million dry mt) of stover available at less than $40/dry t ($44/dry mt) (farm-gate costs) for the year 2005. Anticipating that no-till practices for corn production will increase over time, the new EIA biomass supply curve assumes that no-till practices will increase from the current level of 20% no-till in year 2005 to 30% no-till in 2025. As a result, the new biomass supply curve has corn stover supplies increasing to 68.4 million dry t/yr (62.0 million dry mt/yr) by 2025 at stover costs of less than $40/dry t ($44/dry mt).* The corn stover supply and cost

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*An increase of (30%–20%)/(100%–20%) = 1/8th of the potential increase from current practices relative to 100% no-till practices.

values used in the new EIA biomass supply curve for year 2025 are provided in Table 2, based on the assumption of 30% no-till practices.

At $2/million Btu ($1.90/GJ) (equivalent to $31/dry t [$34/dry mt], assuming an energy content of 15.5 million Btu/dry t [18.0 GJ/dry mt]), approx 60 million dry t (54 million dry mt) of corn stover would be available under current tillage practices. This amount of corn stover would be equivalent to 0.93 Quads (0.98 EJ) of energy. For comparison purposes, coal use in 2004 amounted to 22.92 Quads (24.18 EJ) of energy. Therefore, at $2/million Btu ($1.90/GJ), corn stover using current tillage practices could displace 4% of the energy provided by coal in the United States if all corn stover were to be used for electricity generation.

Over the last 30 yr, corn productivity has been increasing by about 1%/yr on average (in terms of the bushels of corn grain produced per acre each year). If this trend continues into the future, it is possible that corn stover quantities will also increase over time, along with corn grain productivity. This potential increase in stover availability has not been included in the newly revised biomass supply curve, pending further input and analysis regarding the likelihood that the trend will continue into the future, and the need for further clarification regarding the anticipated relationship between the amount of stover available per pound of grain produced in the future. More evaluation is needed concerning whether the current ratio of about 1 pound of stover produced per pound of corn grain produced is likely to stay the same or change if corn productivity continues to increase in the future.

There has been a substantial amount of debate regarding the appropriate farmer premium that should be included in determining the total delivered price for corn stover as well as the optimum approach and technology for harvesting and storing stover *(8)*. The bulk of the corn stover supply is anticipated to be available at a cost of $30/dry t ($33/dry mt) at the farm gate. Assuming an average transportation distance of 40 miles (64 km) to deliver round bales from the field edge to a biomass conversion site via flat bed truck, ORNL staff has estimated the transportation cost to be about $7.75/dry t ($8.54/dry mt) of stover *(9)*.

Considering a range of factors, the new EIA biomass supply curve assumes an additional fixed cost of $12/dry t ($13/dry mt) on top of the farm-gate costs in calculating the total delivered price for supplying corn stover to conversion facilities. The $12/dry t ($13/dry mt) fixed cost reflects an adjustment to cover transportation and handling costs, plus farmer premium payments. It is recognized that these costs could be higher than $12/dry t ($13/dry mt). However, this estimation is based on the assumption that cost savings and cost containment will be achieved as integrated harvest and supply operations benefit from experience and operational enhancements (in which custom harvesters are likely to play an important role), in combination with anticipated harvesting technology improvements. With a typical $30/dry t ($33/dry mt) farm-gate cost, plus an additional

Table 1
ORNL Estimates Regarding Corn Stover Availability and Costs (7) (in dry t)

	With current tillage practices (i.e., approx 20% no-till)							If 100% no-till corn production					
State	Corn acres (000)	<$25/t (000)	<$30/t (000)	<$35/t (000)	<$40/t (000)	Total available supply t (000)	Gross stover produced t (000)	$25/t (000)	<$30/t (000)	<$35/t (000)	<$40/t (000)	Total available supply t (000)	Gross stover produced t (000)
Alabama	205	0	0	0	0	2	394	0	0	0	0	6	394
Arkansas	142	23	30	30	31	37	404	137	194	194	197	201	404
Arizona	31	0	0	0	0	0	132	0	0	0	0	0	132
California	220	0	0	0	0	0	855	0	0	0	0	0	855
Colorado	1012	1	93	99	100	101	3256	11	797	981	982	983	3256
Connecticut	0	0	0	0	0	0	0	0	0	0	0	0	0
Delaware	154	228	268	268	268	268	428	280	288	288	288	288	428
Florida	55	1	2	3	3	4	105	1	24	31	32	36	105
Georgia	358	8	48	55	55	65	832	58	208	254	259	270	832
Iowa	11,983	10,474	14,465	14,745	14,928	15,116	39,619	16,580	21,618	21,924	22,059	22,311	39,619
Idaho	47	0	0	0	0	0	167	1	1	1	1	1	167
Illinois	10,667	6391	10,916	11,178	11,293	11,563	34,137	16,132	20,049	20,172	20,399	20,542	34,137
Indiana	5535	3005	5717	5941	6038	6207	16,916	7977	9499	9677	9791	9888	16,916
Kansas	2658	7	370	444	579	658	8786	101	2003	2275	2348	2432	8786
Kentucky	1176	0	33	49	62	70	3187	0	73	100	120	133	3187
Louisiana	387	1	56	63	67	69	1009	17	256	256	264	269	1009
Massachusets	0	0	0	0	0	0	0	0	0	0	0	0	0
Maryland	403	141	285	300	303	311	1107	219	414	421	424	430	1107
Maine	0	0	0	0	0	0	0	0	0	0	0	0	0
Michigan	2074	1702	2946	3062	3096	3139	5639	2463	4067	4067	4067	4067	5639
Minnesota	6582	10,637	12,829	12,917	12,964	13,036	21,419	13,885	15,305	15,305	15,305	15,334	21,419
Missouri	2402	384	549	577	588	633	6767	600	1083	1131	1150	1265	6767
Mississippi	400	0	10	11	11	16	960	2	73	85	85	112	960

Montana	16	0	0	0	0	0	46	0	9	10	12	13	46
North Caroli	754	25	528	632	651	684	1649	58	976	986	990	995	1649
North Dakota	685	0	2	3	14	25	1664	0	10	14	200	403	1664
Nebraska	8241	1969	5298	5759	5961	6134	25,937	7576	13,653	13,912	14,001	14,080	25,937
New Hampshire	0	0	0	0	0	0	0	0	0	0	0	0	0
New Jersey	82	0	0	0	0	1	197	0	0	0	0	6	197
New Mexico	80	0	9	9	10	10	322	0	65	67	76	83	322
Nevada	0	0	0	0	0	0	0	0	0	0	0	0	0
New York	579	0	64	102	102	138	1444	5	591	707	719	738	1444
Ohio	3214	2061	2737	2812	2828	2885	9938	3414	4935	5046	5077	5126	9938
Oklahoma	207	0	20	20	20	20	684	2	201	205	207	210	684
Oregon	30	6	12	12	12	12	124	25	25	25	25	25	124
Pennsylvania	1005	0	18	39	54	89	2491	0	180	251	300	430	2491
Rhode Island	0	0	0	0	0	0	0	0	0	0	0	0	0
South Caroli	299	0	146	172	177	195	525	0	282	296	300	310	525
South Dakota	3354	38	478	478	478	659	8323	320	3281	3283	3283	4562	8323
Tennessee	594	11	25	25	36	42	1519	27	50	50	62	72	1519
Texas	1810	0	43	46	91	106	5118	0	645	699	765	868	5118
Utah	21	0	0	0	0	0	67	0	0	0	0	0	67
Virginia	269	58	104	114	115	118	681	60	135	148	150	153	681
Vermont	0	0	0	0	0	0	0	0	0	0	0	0	0
Washington	90	22	26	27	27	27	393	126	179	179	179	179	393
Wisconsin	2940	322	1525	1634	1709	1799	8905	2657	4518	4541	4622	4660	8905
West Virgini	29	0	0	0	0	0	69	0	0	0	0	0	69
Wyoming	51	0	0	1	1	1	151	0	4	40	40	44	151
United States	70,840	37,517	59,652	61,630	62,673	64,242	216,366	72,732	105,692	107,621	108,777	111,526	216,366
Quads equiv.		0.58	0.92	0.96	0.97	1.00							

Table 2
Estimated Corn Stover Availability for Year 2025

	Current stover supplies (20% no-till)				Year 2025 stover supplies (30% no-till)			
State	<$25/t (000)	<$30/t (000)	<$35/t (000)	<$40/t (000)	<$25/t (000)	<$30/t (000)	<$35/t (000)	<$40/t (000)
AL	0	0	0	0	0	0	0	0
AR	23	30	30	31	37	51	51	51
AZ	0	0	0	0	0	0	0	0
CA	0	0	0	0	0	0	0	0
CO	1	93	99	100	2	181	209	210
CT	0	0	0	0	0	0	0	0
DE	228	268	268	268	235	271	271	271
FL	1	2	3	3	1	5	6	6
GA	8	48	55	55	15	68	80	81
HI	0	0	0	0	0	0	0	0
IA	10,474	14,465	14,745	14,928	11,237	15,359	15,642	15,820
ID	0	0	0	0	0	0	0	0
IL	6391	10,916	11,178	11,293	7609	12,058	12,303	12,431
IN	3005	5717	5941	6038	3627	6190	6408	6507
KS	7	370	444	579	19	574	673	800
KY	0	33	49	62	0	38	55	70
LA	1	56	63	67	3	81	87	92
MA	0	0	0	0	0	0	0	0
MD	141	285	300	303	151	301	315	318
ME	0	0	0	0	0	0	0	0
MI	1702	2946	3062	3096	1798	3086	3188	3217
MN	10,637	12,829	12,917	12,964	11,043	13,139	13,215	13,256
MO	384	549	577	588	411	616	647	658
MS	0	10	11	11	1	18	20	20
MT	0	0	0	0	0	1	1	2
NC	25	528	632	651	30	584	677	694
ND	0	2	3	14	0	3	4	38
NE	1969	5298	5759	5961	2670	6343	6778	6966
NH	0	0	0	0	0	0	0	0
NJ	0	0	0	0	0	0	0	0
NM	0	9	9	10	0	16	16	18
NV	0	0	0	0	0	0	0	0
NY	0	64	102	102	1	130	177	179
OH	2061	2737	2812	2828	2230	3012	3091	3109
OK	0	20	20	20	0	42	43	43
OR	6	12	12	12	9	13	13	13
PA	0	18	39	54	0	38	65	85
RI	0	0	0	0	0	0	0	0
SC	0	146	172	177	0	163	188	192
SD	38	478	478	478	74	829	829	829
TN	11	25	25	36	13	29	29	39
TX	0	43	46	91	0	118	127	176

(Continued)

Table 2 *(Continued)*

State	Current stover supplies (20% no-till)				Year 2025 stover supplies (30% no-till)			
	<$25/t (000)	<$30/t (000)	<$35/t (000)	<$40/t (000)	<$25/t (000)	<$30/t (000)	<$35/t (000)	<$40/t (000)
UT	0	0	0	0	0	0	0	0
VA	58	104	114	115	58	108	118	119
VT	0	0	0	0	0	0	0	0
WA	22	26	27	27	35	45	46	46
WI	322	1525	1634	1709	614	1899	1998	2073
WV	0	0	0	0	0	0	0	0
WY	0	0	1	1	0	1	6	6
US	37,517	59,652	61,630	62,673	41,919	65,407	67,379	68,436
Quads	0.58	0.92	0.96	0.97	0.65	1.01	1.04	1.06

$12/dry t ($13/dry mt) in transport and miscellaneous costs, the total delivered price used in EIA's new biomass supply curve is about $42/dry t ($46/dry mt) for the bulk of the stover supplies. In comparison, experience with corn stover harvesting and delivery during 1997–1999 illustrated a range in delivered corn stover prices of between $31.60 and $35.70/dry t ($34.84–$39.36/dry mt) *(10)*.

Non-Corn and Non-Wheat-Based Agricultural Residue Supply Estimates

Although corn stover and wheat straw are anticipated to be the largest potential sources of agricultural residues, there are many other types of crops that could potentially supply biomass residues. Although these other crop residues may tend to represent niche opportunities, on a national aggregate level they offer an expansion in the geographic range and supply for future bioenergy facilities beyond the Corn Belt and Great Plains states. Figure 2 illustrates the limited geographic concentration of corn stover supplies in the United States.

Crop residue supply estimates have been developed for nine crops: sorghum, barley, oats, rye, cotton field trash, cotton gin trash, rice straw, bagasse (the residue from sugar cane processing), and orchard prunings *(3,11)*. Although a large amount of soybeans are produced in the United States, the field residues from this crop are comparatively modest and readily decompose in the field, making collection of soybean plant residues unattractive (at least with the variety of soybean plants currently used by farmers).

In order to reduce the effects of varying yearly crop yields, for each of the "other" crop categories average annual crop production in all US states was calculated over a 3-yr span (1998–2000). The rules-of-thumb used for estimating the dry crop residues produced per pound of crop harvested

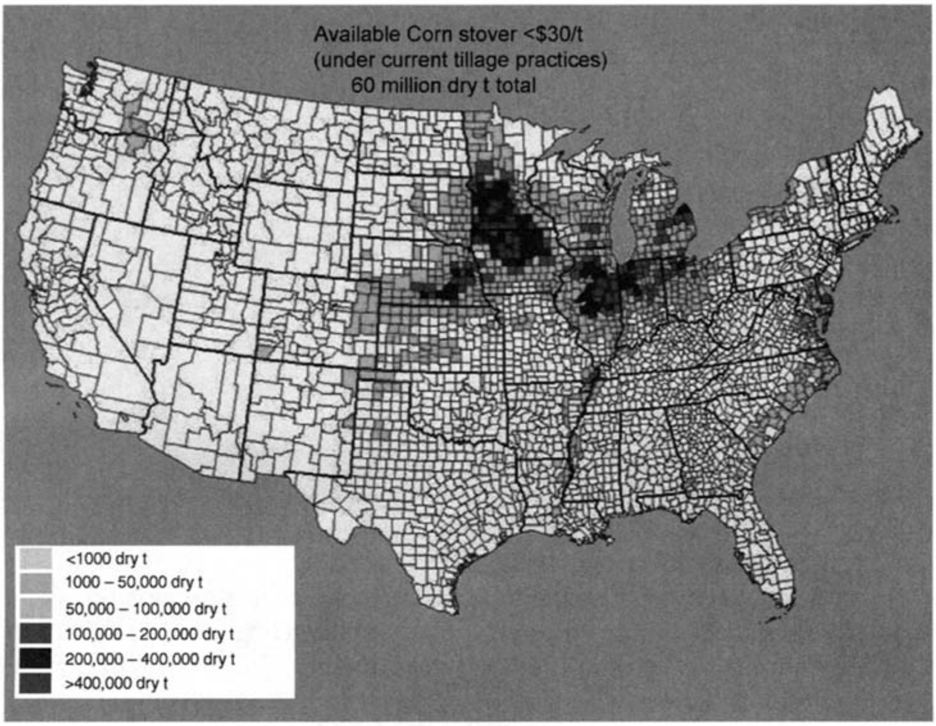

Fig. 2. Geographic distribution of corn stover supplies in the United States (Graham, 2004).

and the estimated percent of sustainably harvestable residues for each crop type were obtained from a variety of sources.*

- Barley: 48 pounds of barley/bushel (0.62 kg/L); 1.67 dry pounds of barley straw/pound of barley; 50% of barley straw harvested (net after erosion requirements and livestock use).
- Rye: 56 pounds of rye/bushel (0.72 kg/L); 1.67 dry pounds of rye straw/pound of rye; 40% of rye straw harvested (net after erosion requirements and livestock use).
- Oats: 32 pounds of oat/bushel (0.41 kg/L); 1.67 dry pounds oat straw/pound of oat; 40% of oat straw harvested (net after erosion requirements and livestock use).
- Sorghum: 56 pounds of sorghum/bushel (0.72 kg/L); 0.74 dry pounds of sorghum stover/pound of sorghum; 30% of sorghum stover harvested (net after erosion requirements and livestock use).

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*For barley, rye, oats, sorghum, rice straw, and bagasse, the rules-of-thumb are from the USDA agricultural residue report *(11)*. Percent harvestable factors were derived by averaging state values in the Gallagher report, taking into account limits related to erosion and competing livestock demand for the residues. The factor for orchard prunings is an average for orchard prunings from a California Energy Commission report on biomass residues *(12)*. Cotton gin trash and cotton field residue factors are based in input from staff at the USDA Cotton Ginning Research Laboratory *(13)*.