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2016 BILLION-TON REPORT
Advancing Domestic Resources
for a Thriving Bioeconomy

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2016 BILLION-TON REPORT

Advancing Domestic Resources for a Thriving Bioeconomy

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U.S. DEPARTMENT OF
ENERGY

2016 BILLION-TON REPORT

Advancing Domestic Resources for a Thriving Bioeconomy

A Study Sponsored by U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Bioenergy Technologies Office

Volume 1:
Economic Availability of Feedstocks

July 2016

Prepared by
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for the
U.S. DEPARTMENT OF ENERGY

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Availability

This report, as well as supporting documentation, data, and analysis tools, can be found on the Bioenergy Knowledge Discovery Framework at bioenergykdf.net. Go to https://bioenergykdf.net/billionton2016/reportinfo for the latest report information and metadata.

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U.S. Department of Energy. 2016. *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks*. M. H. Langholtz, B. J. Stokes, and L. M. Eaton (Leads), ORNL/TM-2016/160. Oak Ridge National Laboratory, Oak Ridge, TN. 448p. doi: 10.2172/1271651. http://energy.gov/eere/bioenergy/2016-billion-ton-report.

Additional Information

The U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy's Bioenergy Technologies Office and Oak Ridge National Laboratory provide access to information and publications on biomass availability and other topics. The following websites are available:

energy.gov
eere.energy.gov
bioenergy.energy.gov
web.ornl.gov/sci/transportation/research/bioenergy/

Front cover images courtesy of ATP^3, Oak Ridge National Laboratory, Abengoa, Solazyme, and BCS, Incorporated.

DISCLAIMER

The authors have made every attempt to use the best information and data available, to provide transparency in the analysis, and to have experts provide input and review. However, the *2016 Billion-Ton Report* is a strategic assessment of potential biomass. It alone is not sufficiently designed, developed, and validated to be a tactical planning and decision tool, and it should not be the sole source of information for supporting business decisions. This analysis provides county by county estimates of the feedstocks at a selected cost, yet users should use associated information on the Bioenergy Knowledge Discovery Framework (bioenergykdf.net/billionton) to understand the assumptions and ramifications of using this analysis. The use of tradenames and brands are for reader convenience and are not, nor does their use imply, an endorsement by the U.S. Department of Energy or Oak Ridge National Laboratory.

The foundation of the agricultural sector analysis is the USDA Agricultural Projections to 2024. From the report, "projections cover agricultural commodities, agricultural trade, and aggregate indicators of the sector, such as farm income. The projections are based on specific assumptions about macroeconomic conditions, policy, weather, and international developments, with no domestic or external shocks to global agricultural markets." The *2016 Billion-Ton Report* agricultural simulations of energy crops and primary crop residues are introduced in alternative scenarios to the 2015 USDA Long Term Forecast. Only 2015-2024 Billion-Ton national level baseline scenario results of crop supply, price, and planted and harvested acres for the 8 major crops are considered to be consistent with the 2015 USDA Long Term Forecast. Additional years of 2025–2040 in the *2016 Billion-Ton Report* baseline scenario and downscaled reporting to the regional and county level were generated through application of separate data, analysis, and technical assumptions led by Oak Ridge National Laboratory and do not represent nor imply U.S. Department of Agriculture or U.S. Department of Energy quantitative forecasts or policy. The forest scenarios were adapted from U.S. Forest Service models and developed explicitly for this report and do not reflect, imply, or represent U.S. Forest Service policy or findings.

The biomass supply projections presented in this report are policy independent and estimate the potential economic availability of biomass feedstocks using specified market scenarios and guiding principles intended to be conservative and to reflect certain environmental and socio-economic considerations. For example, some principles aim to maintain food availability and environmental quality, including improved tillage and residue removal practices, exclusion of irrigation, and reserved land areas to protect biodiversity and soil quality. In this sense, this report (volume 1) and related analyses on environmental effects (forthcoming in volume 2) may differ from other efforts seeking to depict potential biomass demand and related market, environmental and land use interactions under business-as-usual or specific policy conditions.

Preface

On behalf of all the authors and contributors, it is a great privilege to present the *2016 Billion-Ton Report* (*BT16*), *Volume 1: Economic Availability of Feedstocks.* This report represents the culmination of several years of collaborative effort among national laboratories, government agencies, academic institutions, and industry. *BT16* was developed to support the U.S. Department of Energy's efforts towards national goals of energy security and associated environmental and economic benefits.

As director of the U.S. Department of Energy's Bioenergy Technologies Office, I would like to thank Alison Goss Eng, the program manager of Advanced Algal Systems and Feedstock Supply and Logistics, and Mark Elless, technology manager in the Feedstock Supply and Logistics Team, for their leadership. I would especially like to express gratitude to the report leads: Matthew Langholtz, Research Scientist at Oak Ridge National Laboratory; Bryce Stokes, Senior Advisor of Allegheny Science and Technology; and Laurence Eaton, Research Scientist at Oak Ridge National Laboratory.

This product builds on previous efforts, namely the 2005 *Billion-Ton Study* (*BTS*) and the 2011 *U.S. Billion-Ton Update* (*BT2*).With each report, greater perspective is gained on the potential of biomass resources to contribute to a national energy strategy. Similarly, each successive report introduces new questions regarding commercialization challenges. *BTS* quantified the broad biophysical potential of biomass nationally, and *BT2* elucidated the potential economic availability of these resources. These reports clearly established the potential availability of up to one billion tons of biomass resources nationally. However, many questions remain, including but not limited to crop yields, climate change impacts, logistical operations, and systems integration across production, harvest, and conversion. The present report aims to address many of these questions through empirically modeled energy crop yields, scenario analysis of resources delivered to biorefineries, and the addition of new feedstocks. Volume 2 of the *2016 Billion-Ton Report* is expected to be released by the end of 2016. It seeks to evaluate environmental sustainability indicators of select scenarios from volume 1 and potential climate change impacts on future supplies.

Consistent with *BTS* and *BT2,* we identify potential biomass resources of one billion tons or more per year in the United States. Recognizing this great potential, attention then logically turns to questions of how to mobilize this resource. While bioenergy currently is the greatest single source of renewable energy in the United States, there are still economic and technological barriers that limit efforts to mobilize biomass resources for more biofuels, biopower, and bioproducts. Energy crops in particular are wholly dependent on future market demand.

BT16 is not a final answer, but rather a step to help the nation develop strategies for realizing a broader bioeconomy potential. At bioenergykdf.net, the reader can find online companion data sets and interactive visualization for all biomass resources in this report. While we are confident in the rigor and depth of our analysis, the potential implications of our results have only begun to be assessed. We invite the user community to take a step forward and use this report and associated data to perform further analyses, ask more questions, and inform strategies to mobilize national biomass resources toward realization of a bioeconomy.

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Contributors

Many people contributed to the analysis and reporting of the *2016 Billion-Ton Report*. An even more significant aspect is that chapters and sections were written by the researchers who completed the analyses. This provides an additional level of detail and expertise in both the development of the biomass potential estimates and the clarity of the presentation of the methodologies and scientific approaches.

Others contributed various technical, managerial, and production skills and knowledge, both to the accuracy and comprehensiveness of the analyses and to the delivery of the information and data in in both the text and electronic formats. The many contributors are listed below by their organizations.

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This report, in the same spirit of the 2005 *Billion-Ton Study* and the 2011 *U.S. Billion-Ton Update*, is the product of a multidisciplinary collaboration across institutions, and across the breadth of the analysis, from fundamental assumptions to analysis, to review, and report development. This collaboration ranges from federal agency scientists and national laboratories to universities and contractors. A specials thanks and recognition goes to the U.S. Forest Service in the U.S. Department of Agriculture (USDA) for their long-established support and contribution to the Billion-Ton studies. USDA has always been a significant collaborator. We also acknowledge the use of USDA data for both agricultural and forestry.

Biomass crop and residue yields, the foundation of the assessment, were produced from field trials by the Sun Grant Regional Feedstock Partnership between 2007 and 2015, providing empirical yield data. These contributors are identified in the section "Sun Grant Yield Mapping Workshop Participants." In turn, these data were used in collaboration with the Oregon State University PRISM Climate group, to generate county-level data assumptions. Agronomic assumptions were informed and reviewed by counterparts with USDA, universities, and industry. These data serve as inputs to the national simulation models developed and maintained by the University of Tennessee Agricultural Policy Analysis Center. At the review workshop for volume 1 of the *2016 Billion-Ton Report* on December 9–10, 2015, twenty-eight external reviewers provided critical appraisal of assumptions, methods, and results.

The authors of chapter 2 on currently used resources would like to give special thanks to Zia Haq (DOE Bioenergy Technologies Office) and Harry Baumes (USDA Office of Energy Policy and New Uses), as well as participants of the peer review workshop who provided written and oral comments on the chapter.

The forestry analysis required development of a forestry model that is comparable to the POLYSYS model used in the agricultural analysis. This was a significant achievement, culminating considerable effort that included model development as well as scenario development, harvest system development and costing, data assimilation, and model verification. The authors of chapter 3 on forest resources (roadside) would like to recognize the substantial contributions of Matthew Langholtz (Oak Ridge National Laboratory [ORNL]) in the model development and Craig Brandt (ORNL) in data management and distribution. Patrick Miles (U.S. Forest Service) provided the Forest Inventory and Analysis databases and guidance on their use in the model. Marilyn Buford consulted and provided guidance on forest management options. Dennis Dykstra (U.S. Forest Service; retired) assisted with updating the harvest costs calculations. Kenneth Skog assisted with the scenarios and provided much support overall. Jessica McCord and Nicolas Andre (University of Tennessee) worked through the tedious process of developing stand diameter growth increments that were fundamental to having a dynamic inventory in the model. The forestry reviewers were greatly appreciated for helpful comments and edits, and their willingness to participate in the review workshop. Also thanks to Wade Salverson with the (Bureau of Land) Management for his contributions of needed information.

Special thanks goes to those that reviewed the chapter on forestry (chapter 3). These include Chris Clark (U.S. Environmental Protection Agency [EPA]), Jim Dooley (Forest Concepts), Eric Vance (National Council for Air and Steam Improvement), Catherine Mater (Mater Engineering), Steve Kelley (North Carolina State) and Al Sample (Pinchot Institute for Conservation).

Authors of chapter 4 on agricultural residues and biomass energy crops (farmgate) want to give special thanks to Lynn Wright (Wrightlink Consulting); Richard Hess, Erin Searcy, and Gary Gresham (Idaho National Laboratory); and Timothy G. Rials and Jessica McCord (University of Tennessee Center for Renewable Carbon) for feedback during early stages of analysis and visualization. Daniel De La Torre Ugarte and Brad Wilson (University of Tennessee Agricultural Policy Analsyis Center) provided POLYSYS modeling support. The team conducted numerous webinars to review assumptions and scope with field trial partners from the Sun Grant Regional Feedstock Partnership, including Vance Owens (South Dakota State University and North Central Sun Grant Center) and Robert Mitchell (USDA-Agricultural Research Service; Lincoln, Nebraska), Tim Volk (State University of New York [SUNY]), Bijay Tamang (Arborgen), Timothy G. Rials and Jessica McCord (both from University of Tennessee Center for Renewable Carbon). In addition to the participants of the yield mapping workshops mentioned in the report, the authors give special thanks to Mike Halbleib and Chris Daly (Oregon State University, PRISM Climate Group) for yield modeling and data support. Special thanks goes to participants of the Chapter 4 peer review session, especially Chris Clark, Vince Camobreco (EPA), Marty Schmer, Jane Johnson (USDA Agricultural Research Service), Nathan Parker (Arizona State University), Emily Heaton (Iowa State), and Tim Volk (SUNY).

The chapter on waste resources (chapter 5) benefitted from the many people who assisted by providing data and insights into the resources included. The authors thank Jerry Bingold (Dairy Management Inc.), Nathan Brown (Federal Aviation Administration), Vince Camobreco (EPA), Meltem Urgun Dermitas (Argonne National Laboratory), Jim Dooley (Forest Concepts), Brett Hogarth and JP Iamonaco (ECOSTRAT), George Kervitsky (The Hannon Group), Paul Lemar (Resource Dynamics), Anelia Milbrandt (National Renewable Energy Laboratory), Nathan Parker (Arizona State University), Mark Philbrick (DOE Bioenergy Technologies Office), Corrine Drennan and Richard Skaggs (Pacific Northwest National Laboratory), Kenneth E. Skog (U.S. Forest Service; retired), Sam Tagore (DOE Bioenergy Technologies Office), and the Landfill Methane Outreach Program (EPA).

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The algae chapter authors appreciate the assistance from the Algae Biomass Organization and its leadership, with special thanks to Matt Carr for organizing interactions with our team and participating in the Peer Review workshop. Assumptions and the scope of chapter 7 were discussed with Algae Biomass Organization leadership and industry members in webinars and phone calls and a special meeting at the Algae Biomass Summit on October 1, 2015. In addition to participants in the peer review workshop, ABO members David Hazlebeck and John Benemann provided written review comments on the report. We had helpful discussions with Toby Ahrens of Bioprocess Algae, LLC; Yan Poon and Becky Ryan of Sapphire Energy, Inc.; Jacques Beaudry-Losique and Timothy Zenk of Algenol, LLC; Martin Sabarsky of Cellana, Inc., Mark Allen of Accelergy, Inc., David St. Angelo and Sissi Liu of Joule Unlimited, Inc.; David Hazlebeck of Global Algae Innovations, Inc.; John Benemann of MicroBio Engineering; Al Darzins of the Gas Technology Institute; Greg Mitchell of the Scripps Institution of Oceanography; Laurie Purpuro of K&L Gates, Colin Beal of B&D Engineering and Consulting, LLC; Michael Huesemann and Richard Skaggs from Pacific Northwest National Laboratory; Ron Kent of the Southern California Gas Company; Alexis Wolfe (National Oceanic and Atmospheric Administration Sea Grant Fellow); Rebecca White of Qualitas Health; and Prof. Dr. Hans Kistenmacher of Linde AG.

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Review Workshop Participants

The workshop titled "Presentation and Expert Review of the *2016 Billion-Ton Report*" was held December 9–10, 2015, in Washington, D.C. Twenty-eight external reviewers participated, providing critical review of methods, assumptions, and results of volume 1 of this report. On day 1 of the workshop, contributors presented an overview of their work, and reviewers responded directly with follow-up through written feedback. Reviewer comments were addressed during the subsequent revision of the report. Day 2 provided opportunities for volume 1 reviewers and stakeholders to learn more about the sustainability analyses in volume 2.

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Sun Grant Yield Mapping Workshop Participants

In 2012 and 2013, a series of workshops were conducted to review and synthesize energy crop yields and management information from the field trial network of the Sun Grant Regional Feedstock Partnership. The following participants contributed significant information necessary to model the expected crop yields used in the analysis of the *2016 Billion-Ton Report*:

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Table of Contents

Executive Summary

Consumption of renewable energy in the United States is the highest in history, contributing to energy security, greenhouse gas reductions, and other social, economic, and environmental benefits. The largest single source of renewable energy is biomass, representing 3.9 quadrillion of 9.6 quadrillion British thermal units (Btu) in 2015 (EIA 2016). Biomass includes agricultural and forestry resources, municipal solid waste (MSW), and algae.

For more than a decade, the U.S. Department of Energy (DOE) has been quantifying the potential of U.S. biomass resources, under biophysical and economic constraints, for production of renewable energy and bioproducts. The *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy* (*BT16*) evaluates the most recent estimates of potential biomass that could be available for new industrial uses in the future. *BT16* consists of two volumes: Volume 1 (this volume) focuses on resource analysis—projecting biomass potentially available at specified prices. Volume 2 evaluates changes in environmental sustainability indicators—water quality and quantity, greenhouse gas emissions, air quality, soil organic carbon, and biodiversity—associated with select production scenarios in volume 1. The following is a summary of *BT16*, volume 1:

Goals of the Analysis

BT16 is the third DOE-sponsored report to evaluate biomass resource availability in the conterminous United States. Each report addressed different goals. The 2005 *Billion-Ton Study* (*BTS*) was a strategic assessment of the potential biophysical availability of biomass. It identified the potential to produce more than one billion tons per year of agricultural and forest biomass sources—sufficient to produce enough biofuel to displace 30% of then-current petroleum consumption. However, this biophysical potential was not restricted by price, which is a key factor in the commercial viability of bioenergy and biofuels strategies.

The 2011 *U.S. Billion-Ton Update* (*BT2*) evaluated the availability of biomass supply as a function of price. Employing an economic model to simulate potential biomass supply response to market demands, *BT2* evaluated the potential economic availability of biomass feedstocks under a range of offered prices and yield scenarios between 2012 and 2030. It again projected the potential for more than 1 billion dry tons of biomass per year to be potentially available by 2030, assuming market prices of $60 per dry ton at the farmgate or roadside (i.e., after harvest, ready for delivery to a processing facility).

This report (*BT16*) builds on previous research to address key questions:

- What is the potential economic availability of biomass resources using the latest-available yield and cost data?
- How does the addition of algae, miscanthus, eucalyptus, wastes, and other energy crops affect potential supply?
- With the addition of transportation and logistics costs, what is the economic availability of feedstocks delivered to the biorefinery?

Scope of Analysis

Building on previous analyses, *BT16* (1) updates the farmgate/roadside analysis using the latest available data and specified enhancements; (2) adds more feedstocks, including algae and specified energy crops; and (3) expands the analysis to include a scenario study to illustrate the cost of transportation to biorefineries under specified logistical assumptions.

The analysis is applied to a range of biomass resources. Currently used resources (biomass resources allocated to energy production) are described in chapter 2 and include resources from agricultural lands (grains and oilseeds for liquid fuels), forestlands (logging residues and forest thinnings for pellets, heat, and power), and wastes (black liquor, mill wastes, biosolids, and MSW for industrial sector power). Forestland resources, evaluated in chapter 3, include logging residues and whole-tree biomass. Agricultural land resources, addressed in chapter 4, include crop residues, herbaceous energy crops, and woody energy crops. The waste resources in chapter 5 include secondary and tertiary wastes from processing agricultural and forestry products, and urban wastes (e.g., mill wastes, grain hulls, manures).

The projections of potential biomass supplies in BTS and *BT2* were limited in scope to the farmgate or forest roadside. As noted in the 2011 report, "It is important to understand that the estimates in the report do not represent the total cost or the actual available tonnage to the biorefinery. There are additional costs to preprocess, handle, and transport the biomass" (DOE 2011, xxiii). Chapter 6 of this report broadens the scope of analysis with case studies to characterize the potential economic availability of select biomass resources as delivered to biorefineries.

Differences between the scope of this report and earlier reports, as well as differences in data sources, are summarized in chapter 1. Demands for food, feed, fiber, and timber are met before considering the biomass resources for bioenergy and bioproducts in this report. The simulation period for agricultural and forestry resources in this report is 2015 to 2040. Currently available resources are reported as those present in 2015, unless otherwise specified. For energy crops, the specified prices are applied nationally for all years from 2019 to 2040. Algae biomass is simulated under current productivities, 2014 costs, and higher future productivities.

Although the economic availability of future algal biomass is difficult to quantify, *BT16* includes potential open-pond algal biomass production that may be associated with select resource co-location opportunities—co-location with carbon dioxide (CO_2) from ethanol plants, coal power plants, and natural gas plants. Biomass, and price ranges for that biomass, are estimated for *Chlorella sorokiniana* (a freshwater strain) and *Nannochloropsis salina* (a saline strain) in chapter 7. Costs for freshwater production assume that only minimal lining is needed, whereas the costs of saline production are estimated using minimal and full liners.

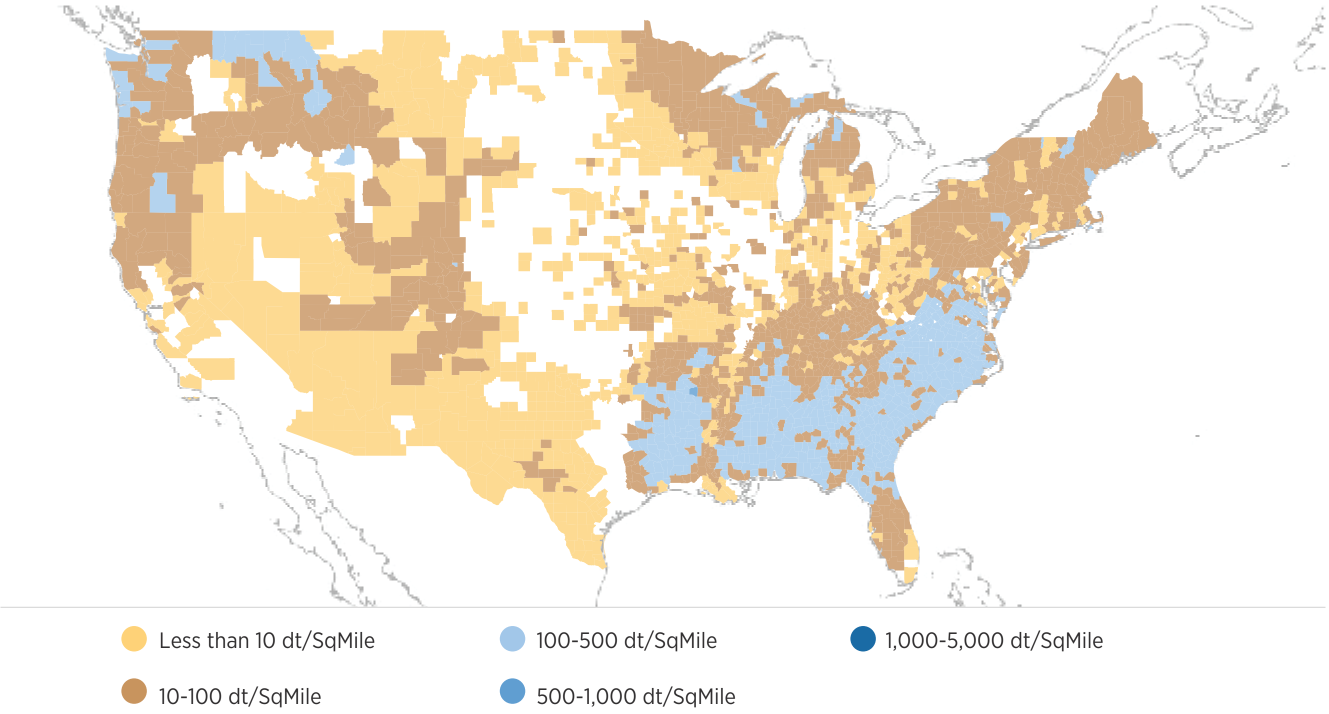
Roadside: Forest Resources and Urban Wood Waste

Potential forest residues and forest thinnings were quantified from an empirical model using forest inventory and analysis data. Scenarios evaluated include combinations of housing demand (moderate or high), wood energy demand (low, moderate, or high), and plantation management intensity in the South (moderate or high). At prices of up to $60 per dry ton, 103 million and 97 million tons per year of biomass resources are potentially available from forestlands in 2017 and 2040, respectively, in the base-case scenario (all timberland, including federal lands). A summary of currently used and potential additional supplies from forestlands is shown in table ES.1. These results represent a least-cost mix of resources up to a specified level of demand. Spatial distribution of the 97 million tons available at $60 per ton in 2040 are shown in figure ES.1.[1]

At the Farmgate: Agricultural Supplies

Resources from agricultural lands include crop residues and biomass energy crops. While energy crops in *BT2* were generalized to simulate energy crop categories, switchgrass, miscanthus, energy cane, biomass sorghum, willow, eucalyptus, poplar,

Figure ES.1 | Forest resource totals, 2040, $60 per dry ton or less, roadside (with federal lands, base-case scenario)[1]



and pine are simulated as individual crops in *BT16*. Energy market demand for energy crops is simulated starting in 2019.[2] Cellulosic biomass energy crop yields were derived from an empirical model calibrated with agricultural field trial data from across the United States. A base-case scenario assumes a 1% annual yield improvement for energy crop genotypes through the 2015–2040 simulation period; high-yield scenarios assume 2%, 3%, or 4% annual energy crop yield improvements and high-yielding corn. A $60 farmgate price offered over 25 years (offered from 2015–2040 for residues, and from 2019–2040 for energy crops) in the base-case scenario (1%) produces a potential 588 additional million tons in 2040; a 3% annual yield improvement scenario under the same farmgate price and time horizon results in a potential 936 million tons in 2040.[3] Farmgate resources potentially available at specified market prices under the base-case and high-yield scenarios, in addition to currently used agricultural resources, are described in table ES.1. The spatial distribution of the 588 million tons potentially available at $60 or less in 2040 is shown in figure ES.2.[4]

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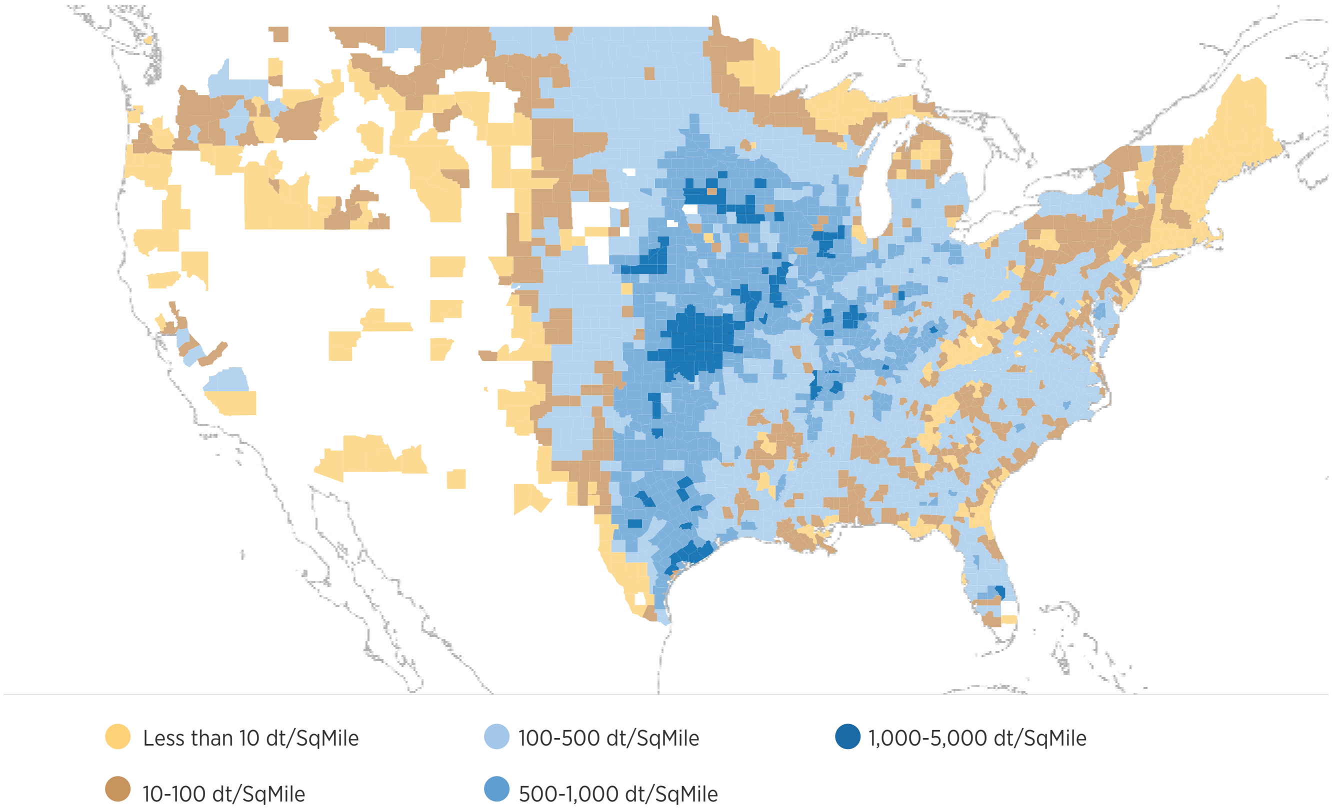
[1] Interactive visualization: https://bioenergykdf.net/billionton2016/1/3/tableau

[2] *BT2* assumed a 2014 start year for energy crops.

[3] Farmgate supply results are similar in scale to those of the 2011 *BT2*. The potential biomass under the same price (offered from 2010–2030 for residues and from 2014–2030 for energy crops) was 580 million dry tons in the *BT2*, and the 4% annual yield improvement scenario at the same price and time horizon results in a potential 1.1 billion dry tons per year in the *BT2*.

[4] Interactive visualization: https://bioenergykdf.net/billionton2016/1/3/tableau

Figure ES.2 | Agricultural resource totals, base case, 2040, $60 per dry ton or less, roadside[5]



Wastes

Estimates for agricultural wastes, forestry wastes, and MSW were drawn from a variety of sources, as described in chapter 5. Total supplies nationally of potential waste resource above current uses range from approximately 137 million dry tons to 142 million dry tons from 2017 to 2040 at $60 per dry ton or less. Currently used and potential additional waste resources are shown in table ES.1. The spatial distribution of 132 million tons of MSW, secondary crop residues, and manure (estimated available at roadside at $60 per ton or less), is shown in figure ES.3.[6]

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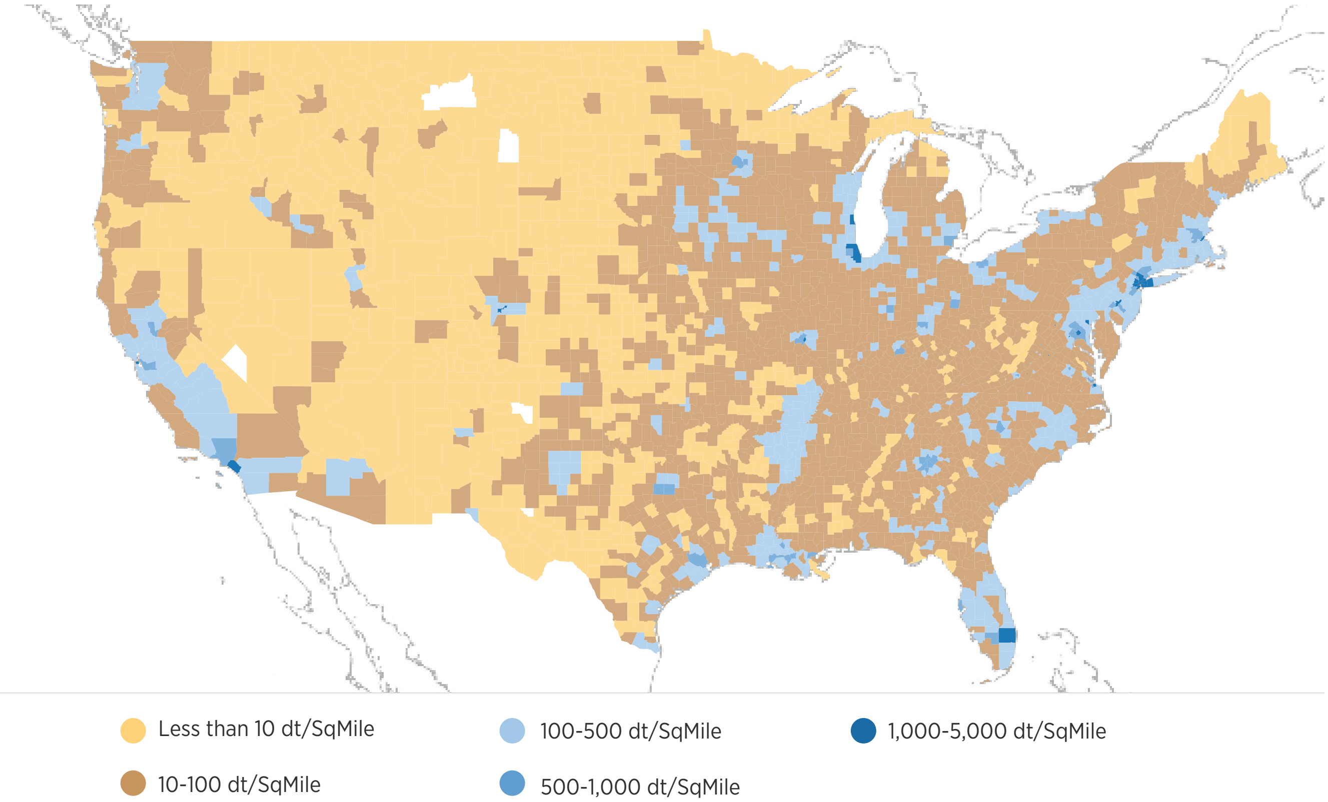
[5] Interactive visualization: https://bioenergykdf.net/billionton2016/1/4/tableau

[6] Interactive visualization: https://bioenergykdf.net/billionton2016/1/5/tableau

Figure ES.3 | Construction and demolition waste, and municipal solid waste resources, totals to 2040 up to $60 per dry ton, roadside (excludes 10 million tons of fats and oils, data not available at the county level)[7]



Combined Resources from Forestry, Agriculture, and Wastes

Combined forestry resources, agricultural resources, wastes, and currently used supplies potentially available at $60 or less in select years are shown in table ES.1.[8] Combined resources total 1.2 billion tons under the base-case scenario and 1.5 billion under tons a high-yield scenario by 2040. Notably, resources potentially available in the near term include agricultural residues, wastes, and forest resources, totaling 343 million tons in 2017 in the base-case scenario. Conversely, energy crops shown are scarce in the near term, but are the greatest source of potential biomass in the future, contributing 411 million tons and 736 million tons in 2040 under the base-case and high-yield scenarios, respectively. Combined potential supplies from forestry, wastes, and agricultural resources under the base case in 2040 are shown in figure ES.4. Potential forestry, agricultural, and waste biomass resources as a function of marginal and average prices at the roadside in 2040 are shown in figures ES.5 and ES.6.

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[7] Interactive visualization: https://bioenergykdf.net/billionton2016/1/5/tableau

[8] Interactive visualization: https://bioenergykdf.net/billionton2016/1/1/table

Table ES.1 | Summary of Currently Used and Potential Forest, Agricultural, and Waste Biomass Available at $60 per Dry Ton or Less, Under Base-Case and High-Yield Scenario Assumptions (microalgae resources reported in table ES.2)[9]

Feedstock	2017	2022	2030	2040
	Million dry tons			
Currently used resources				
Forestry resources	154	154	154	154
Agricultural resources	144	144	144	144
Waste resources	68	68	68	68
Total currently used	**365**	**365**	**365**	**365**
Potential: Base-case scenario				
Forestry resources (all timberland)[a, b]	103	109	97	97
Forestry resources (no federal timberland)[a, b]	84	88	77	80
Agricultural residues	104	123	149	176
Energy crops[c]		78	239	411
Waste resources[d]	137	139	140	142
Total base-case scenario potential (all timberland)	**343**	**449**	**625**	**826**
Total base-case scenario (currently used + potential)	***709***	***814***	***991***	***1,192***
Potential: High-yield scenario				
Forestry resources (all timberland)[b, e]	95	99	87	76
Forestry resources (no federal timberland)[b, e]	78	81	71	66
Agricultural residues	105	135	174	200
Energy crops[c,f]		110	380	736
Waste resources[d]	137	139	140	142
Total high-yield scenario potential (all timberland)	**337**	**483**	**782**	**1,154**
Total high-yield scenario (currently used + potential)	***702***	***848***	***1,147***	***1,520***

Note: Numbers may not add because of rounding. Currently used resources are procured under market prices.

[a] Forestry baseline scenario.

[b] Forestry resources include whole-tree biomass and residues from chapter 3 in addition to other forest residue and other forest thinnings quantified in chapter 5.

[c] Energy crops are planted starting in 2019. Note: *BT2* assumed a 2014 start for energy crops.

[d] The potential biogas from landfills is estimated at about 230 billion ft^3 per year as shown in table 5.12.

[e] Forestry high-housing, high biomass-demand scenarios.

[f] The high-yield scenario assumes 3% annual increase in yield.

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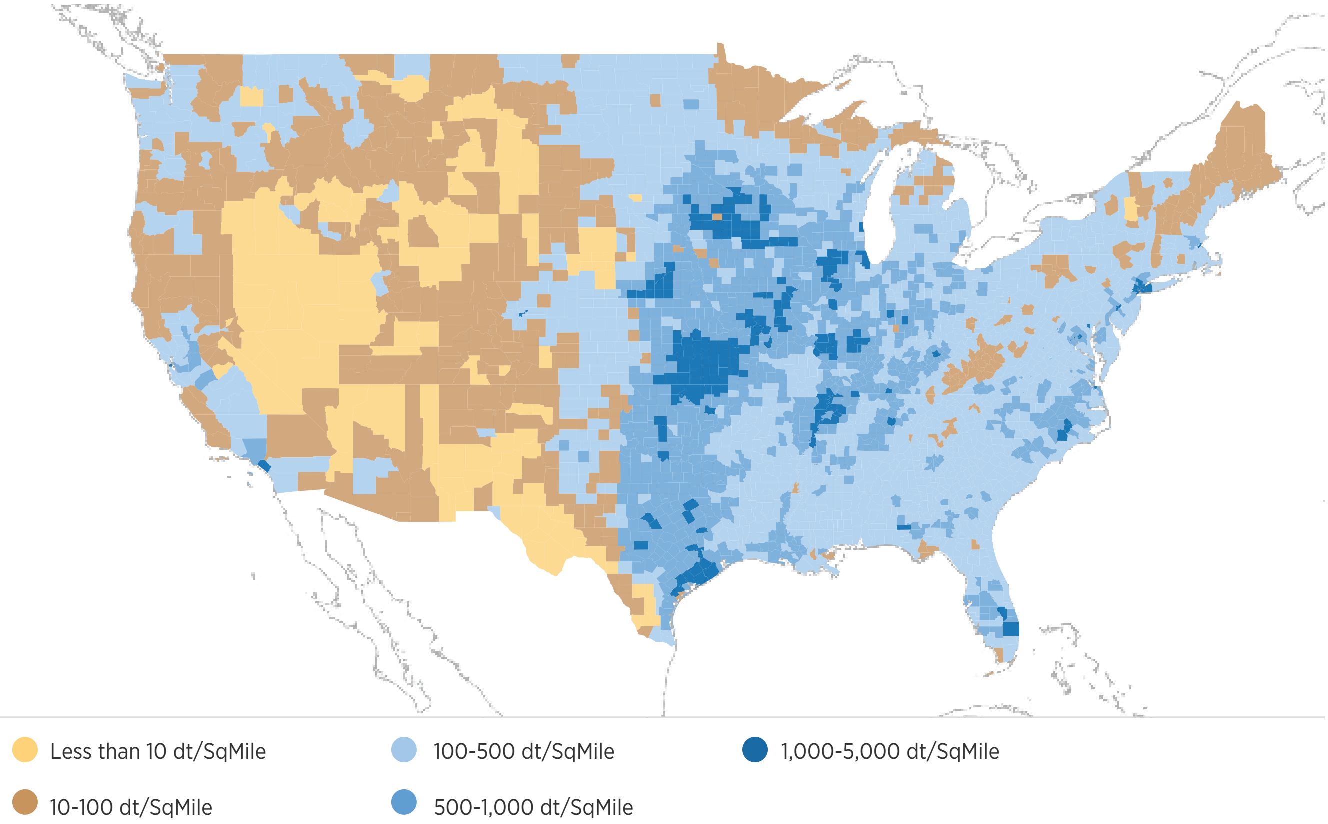
[9] Interactive visualization: https://bioenergykdf.net/billionton2016/1/1/table

Figure ES.4 | Combined potential supplies from forestry, wastes, and agricultural resources, base case, 2040[10]



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[10] Interactive visualization: https://bioenergykdf.net/billionton2016/1/2/tableau

Figure ES.5 | Potential forestry, agricultural, and waste biomass resources shown as a function of marginal and average prices at the roadside In 2040 (base case)

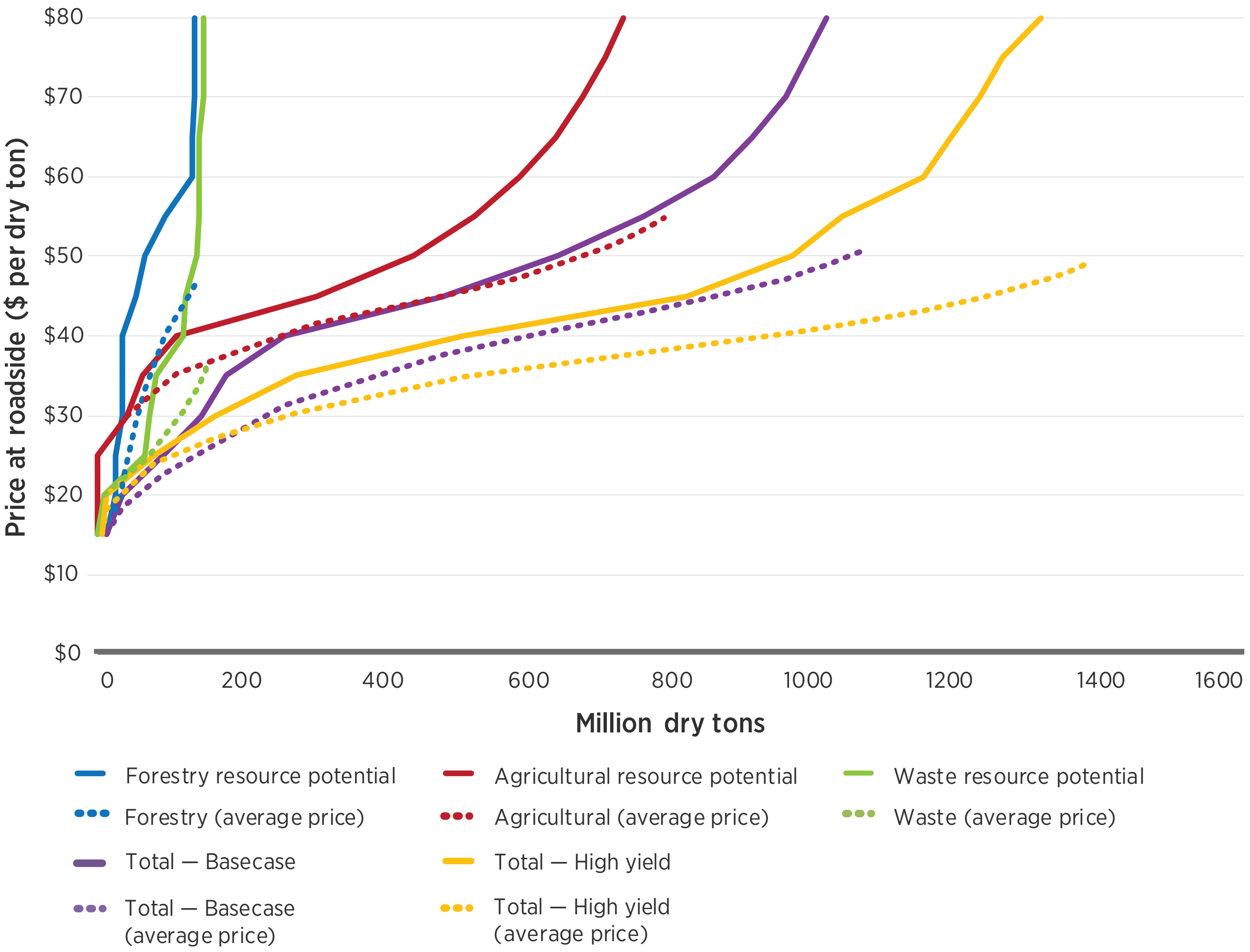
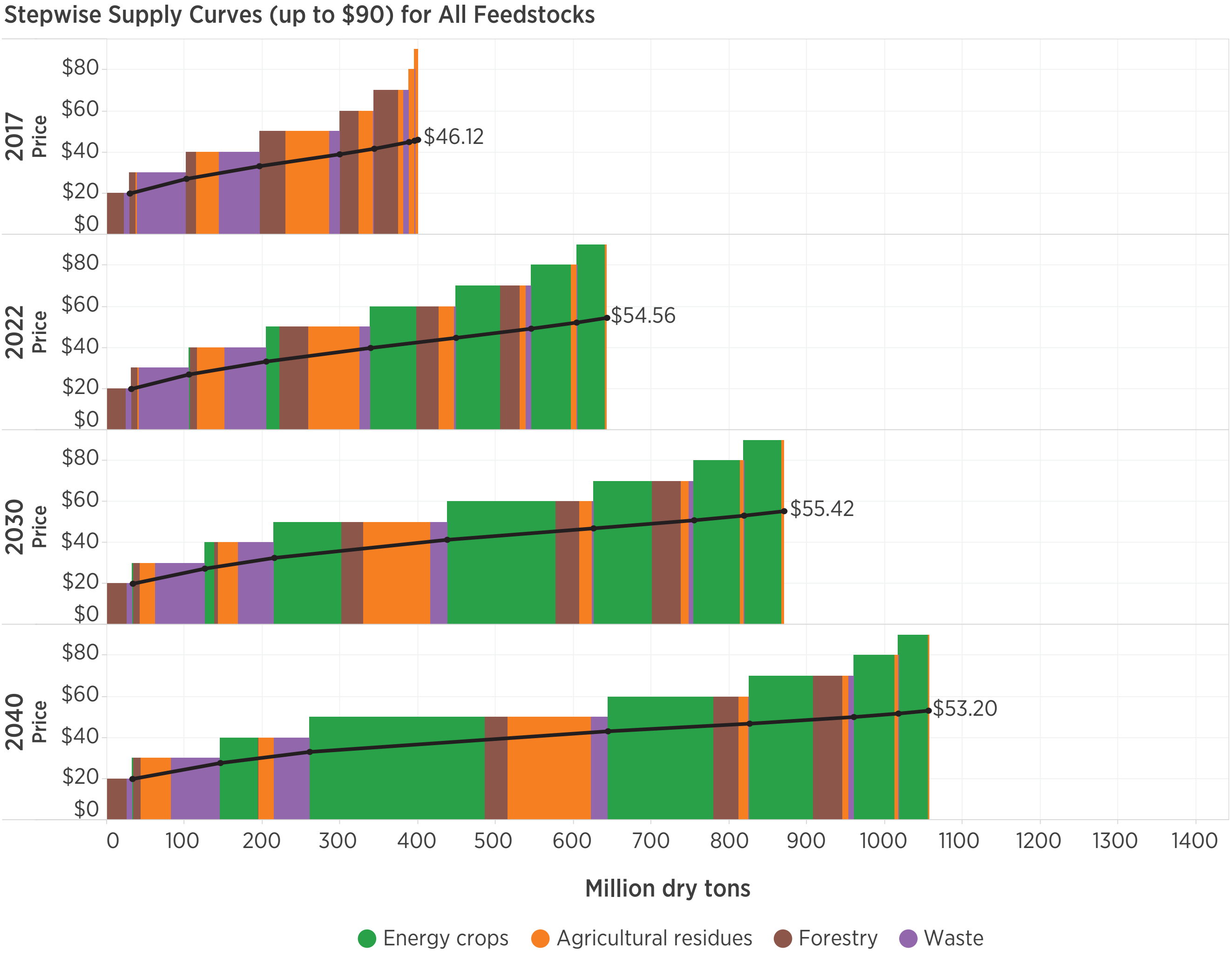


Figure ES.6 | Combined potential forestry, agricultural, and waste biomass resources shown as a function of marginal and average prices at the roadside for select years (base case)[11]



Algae

Biomass estimates for algae grown in open pond-raceway systems using freshwater or saline water sources were derived from a biophysical model calibrated with algae production data and using costs from an established techno-economic model. The national biomass potential for algae co-located with ethanol production plants, coal-fired power plants, and natural gas-fired power plants is highly dependent on the algae strain, media, local meteorology, and assumed productivities. Under current productivities and operational assumptions, biomass potential for *Chlorella sorokiniana* in freshwater media is estimated to be 12 million, 19 million, and 15 million dry tons for co-location scenarios with CO_2 from ethanol production plants, coal-fired electric generating

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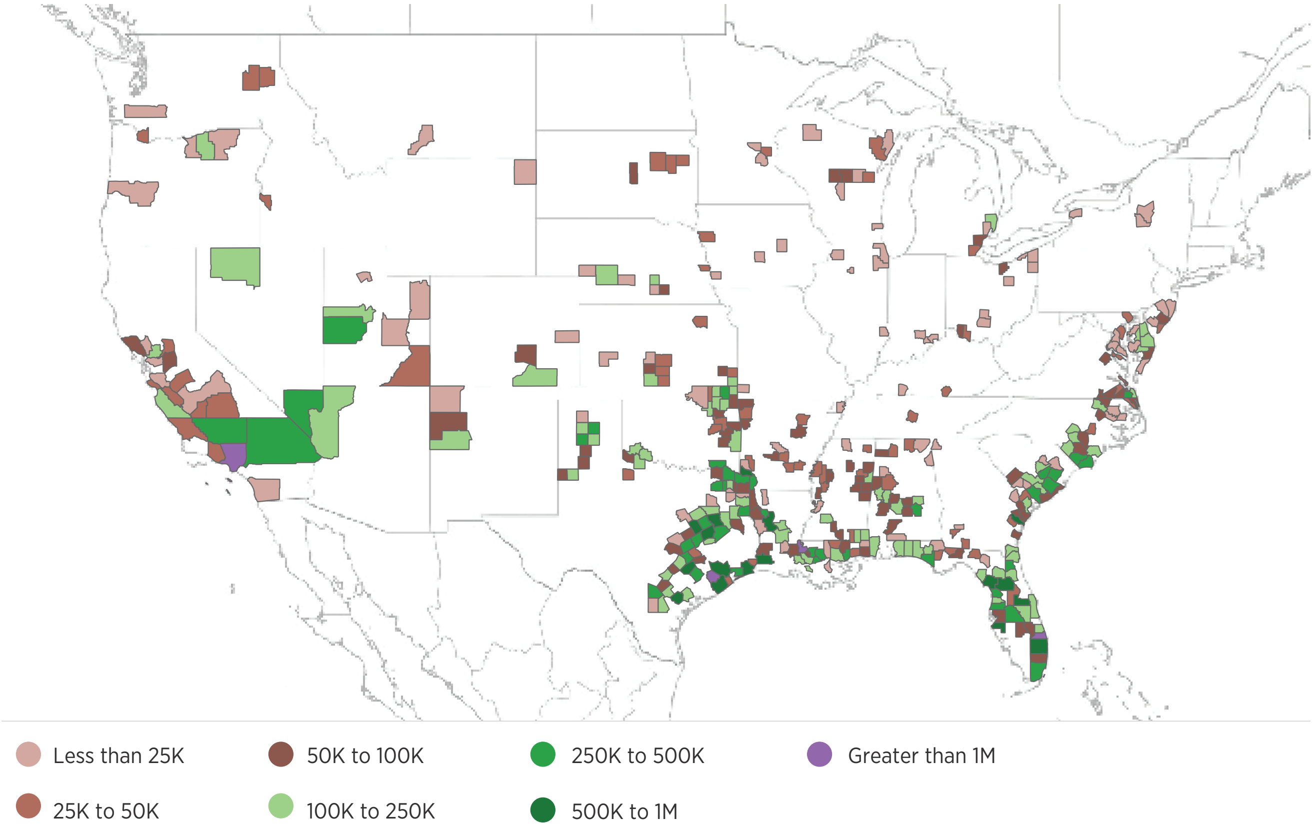
[11] Interactive visualization: https://bioenergykdf.net/billionton2016/1/9/tableau

units (EGUs), and natural gas EGUs, respectively. Current productivities for *Nannochloropsis salina* in saline media are potentially higher (table ES.2). Costs (equivalent to minimum prices) for algae production and dewatering to a 20% solids content are estimated to range from $490 to $2,889 per dry ton depending on production scenario (table ES.2). The broad range of costs reflects regional annual productivity differences, as well as source of CO_2 and distance to that source. The spatial distribution of potential co-located algae production using saline water assuming present productivities is shown in figure ES.7. A summary of the biomass available under other scenarios is shown in table ES.2. (Interactive visualizations are available for both.) Minimum prices are much lower when future, higher productivities are used than when current productivities are used in simulations. Minimum prices of potentially available biomass are also dependent on the extent of pond liner coverage (i.e., minimal [only covering corners prone to erosion] or full). Cost savings from co-location are clear in many regions of the country but are lower than cost savings from doubling productivity or reducing liner costs. Minimum prices per ton for algae are much higher than those for terrestrial feedstocks, but algae has potential for higher fuel yields per dry ton of biomass than terrestrial feedstocks. Reducing the cost of algae feedstock production is a research priority. However, algae has other benefits, such as flexibility in land and water requirements, use of less land for an equivalent yield, and flexibility in coproduct options.

Figure ES.7 | Spatial distribution of potential co-located algae production (near-term saline scenario, prices ranging from $755 to $2,889 per dry ton)[12]



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[12] Interactive visualization: https://bioenergykdf.net/billionton2016/7/1/tableau

Table ES.2 | Summary of Biomass Potential from Co-Location (million tons/year); *Chlorella sorokiniana* Is the Example Algae Strain Grown in Freshwater Media, and *Nannochloropsis salina* Is the Example Algae Strain Grown in Saline Media[13]

Scenario	Ethanol plant	Coal GU	Natural gas EGU	Total[a]	Range of minimum prices per dry ton[b]
Present productivities, freshwater media	12	19	15	<46	$719–$2,030
Present productivities, saline media	10	54	21	<86	$755–$2,889
Future productivities, freshwater media	13	10	0	<23	$490–$1,327
Future productivities, saline media	11	12	0	<24	$540–$2,074

[a] Totals are uncertain, because analyses of different co-location sources were run independently; therefore, some production facilities that are close to multiple CO_2 sources may be double-counted.

[b] For *Nannochloropsis salina*, the range of minimum prices includes both minimally lined ponds and lined ponds. For C*hlorella sorokiniana*, the range of minimum prices includes only minimally lined ponds.

Delivered Resources

Major categories of forest, agricultural, and waste resources available at $60 per ton or less at the roadside[13] are included in the scenario analysis of resources delivered to the throat of the biorefinery. This subset of the total potential supply includes 310, 679, and 985 million dry tons in the near-term, long-term base-case, and long-term high-yield scenarios, respectively. Results indicate that 45%, 37%, and 54% of the supplies for the near-term, long-term base-case, and long-term high-yield scenarios, respectively, can be delivered at prices of $84 per dry ton (including production, harvest, transportation, and grinding) or less. When calculated as weighted average prices, 70%, 69%, and 84% of the near-term, long-term base-case, and long-term high-yield scenarios, respectively, can be delivered at prices up to $84 per ton. Near-term and long-term base-case results are shown in figure ES.8.

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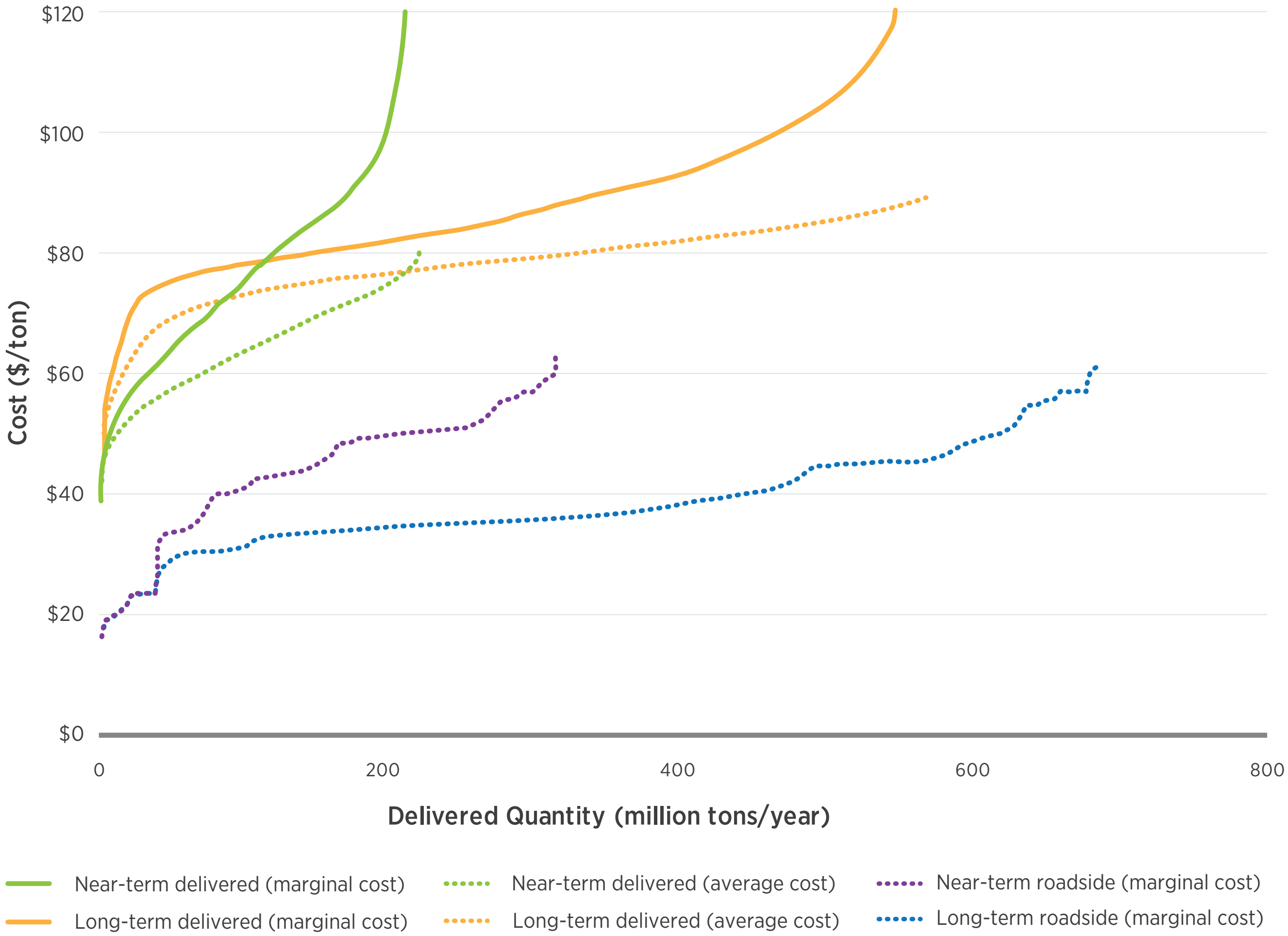
[13] Interactive visualization: https://bioenergykdf.net/billionton2016/7/4/table

Figure ES.8 | Marginal and weighted average costs ($/dry ton) of select herbaceous and woody feedstocks at the roadside and delivered to the reactor throat (base case)



BT16 results are generally consistent with *BT2* and *BTS* in terms of total potential supply. All three reports show a potential supply in approximately 20 years of more than 1 billion tons of biomass annually. It should be noted that prices for energy crops in this report are simulated to begin in 2019, five years later than simulated in *BT2*. Thus, the expansion of energy crops is delayed 5 years from that of *BT2*. Energy crops comprise approximately 400 to 700 million tons of the total potential supply depending on the scenario assumed. As with the *BTS* and the *BT2*, realization of the potential described on this report is contingent upon research, development, commercialization, and markets.

References

EIA (U.S. Energy Information Administration). 2016. Short-Term Energy Outlook. https://www.eia.gov/forecasts/steo/report/renew_co2.cfm.

01 | Introduction

1.1 Background

With the goal of informing national bioenergy and biofuels policies and research, development, and deployment strategies, this report, the *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy* (*BT16*), is the third in a series of national biomass resource assessments commissioned by the U.S. Department of Energy (DOE). *BT16* is composed of two volumes: Volume 1 (this document) is focused on biomass resource analysis (i.e., the potential economic availability of cellulosic and other feedstocks under specified market scenarios). High-level results of volume 1 are generally consistent with the two previous Billion-Ton reports. In volume 1, supplies are quantified under specified sustainability constraints. Volume 2, to be published later in 2016, will evaluate the potential environmental sustainability effects of selected production scenarios described in volume 1.

Improvements with each Billion-Ton report have advanced the analyses from a broad assessment of biomass resources in 2005 to an assessment of the potential economic availability of biomass resources as delivered to biorefineries in this volume of *BT16*. The first report, *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply* (generally referred to as the *Billion-Ton Study* or 2005 *BTS*), was designed to provide a conservative estimate of national biomass resource potential. It identified more than one billion tons[1] of biomass resources from agricultural land and forestland, enough to displace 30% of 2005 U.S. petroleum consumption. The 2005 *BTS* was a national-level assessment with no distinct time frame and no costing analysis. In response to the need for information regarding potential feedstock prices and spatial distribution by feedstock type, in 2011, DOE published the *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry* (generally referred to as the *U.S. Billion-Ton Update* or 2011 *BT2*).

The 2011 *BT2* advanced the analysis of the 2005 *BTS* by reporting potential future supplies under specified market simulations, developed through modeling agricultural sector responses to potential feedstock prices. Supply curves (i.e., supplies in response to prices) were presented under a range of biomass crop improvement scenarios. These included a base-case scenario (1% annual improvement) and high-yield scenarios (2%, 3%, and 4% annual improvement). These yield improvement values, attributable to a mix of future biomass crop breeding and enhanced management practices, were based on input from a series of workshops incorporating expert input (DOE 2009). Under an assumed price of $60/dry ton, *BT2* reported the potential availability of 1.1 billion tons and 1.4–1.6 billion tons under the base-case and high-yield scenarios, respectively, by 2030. By 2022, a range of biomass potential of 0.6–1.0 billion tons was estimated, three to four times the amount needed to meet the advanced biofuels target (EPA 2015) for the same year (Langholtz et al. 2012). *BT2* reported these supplies as potentially available at the farmgate and forest roadside for agricultural and forest resources, respectively (i.e., herbaceous crops baled and stacked, and woody feedstocks chipped and blown into a chip van, excluding transportation costs). Specified secondary waste resources were also included. County-level results of *BT2* analyses were made available for download and visualization from the Bioenergy Knowledge Discovery Framework (KDF) at bioenergykdf.net.

These results were used for a variety of analyses, including the DOE Bioenergy Technologies Office Multi-Year Program Plan (DOE 2016), biorefinery sizing studies (e.g., Muth et al. 2014; Argo et al. 2013), and environmental studies (Parish et al. 2012; Baskaran et al. 2010; Jager et al. 2015). *BT2* data from the Bioenergy KDF have been downloaded more than 8,000 times, and the 2011 *BT2* has been referenced in hundreds of peer-reviewed publications (Web of Science 2015).

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[1] Tons are reported as dry short tons throughout this report, unless specified otherwise.

1.2 Advancements in the Analysis Leading to *BT16*

An explicit limitation of the 2011 *BT2* was that the analysis stopped at the farmgate or forest roadside for agricultural and forestland resources, respectively. As stated in the report, estimates did not represent the total cost or the actual available tonnage of biomass to the biorefinery (DOE 2011, xxiii). Questions were raised regarding how transportation costs of biomass feedstocks from the roadside to biorefineries may impact the prices of delivered supplies, and therefore, feedstock availability. Ongoing research and development efforts—whether at DOE, other federal agencies, or the private sector—require characterization of the economic availability of biomass resources delivered to biorefineries and not just to the roadside.

Text Box 1.1 | Major Enhancements of the *2016 Billion-Ton* Report

- Two-volume approach: Volume 1, Economic Availability of Feedstocks; Volume 2, Environmental Effects of Select Scenarios
- Scenario study of major biomass resources delivered to biorefineries
- Additional sensitivity analyses and specified-demand scenarios
- Interactive visualization of biomass supplies, costs, types, and spatial distribution
- Addition of miscanthus, energy cane, poplars, and eucalyptus as distinctly modeled crops
- Biomass crop yields derived from empirical model of 30-year climate average
- Development and application of POLYSYS forest module for primary forest resources
- Supplies and prices of algae from co-located production systems

While future economic availability of delivered biomass resources will depend on local markets, regulations, policies, spatial distribution of biorefineries, and other factors, this *BT16*, volume 1, provides a scenario study of feedstock supplies and prices as delivered to potential biorefineries. This analysis can be found in chapter 6, “To the Biorefinery: Delivered Forestland and Agricultural Resources.” Although generalized assumptions were made to evaluate supplies and prices of delivered biomass, chapter 6 is a first effort at accounting for tradeoffs between transportation costs and farmgate prices in quantifying potential delivered biomass resources at the national level.

Compared with *BT2*, this volume of *BT16* also adds other enhancements to improve the reliability of the Billion-Ton analyses: (1) the addition of *Miscanthus x giganteus* (hereafter “miscanthus”), energy cane, poplars, and eucalyptus, and municipal solid waste (MSW)[2] as distinctly modeled resources; (2) empirical modeling of biomass crop yields on a 30-year historical climate average; (3) evaluation of forest biomass resources accounting for stand age-class distribution; and (4) addition of potential algal supplies from co-location production strategies. Text box 1.1 presents a summary of enhancements in this report. Table 1.1 is a comparison of this report with previous Billion-Ton reports. More detailed modifications (e.g., crop budget updates, geographic distributions, inflation adjustments) are specified throughout the report. Unless otherwise specified, costs and prices are reported as 2014 dollars.

1.3 Economic and Policy Climate

Since the 2011 *BT2*, the U.S. economy has continued a sluggish recovery from the Great Recession of 2007–2010. From 2011 to 2015, the national unemployment rate decreased from about 9% to about 5% (U.S. Bureau of Labor Statistics 2015), gross

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[2] Biogas from animal manures and landfills is analyzed in chapter 5.

Table 1.1 | Comparison of *BTS*, *BT2*, and *BT16*

	2005 *BTS*	2011 *BT2*	*BT16*
Cost analyses	No cost analyses—just quantities	Supply curves by feedstock by county, costing at the farmgate/forest landing	Costing both at the farmgate/forest landing and at the biorefinery delivery point
Spatial scale	National estimates—no spatial information	County-level estimates with aggregation to state, regional, and national levels	County-level estimates with regional analysis of potential delivered supply
Time horizon	Long-term, inexact time horizon (2005, ~2025, and 2040–2050)	2012–2030 timeline (annual time step)	2016–2040 timeline (annual time step)
USDA projections	2005 USDA agricultural projections; 2000 forestry RPA/TPO	2009 USDA agricultural projections; 2007 USDA Census; 2010 FIA inventory; 2007 forestry RPA/TPO	2015 USDA agricultural projections; 2012 USDA Census; 2015 FIA inventory
Crop residue modeling	Crop residue removal sustainability addressed from national perspective; erosion only	Crop residue removal sustainability modeled at soil level (wind and water erosion, soil carbon)	Crop residue considered in scenario of integrated landscape management
Environmental constraints and impacts	Erosion constraints to forest residue collection	Greater erosion plus wetness constraints to forest residue collection	Similar constraints assumed in volume 1 as in *BT2*. Volume 2 will feature evaluation of key environmental sustainability indicators of select biomass production scenarios from volume 1.
Data reporting format	No external data	County-level data as a function of farmgate price and scenario	County-level data, plus online companion data available for interactive visualization linked to select figures and tables

USDA = U.S. Department of Agriculture; RPA/TPO = Resources Planning Act/Timber Product Output; FIA = Forest Inventory and Analysis

domestic production increased by about 7% (U.S. Bureau of Economic Analysis 2015), and construction increased by about 2% (U.S. Census 2015). A factor in this recovery was low energy prices. According to the U.S. Energy Information Administration (EIA), between 2011 and 2015, national average oil prices dropped from about $90 to $55 per barrel (EIA 2015c), gasoline prices dropped from about $3.50 to $2.20 (EIA 2015d), and natural gas prices remained low, decreasing from about $5.00 to about $3.00 per thousand cubic feet (EIA 2015b).

The Energy Independence and Security Act of 2007 (EISA) was enacted to promote the use of domestic biofuel and to help mitigate oil price volatility (see text box 1.2). When EISA was enacted, gasoline consumption had been increasing consistently.

However, the downturn in the economy reduced total vehicular miles traveled, and new Corporate Average Fuel Economy standards have increased global fuel economy. The net impact is that gasoline consumption hit a peak in 2007 at about 139 billion gallons and declined for several years but is increasing once again (EIA 2015a).

Text Box 1.2 | Energy Independence and Security Act of 2007

EISA was enacted "to move the United States toward greater energy independence and security, to increase the production of clean renewable fuels …" (EISA 2007). EISA instituted RFS2, which mandated the use of renewable fuels, including conventional and advanced biofuels. RFS2 categorizes biofuels as the following:

- *Cellulosic ethanol*, including all ethanol derived from cellulose, hemi-cellulose, or lignin with at least a 60% reduction in greenhouse gas (GHG) emissions
- *Biomass-based diesel*, including biodiesel and renewable (or green) diesel, with a 50% or greater reduction in emissions
- *Other advanced biofuels*, such as butanol, renewable jet fuels, or drop-in biofuels derived from renewable biomass with at least a 50% reduction in emissions
- *Conventional biofuels* or corn-based ethanol.

The renewable volumes mandated by RFS2 in each category are shown in figure 1.1. A total of 36 billion gallons of renewable fuel is required in 2022, with conventional biofuel capped at 15 billion gallons. Advanced biofuels, including cellulosic ethanol and biomass-derived diesel increase to 21 billion gallons in 2022. All volumes are on an energy equivalent basis with ethanol, except for biodiesel, which is the actual volume.

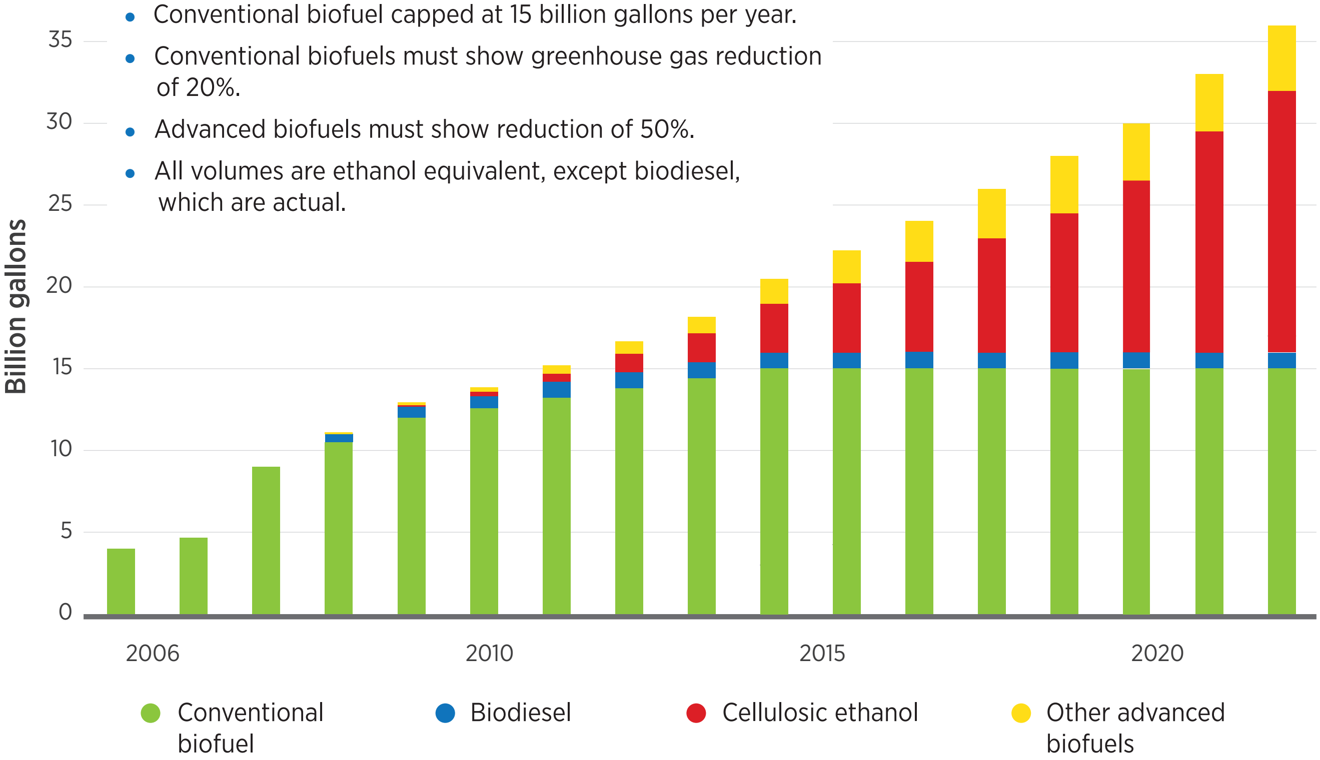
The vast majority of ethanol consumption is through the use of E10 (10% ethanol in gasoline), and virtually all motor gasoline sold in the United States is E10 (EIA 2015a) (see also chapter 2, section 2.3). Both E15 and E85 have been available in the market since the early 2000s but with limited use. This combination tends to set an upper limit on the amount of ethanol that can be easily used in the United States—the so-called "blend wall"—at about 13 billion gallons. The blend wall, coupled with delays in producing cellulosic fuels and the difficulty of commercializing these new advanced biofuels, has prevented the consumption of cellulosic ethanol and other advanced biofuels at the original volumes outlined in the Renewable Fuel Standard (RFS2), although in 2015, biogas and cellulosic ethanol are available.

Biobased diesel fuel is not subject to the gasoline blend wall, and its use has been steadily increasing since the passage of EISA. In fact, the 2015 renewable fuel obligation for biodiesel is greater than originally mandated in 2007 (EPA 2015).

Renewable identification numbers (RINs) are assigned to all renewable fuels produced in the country or imported and are used to ensure and track compliance with RFS2 mandates. Refiners and importers are obligated parties and meet their renewable fuel obligations through the renewable volume obligations (RVOs) that are assigned and tracked by the U.S. Environmental Protection Agency (EPA). RINs can be attached to or separated from the original renewable fuel and can be banked or traded for obligated parties to meet their RVOs. The original targeted volumes and the annual RVOs found in RFS2 since the passing of the law are listed in table 1.2. Figure 1.1 plots the original targeted volumes, which include an increase in cellulosic ethanol from 2012 to 2022.

Feedstock prices simulated in the 2011 *BT2*, and associated potential biomass production, have not been fully realized to date at a national level. The slow economic recovery, increased vehicle fuel economy, and difficult market conditions have caused down-

Figure 1.1 | RFS2 original mandates by biofuels category



ward pressure on biofuels development. In addition, risk aversion has constrained investment in biofuels commercialization. Although risk-management strategies have been proposed (Langholtz et al. 2014), advanced biofuels incur a variety of risks across the supply chain, including but not limited to technology risks, extreme climatic events, agronomic challenges, resource competition, and market volatility.

1.4 Toward Commercialization

The commercialization of biomass resources requires viable markets for multiple products. Biomass is increasingly seen as a valuable domestic resource that not only can displace imported petroleum through domestic biofuels production, but also be used to produce biopower and bioproducts (including chemicals and materials). A thriving bioeconomy would utilize domestic biomass resources available and convert them to a wide array of renewable chemicals and other products, transportation fuels, and fuel for power production. The impact would be substantial in terms of environmental benefits, with reduced GHG emissions from biofuels, bioproducts, and biopower; energy security with increased domestic production of fuels and renewable chemicals; and economic benefits through the development of biorefinery conversion facilities and markets for rural crops, residues, and wastes. Bioproducts offer substantial economic opportunities and could enable the development of the nascent advanced biofuel industry. It is important for a growing bioeconomy to provide viable markets that encourage the development of sustainable biomass resources. These markets would provide additional local environmental benefits such as improved water quality, reduced fertilizer loadings, improved land utilization, and more-sustainable agriculture and timber resources overall.

A large-scale bioeconomy vision using resources quantified in this report is contingent upon the development of markets offering prices simulated in the analyses. Innovations across the feedstock and biofuels supply chain can help mobilize production, harvest, delivery, and commercialization of these feedstocks toward realization of this vision.

1.5 *BT16* Volume 1 Organization

This first volume of *BT16* focuses on the potential economic availability of biomass feedstocks under specified market scenarios. Chapter 2 quantifies currently used biomass resources (e.g., wood pellets, transportation fuels, heat and power, and anaerobic digestion). Chapters 3 and 4 quantify forestland and agricultural land resources, respectively, and report potential economic availability at the forest roadside and at the farmgate, consistent with the 2011 *BT2*. Results from chapters 3 and 4 are combined with select waste resources from chapter 5 to characterize feedstocks delivered to potential biorefinery locations in chapter 6. Algal resources potentially available through resource co-location strategies are considered separately in chapter 7. Volume 1 results are summarized in chapter 8. Figure 1.2 illustrates the taxonomy of the evaluated biomass resources. Figure 1.3 illustrates three main price stages across the biomass supply chain and chapters associated with each step. Similar figures are used throughout the report to specify stages in the supply chain associated with the various chapters.

A key feature of this report is the companion online visualization and data delivery via the Bioenergy KDF. Select figures include hyperlinks to direct

Table 1.2 | Original RFS2 Targeted Volumes and the Annual RVOs (billion gallons per year)

Year	Advanced biofuels								Conventional		Total renewable	
	Cellulosic ethanol		Biomass-based diesel		Other advanced biofuels		Total advanced biofuels		Conventional biofuels		Renewable fuel	
	Original/ adjusted		Original/ adjusted		Original/ adjusted		Original/ adjusted		Original/ adjusted		Original/ adjusted	
2011	0.25	0.0066	0.80	1.20	0.30	0.14	1.35	1.35	12.20	12.60	13.95	13.55
2012	0.50	0.00865	1.00	1.00	0.50	0.99	2.00	2.00	13.20	13.20	15.20	15.20
2013	1.00	0.0060	1.00	1.28	0.75	1.46	2.75	2.75	13.80	13.80	16.55	16.55
2014	1.75	0.0330	1.00	1.63	1.00	1.01	3.75	2.67	14.40	13.61	18.15	16.28
2015	3.00	0.1230	1.00	1.73	1.50	1.03	5.50	2.88	15.00	14.05	20.50	16.93
2016	4.25	0.2300	1.00	1.90	2.00	1.48	7.25	3.61	15.00	14.50	22.25	18.11

Source: Data from EPA (2015).

Note: Quantities in billion gallons per ethanol equivalent, except biodiesel, which is the actual volume.

Figure 1.2 | Taxonomy of biomass resources evaluated in *BT16*

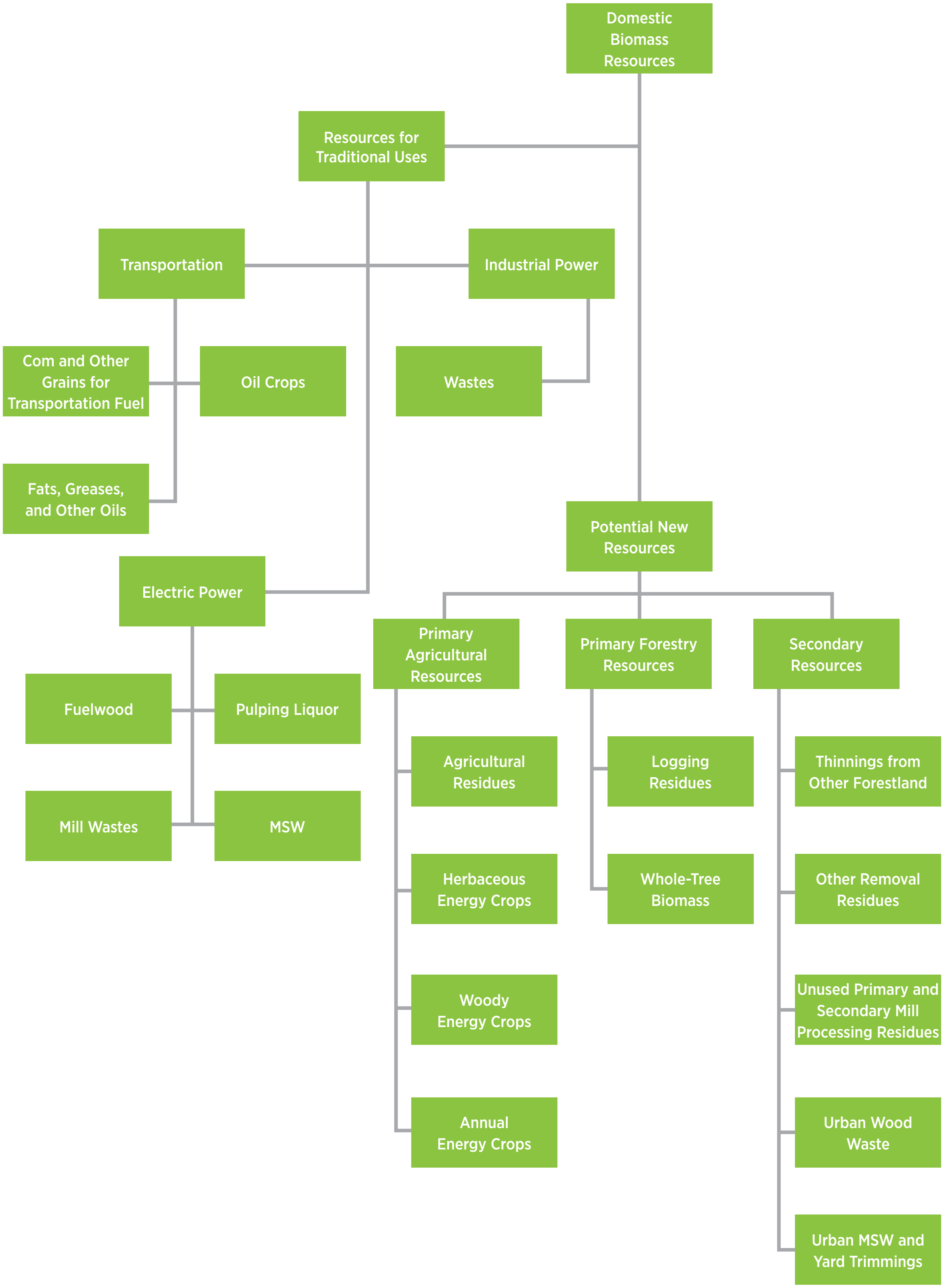
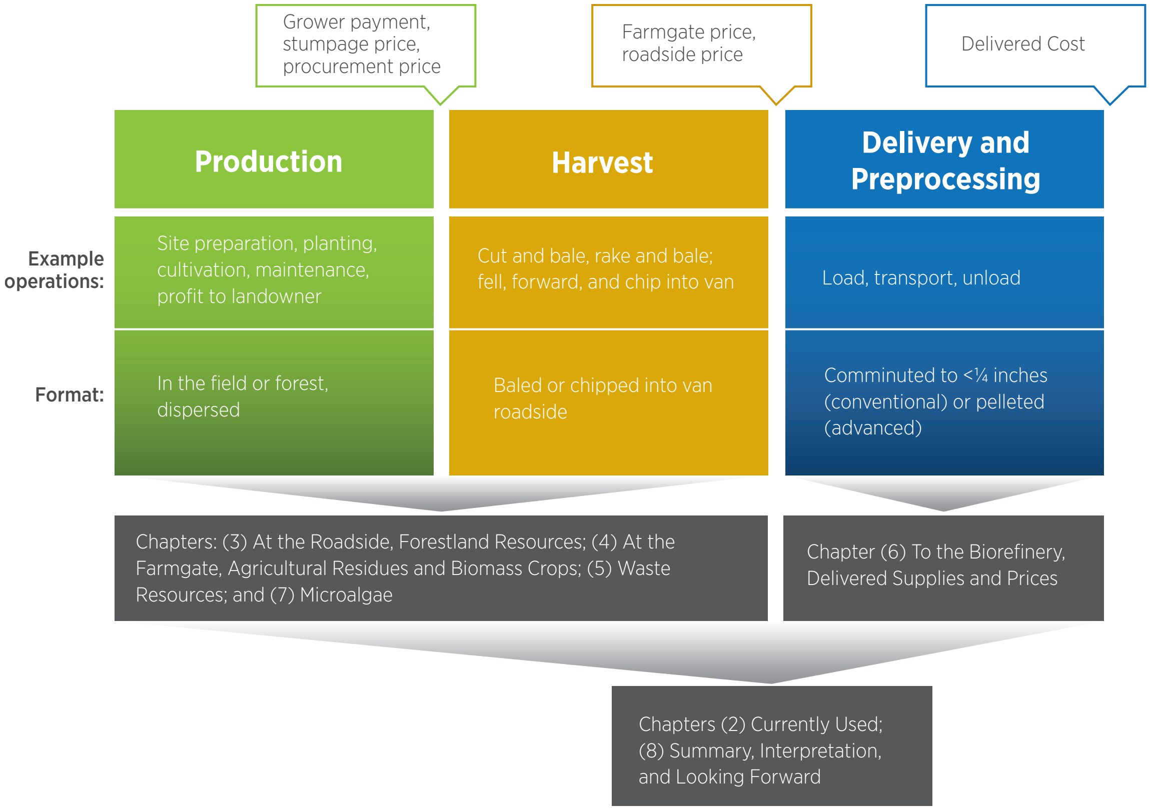


Figure 1.3 | Schematic of biomass resource supply chain, example operations, feedstock condition, cost stages, and chapter scopes



online readers to dynamic visualizations generated through Tableau® where readers can customize graphs, maps, and other formats. These online visualizations elucidate interactions of prices, feedstock types, yield assumptions, and spatial distributions of resources according to specific interests. Tableau visualizations are annotated with this icon 🖥 and a linked footnote. All visualizations can be viewed at bioenergykdf.net/billionton.

Looking forward, volume 2, targeted for publication in 2016, will be a first-of-a-kind assessment of the potential environmental sustainability effects of a subset of production and delivery scenarios of biomass supplies presented in volume 1. An ongoing effort across multiple national laboratories in collaboration with the U.S. Department of Agriculture (USDA) is evaluating changes in key sustainability indicator categories, including soil quality, water quality and quantity, biodiversity, GHG emissions, and air quality (based on McBride et al. 2011). The analyses are being applied to resources derived from both agricultural lands and forest lands. The sustainability of algal biomass production will be considered qualitatively. Weather variability and climate change impacts, land use and land management changes, tradeoffs among aspects of sustainability, and strategies to enhance environmental sustainability will also be discussed.

1.6 References

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08

Summary, Interpretation, and Looking Forward

8.1 Summary of Results

In this report, an effort was made to reevaluate potential forestland, agricultural, and waste resources at the roadside, and then to extend the analysis by adding transportation costs to major fractions of these resources under specified logistics assumptions. The following are results summarized at these two steps along the supply chain:

8.1.1 Roadside: Forestland, Agricultural, and Waste Resources

Biomass resources from timberlands are estimated with a new model—the Forest Sustainable and Economic Analysis Model (ForSEAM). Much of the methodology and several assumptions are revised from the *BT2* analysis for forestry (chapter 3). The feedstock categories are simplified as either logging residues or the harvest of small-diameter trees as whole-tree biomass. The model is used to estimate costs for various scenario demands, which are then transformed into price supply curves. Demand scenarios are based on the 2010 Resources Planning Act (RPA) Assessment using the U.S. Forest Products Module and the Global Forest Products Model. Biomass availability estimates are for privately owned and federal timberlands. At a cost of $60 per dry ton at the roadside, 82 million dry tons are potentially available in 2040 (table 8.1). Without the federal lands, about 65 million dry tons are available from just private timberlands for the same price and year. Less is available in the high demand scenario because natural forests were not converted to energy plantations as discussed in the 2010 RPA Assessment (USDA Forest Service 2012).

Text Box 8.1: Conclusions

Consistent with *BTS* and *BT2,* this report shows the potential availability of more than 1 billion dry tons[1] of biomass for bioenergy and coproducts in the conterminous United States. At a price of $60 per dry ton at roadside[2,3] by 2040, total currently used and potential new supplies range from 1.2 to 1.5 billion tons under base-case and high-yield scenarios, respectively. An analysis of major herbaceous and woody feedstocks potentially available in 2040 suggests that more than half of this supply is available at weighted-average delivered costs of $84 per ton or less.[4] Additional algae biomass could be available at higher prices. The following is a summary of results, caveats, key conclusions, implications, and recommendations for future research.

Biomass resources from agricultural lands are quantified with the same economic model used in *BT2*, with specified updates and revised assumptions as described in chapter 4. By 2040, at prices up to $60 per dry ton, 588 and 936 million tons of biomass resources, beyond current uses, are potentially available from agricultural lands at the farmgate, under the base-case and high-yield scenarios, respectively. A summary of potential supplies at the farmgate as a function of price and yield scenario is shown in table 8.2 and figure 8.1, and as an interactive visualization.[5]

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[1] All tons and prices per ton reported on a dry weight basis unless otherwise specified.

[2] All prices reported as 2014 real dollars.

[3] "Roadside" or "farmgate" refers to forest and agricultural resources after production, harvest, but before transportation and logistics.

[4] The $84 target is derived from the 2016 *Bioenergy Technologies Office Multi-Year Program Plan* in 2014 dollars (inflated from $80 per dry ton in 2011 dollars).

[5] Interactive visualization: https://bioenergykdf.net/billionton2016/4/2/tableau

Table 8.1 | Summary of Baseline and High Forest Resources by Cost, Year, and Feedstock Type

Feedstock	≤$40				≤$60				≤$80			
	2017	2022	2030	2040	2017	2022	2030	2040	2017	2022	2030	2040
	Million dry tons											
Baseline ML (Baseline scenario)[a]												
All land												
Logging residues	18	19	21	21	18	19	21	21	18	19	21	21
Whole-tree biomass	3.1	1.0	0.3	0.0	70	74	60	61	98	97	95	95
Federal land excluded												
Logging residues	16	17	19	18	16	17	19	18	16	17	19	18
Whole-tree biomass	2.8	1.0	0.3	0.0	52	55	43	46	76	75	72	73
Total—baseline (all land)	**21**	**21**	**22**	**21**	**88**	**93**	**81**	**82**	**116**	**116**	**116**	**116**
Total—baseline (no federal)	**19**	**18**	**19**	**18**	**68**	**73**	**62**	**65**	**92**	**92**	**91**	**92**
HH (High-yield scenario)[b]												
All land												
Logging residues	18	19	21	20	18	19	21	20	18	19	21	20
Whole-tree biomass	2.7	0.7	0.1	0.0	61	64	51	41	65	64	62	63

[a] The baseline is "moderate low": moderate growth in housing starts, plantation intensity, paper, and foreign demand and low growth in biomass for energy.

[b] HH is "high high" scenario: high growth in housing starts and planation intensity, moderate growth in paper and foreign demand, and high growth in biomass for energy. HH does not produce the most biomass because there was no conversion of natural stands to plantations in the model.

Table 8.1 ***(continued)***

Feedstock	≤$40				≤$60				≤$80			
	2017	2022	2030	2040	2017	2022	2030	2040	2017	2022	2030	2040
	Million dry tons											
Federal land excluded												
Logging residues	16	17	18	18	16	17	18	18	16	17	18	18
Whole-tree biomass	2.5	0.7	0.1	0.0	46	48	37	33	49	48	47	51
Total—High scenario (all land)	**21**	**20**	**21**	**20**	**79**	**83**	**72**	**61**	**83**	**83**	**83**	**83**
Total—High scenario (no federal)	**18**	**18**	**18**	**18**	**62**	**65**	**55**	**51**	**64**	**65**	**65**	**69**

Table 8.2 | Summary of Agricultural Resources (million dry tons) under the Baseline and High-Yield Scenarios by Farmgate Price and Year

Feedstock	≤$40				≤$60				≤$80			
	2017	2022	2030	2040	2017	2022	2030	2040	2017	2022	2030	2040
Baseline scenario (1% annual growth)												
Crop residues	30	37	46	58	104	123	149	176	117	137	163	188
Herbaceous	N/A	0	6	34	N/A	74	190	340	N/A	177	321	491
Woody crops	N/A	1	6	16	N/A	3	50	71	N/A	10	53	56
Total	**30**	**38**	**59**	**108**	**104**	**201**	**388**	**588**	**117**	**323**	**537**	**734**
High-yield (3% annual growth)												
Crop residues	30	42	63	83	105	135	174	200	121	148	184	214
Herbaceous	N/A	1	18	170	N/A	104	298	594	N/A	230	446	729
Woody crops	N/A	1	22	106	N/A	7	83	142	N/A	16	85	125
Total	**30**	**44**	**103**	**358**	**105**	**245**	**554**	**936**	**121**	**394**	**716**	**1,068**

Figure 8.1 | Potential agricultural resources by price and yield scenario[6]

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[6] Interactive visualization: https://bioenergykdf.net/billionton2016/4/2/tableau

Table 8.3 | Summary of Currently Used and Potential Forest, Agricultural, and Waste Biomass Available at $60 per Dry Ton or Less, Under Base-Case and High-Yield Scenario Assumptions (microalgae resources reported in table 8.4)[7]

Feedstock	2017	2022	2030	2040
	Million dry tons			
Currently used resources				
Forestry resources	154	154	154	154
Agricultural resources	144	144	144	144
Waste resources	68	68	68	68
Total currently used	**365**	**365**	**365**	**365**
Potential: Base-case scenario				
Forestry resources (all timberland)[a, b]	103	109	97	97
Forestry resources (no federal timberland)[a, b]	84	88	77	80
Agricultural residues	104	123	149	176
Energy crops[c]		78	239	411
Waste resources[d]	137	139	140	142
Total base-case scenario potential (all timberland)	**343**	**449**	**625**	**826**
Total base-case scenario (currently used + potential)	***709***	***814***	***991***	***1,192***
Potential: High-yield scenario				
Forestry resources (all timberland)[b, e]	95	99	87	76
Forestry resources (no federal timberland)[b, e]	78	81	71	66
Agricultural residues	105	135	174	200
Energy crops[c, f]		110	380	736
Waste resources[d]	137	139	140	142
Total high-yield scenario potential (all timberland)	**337**	**483**	**782**	**1,154**
Total high-yield scenario (currently used + potential)	***702***	***848***	***1,147***	***1,520***

Note: Numbers may not add because of rounding. Currently used resources are procured under market prices.

[a] Forestry baseline scenario.

[b] Forestry resources include whole-tree biomass and residues from chapter 3 in addition to other forest residue and other forest thinnings quantified in chapter 5.

[c] Energy crops are planted starting in 2019. Note: *BT2* assumed a 2014 start for energy crops.

[d] The potential biogas from landfills is estimated at about 230 billion ft^3 per year as shown in table 5.12.

[e] Forestry high-housing, high biomass-demand scenarios.

[f] The high-yield scenario assumes 3% annual increase in yield.

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[7] Interactive visualization: https://bioenergykdf.net/billionton2016/1/1/table

In addition to the biomass resources potentially available from forestland and agricultural lands identified in tables 8.1 and 8.2 and figure 8.1, 365 million dry tons of currently used biomass resources and 142 million dry tons of waste resources are identified in chapter 2 and chapter 5, respectively. Combining currently used and waste resources with forestland and agricultural resources that are potentially available at the roadside at $60 per ton, yields an estimated 1.2 and 1.5 billion dry tons by 2040 under the base-case and high-yield scenarios, respectively (table 8.3). As with *BT2*, biomass supply increases with increasing price, higher yields, and over time. A major difference between *BT2* and *BT16* is the delayed start date of simulation of energy crops, starting in 2014 in *BT2* and in 2019 in *BT16*. However, out-year results of both energy crops and total supplies are similar for both studies under base-case and high-yield scenarios (fig. 8.2).

Figure 8.2 | Summary of currently used and potential resources at $60 per dry ton or less identified under base-case and high-yield assumptions of *BT16* compared with *BT2*

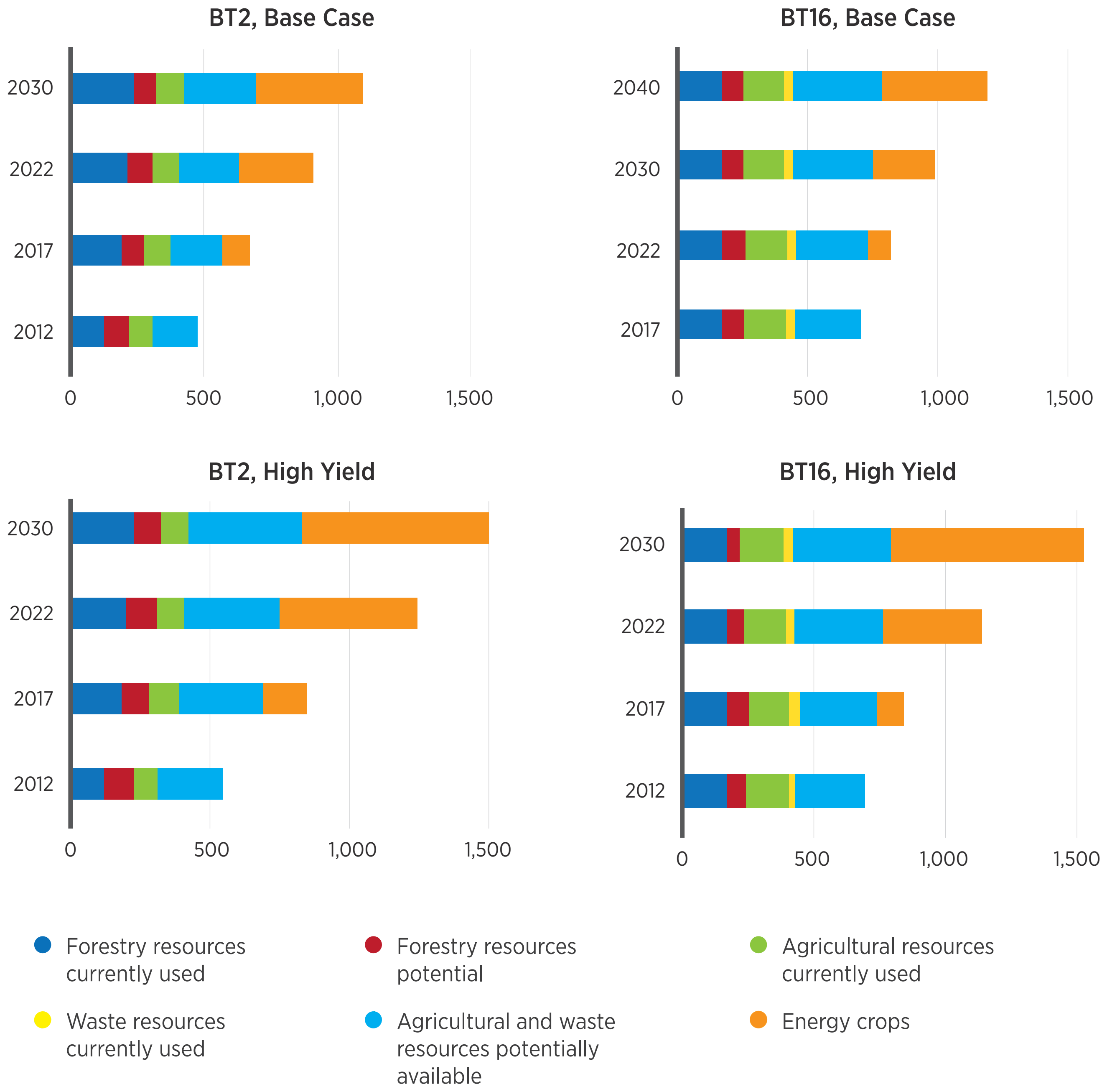
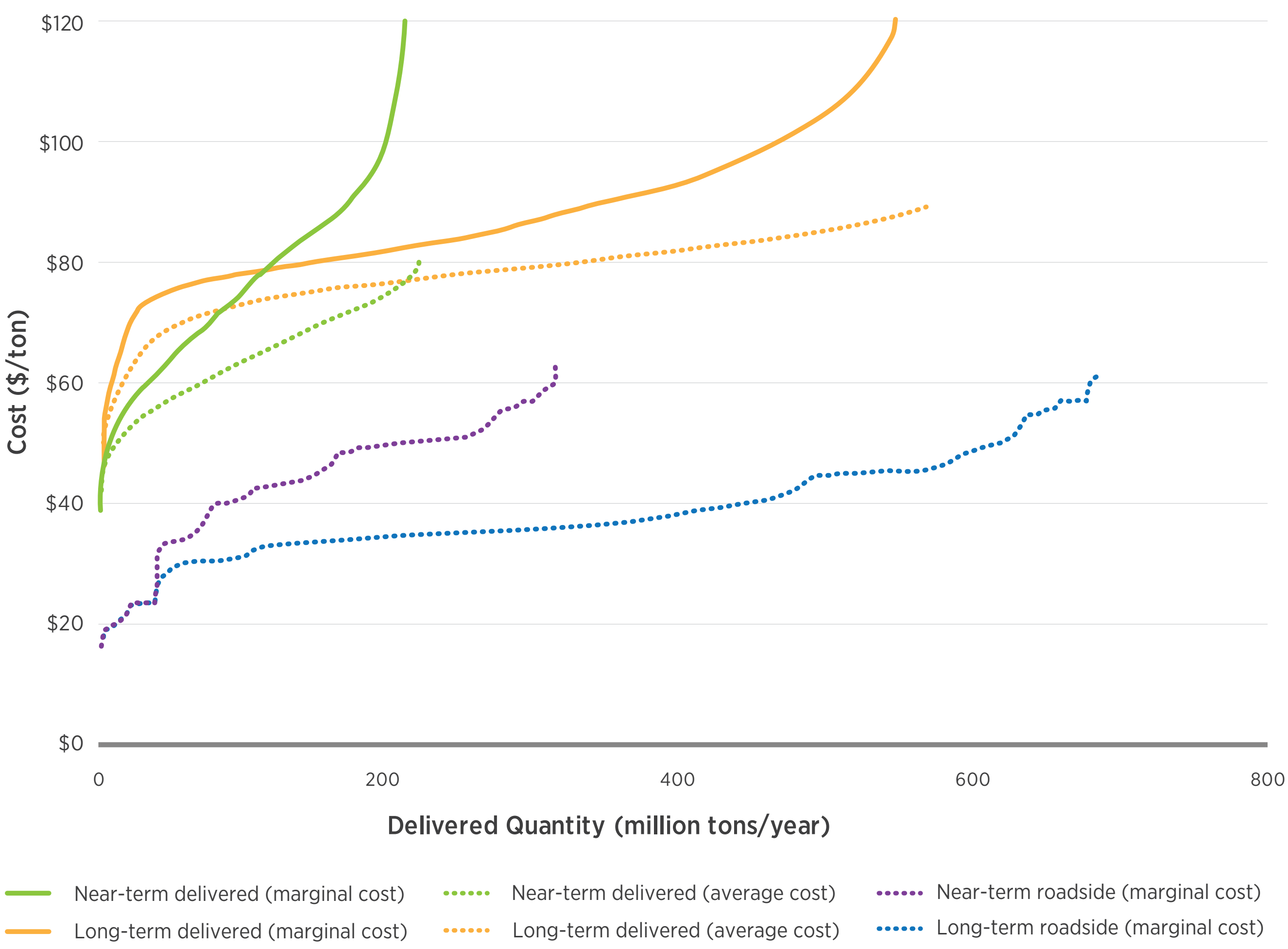


Figure 8.3 | Marginal and weighted average costs ($/dry ton) of select herbaceous and woody feedstocks at the roadside and delivered to the reactor throat (base case)



8.1.2 Delivered Supplies: Advancing Resources from Roadside to the Biorefinery

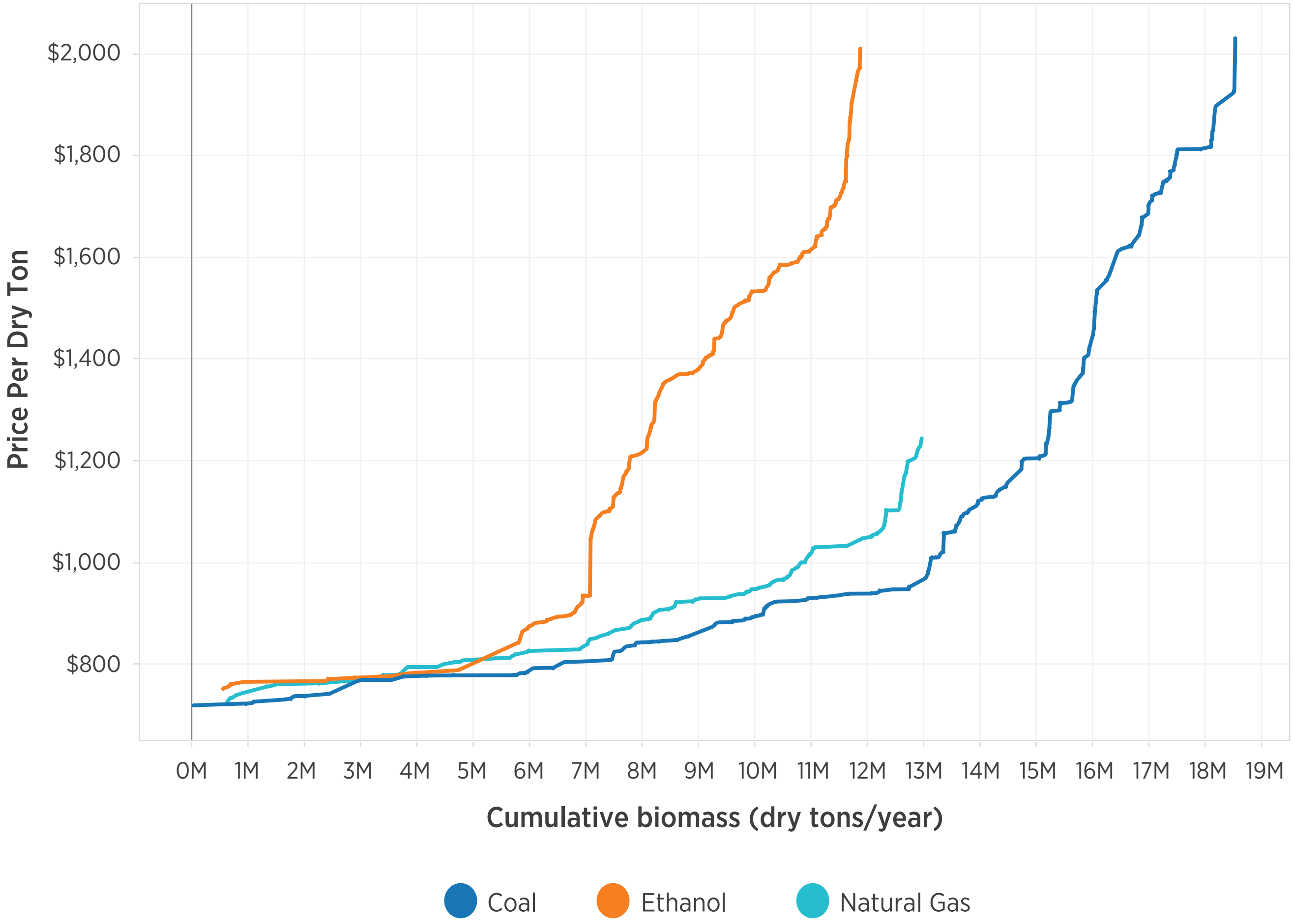
Chapter 6 advances the analysis beyond the roadside with a scenario analysis of the potential economic availability of delivered supplies. A spatially explicit resource allocation model was used to quantify transportation costs and to characterize quantities and costs of resources as delivered to a grid of hypothetical biorefinery locations across the conterminous United States. The delivered analysis is run on a subset of the total resources from chapters 3, 4, and 5 that are potentially available at roadside at $60 per ton or less in 2022 and 2040. This subset includes major herbaceous feedstocks (biomass sorghum, corn stover, miscanthus, switchgrass, and yard trimmings) and major wood feedstocks (whole tree chips, logging residues, short-rotation woody crops, urban wood waste, and construction and demolition waste). This subset of the total potential supply at roadside includes 310, 679, and 985 million dry tons in the near-term, long-term base, and long-term high-yield scenarios, respectively. Given the unique logistical characteristics of algae, it was excluded from the delivered analysis and is assumed to be processed at the site of production.

Supply curves are shown for the select near-term and long-term base-case resources at roadside, as delivered at marginal prices, and as delivered as blended average prices in Figure 8.3. Results indicate that 45%, 37%, and 54% of the supplies for the near-term, long-term base, and long-term high-yield scenarios, respectively, can be delivered at a marginal price of $84 per dry ton or less. When calculated as weighted average prices, 70%, 69%, and 84% of the near-term, long-term base-case, and long-term high-yield scenarios, respectively, can be delivered at prices up to $84 per ton.

8.1.3 Algae

While the national biomass potential for algae is difficult to quantify, this report includes potential algal biomass production that may be associated with select CO_2 co-location opportunities. National potential production from open-pond algae production co-located with ethanol plants, coal-fired power plants, and natural gas-fired power plants is estimated to be 12, 19, and 15 million tons, respectively, for the example of *Chlorella sorokiniana*, a freshwater strain, under current productivities in open ponds (fig. 8.4).

Figure 8.4 | Minimum selling price per dry ton vs. cumulative total biomass for each co-location strategy using Chlorella sorokiniana at present productivities[9]



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[8] Interactive visualization: https://bioenergykdf.net/billionton2016/7/1/tableau

[9] Interactive visualization: https://bioenergykdf.net/billionton2016/7/3/tableau

Table 8.4 | Summary of Biomass Potential from Co-Location (million tons per year). *Chlorella sorokiniana* Is the Example Algae Strain Grown in Freshwater Media, and *Nannochloropsis salina* Is the Example Algae Strain Grown in Saline Media

Scenario description	Ethanol plant	Coal EGU	Natural gas EGU	Total[1]	Range of minimum prices per dry ton[2] ($)
Present productivities, freshwater media	12	19	15	<46	719–2,030
Present productivities, saline media	10	54	21	<86	755–2,889
Future productivities, freshwater media	13	10	0	<23	490–1,327
Future productivities, saline media	11	12	0	<24	540–2,074

[1] Totals are uncertain because analyses of different co-location sources were run independently; therefore, some production facilities that are close to multiple CO_2 sources may be double-counted. The lower future biomass totals are largely due to the increased cost of moving larger quantities of CO_2 needed for higher-productivity strains, which often exceeds the $40/ton purchase price of CO_2 under the implemented technology assumptions. Thus, the benefit of co-location with some CO_2 sources may be reduced in the future. However, future research and development should reduce the costs of capturing and transporting CO_2 from flue gas. Moreover, increased yields. could enable production strategies not evaluated here, and high yields could obviate the economic need for nutrient co-location. Clearly, increasing productivity would decrease the overall cost and price of biomass.

[2] For *Nannochloropsis salina*, the range of minimum selling prices includes both minimally lined ponds and lined ponds. For *Chlorella sorokiniana*, the range of minimum selling prices includes only minimally lined ponds.

Additional examples of projections of algae biomass from CO_2 co-location scenarios are shown in table 8.4. These include scenarios involving *Nannochloropsis salina* as an example saline strain, future productivities, and full and minimal pond liners. Minimum selling prices for this species are estimated to range from just under $500 to almost $3,000 per dry ton, depending on the scenario. Algae supplies are estimated as a function of price.[8] It should be noted that algae has a higher fuel yield per unit biomass than terrestrial feedstocks.

8.2 Interpreting the Results: Implications and Further Discussion

8.2.1 Other Assessments

Biomass assessments are being completed at the state level (University of Washington 2012), the regional level (Kruse 2015), and even the local level (Montana DNR 2011). Many states with forests are completing woody biomass assessments, and some states are assessing agricultural biomass resources.

Other assessments may be more than inventories with detailed economic analyses.

Khanna et al. (2011) completed an analysis of the economically viable supply of agricultural biomass. The study uses costs of production, productivity, and land use similar to the 2011 *BT2* and *BT16*. The analysis shows that about a billion dry tons of agricultural biomass is available—slightly more than the base case for *BT16*, but at a higher price of about $150 per dry ton. The National Research Council (2011) completed a comprehensive analysis of biomass availability as part of an RFS review. Several assessments of cellulosic biomass are compared and summarized for cellulosic biomass, including wastes, residues, and energy crops.

Another decision tool, BioSAT (biosat.net), provides spatially explicit information on biomass supply (Zalesny et al. 2016). The model uses readily available GIS-based landscape characterization and socioeconomic inputs to derive and generate visual information on biomass supply/demand, risk potential, biomass accessibility and landscape suitability, opportunity zones, energy crop production potential, and ecological vulnerability.

A supply estimate by the International Renewable Energy Agency (Nakada, Saygin, and Gielen 2014) ranges from 97 exajoules (EJ) to 147 EJ per year. About 40% is from agricultural residues and waste (37 EJ–66 EJ). Energy crops (33 EJ–39 EJ) and forest resources such as residues (24 EJ–43 EJ) are included. The Food and Agriculture Organization provides a dataset on the supply potentials of bioenergy crops and agricultural residues (FAOSTAT 2014). The database includes current and future land use, agricultural productivity, current and future agricultural commodities yields, and current and future production of food. A study by Lauri et al. (2014) estimates the world's woody biomass energy potential by a partial equilibrium model of the forest and agriculture sectors. They estimate that about 18% of the global primary energy consumption can be displaced in 2050 by woody biomass. Such an effort would require an extensive subsidy/tax policy and would lead to substantially higher woody biomass prices. Another global study investigates the sustainable supply of biomass until the year 2050 for all biomass sectors, including food, feed, chemicals and materials, and bioenergy and biofuels (Piotrowski, Carus, and Essel 2015). Projections in demand are approximately 14–25 billion dry tons for low-to-high scenarios. They conclude that demand can be met without threatening nature and biodiversity with less fossil resources, a sustainable growth in biomass supply, and use of other renewables.

8.2.2 Significance of Underlying Assumptions

Biomass availability is dependent on many factors, including but not limited to time, cost, and yields. Thus, results depend on the selection of parameters and the underlying assumptions. Varying technical or economic variables change tonnage amounts or the timeline required to achieve them.

The conclusions chapter of *BT2* discusses the significance of underlying assumptions in that analysis. To quantify biomass resources from agricultural lands potentially available at the farmgate, the present report uses the same modeling framework as was used in *BT2*. Thus, many of the same key assumptions discussed in the conclusions section of *BT2* are also applicable to this report. Deviation from these assumptions impacts potential future availability. Key underlying assumptions of the agricultural analyses include the following:

- *Prices:* Potential resources are contingent upon realization of the specified market prices. This key assumption is discussed in more detail below.
- *Start year of energy crop contracts:* As discussed below and in text box 4.4 in chapter 4, energy crops become available only after prices are offered for them. Availability of energy crops gradually increases over time in response to those prices. In 2011, *BT2* simulated prices for

energy crops from 2014 to 2030. While there are localized examples of energy crop production, we have yet to see a national market for energy crops take hold. This present report simulates prices for energy crops from 2019 to 2040. While the change in the starting year for contracts for energy crops has little impact on the long-term potential of energy crops, the near-term potential is highly sensitive to the starting year of energy crop contracts. Energy crops produced and harvested in the future will be determined by actual market conditions.

- *USDA Agricultural Projections:* As discussed in chapter 4 and appendix C, USDA Agricultural Projections in POLYSYS inform assumptions of projected future demand for conventional crops. It is these conventional crops that both provide biomass in the form of residues, and compete with potential energy crop production in the future. As with the 2009 USDA Agricultural Projections used in the *BT2*, the 2015 USDA Agricultural Projection is based on various macroeconomic assumptions of future United States and world GDP, population growth rates, dollar exchange rate, crude oil prices, and other attributes (USDA-OCE/WAOB 2015). Changes in these macroeconomic assumptions would impact demand for conventional crops, and, in turn, the potential economic availability of biomass resources from agricultural lands.
- *Base-case and high-yield scenarios:* After farmgate price, the sensitivity analysis in chapter 4 shows yield scenario to impact future availability more than any other variable. Near-term yield assumptions in appendix C, table C.3, are largely corroborated by field trial data from the SunGrant Initiative Regional Feedstock Partnership Report (Owens, Karlen, and Lacey 2016). Future yields will be influenced by experience in energy crop production, crop development, and other factors.

Some assumptions from the *BT2* analysis have been modified for greater precision. For example, tillage practice is now endogenously modeled; more conservative operational constraints on residue harvest are added; and energy crops on pasture land are constrained based on a precipitation gradient rather than the 100th meridian. These and other refinements are described in detail in appendix C.

The underlying assumptions are as significant in forestry as in the agricultural analyses. Especially true is that the prices of woody biomass are derived from demand, not supply potential. The potential supplies are therefore limited to the maximum biomass demands in the selected scenarios. As discussed and highlighted several times in chapter 3, the “no conversion of natural forests to plantations” assumption has the largest impact on biomass availability in the future, even to the point of restricting woody biomass availability to less than the base case for the high-demand scenarios. Even then, any or all of the assumptions could be changed and have an impact on final woody biomass availability. These assumptions include the input costs for stumpage (wood cost) and harvest, the clear-cut-to-thinning ratio, the logging residue retention rate, or the harvest intensity level.

Numerous underlying assumptions are described in the algae analyses in chapter 7 as well, the most important being the technologies included in the analysis. These assumptions include three CO_2 co-location scenarios and open-pond production only. Employing other algae co-location (e.g., with cement or fertilizer production or waste water treatment plants) or production strategies not evaluated here would change potential supplies.

This report provides a vision of future biomass-to-energy market development gleaned from very recent advanced feedstock commercialization history. Therefore, it is important to consider a few key principles that guide the interpretation of the data. The potential supply estimates from agriculture and forestry are anchored to the USDA Long-Term Forecast (extended to 2040) and U.S. Forest Service RPA such that all projected demands for food, feed, fiber, fuel, forest products, and exports are satisfied before biomass crops are planted. The approach downscales results to the county scale using weighted averages of land allocation to crops. Critical information relevant for biomass producers, such as contract length and other variables that influence local and regional biomass supply, are beyond the scope of the report.

To achieve commercial-scale production as represented in the base-case (1%) and high-yield (2%–4%) scenarios, a number of market conditions must align to reduce risk and promote adoption. Recent studies have confirmed a number of these factors that affect farmer participation in biomass markets, such as contract length, cost share, and participation incentives (Bergtold, Fewell, and Williams 2014). In simulations of potential biomass supply in this report, it is assumed a mature market has developed from project-level markets, so that many barriers to commercialization are addressed. These would be associated with markets becoming more competitive (e.g., experience in growing, many buyers and sellers, access to crop extension support, and crop insurance programs associated with commodity crop production).

The potential to expand and develop biomass resources for a robust bioeconomy is large yet challenging to quantify. Numerous technical, economic, and policy challenges exist to expand the biomass-based economy. Using a set of agricultural and forestry sector models, this analysis provides a simulation of potential national commercial biomass market development and not a prediction of future biomass supplies. Early energy crop and biomass market participants to supply biomass for advanced energy and products have indicated that the price range to procure commercial-scale biomass supply is within the range of simulated prices.

New to this report is analysis of potential supplies delivered to biorefineries. In addition to the aforementioned assumptions relating to biomass production and harvest, results of the logistics analysis are subject to key assumptions. Examples include the following:

- Delivered supplies are contingent upon roadside supplies, which are subject to the aforementioned assumptions including prices, yield improvement, and time.
- Prices of delivered supplies are subject to logistical assumptions (e.g., the inclusion or exclusion of specific feedstocks, biorefinery size, and spatial distribution, and a variety of technical assumptions).
- Evolution to advanced logistics systems is contingent upon variables beyond the scope of this analysis. One key variable is unquantified benefits of risk reduction, (e.g., supply security, quality control, flowability, and convertibility). Results suggest that if these combined benefits are worth more than $10 per ton, advanced systems will provide more supply at a lower price than conventional logistics systems.
- Logistic operations will evolve over time in response to market demands. This evolution will be influenced by domestic and international markets, feedstock quality specifications, and technological innovations.
- Inclusion of multi-modal logistical options such as transportation by rail or barge, not included in this analysis, would influence delivered supply curves.

8.2.3 Key Conclusions

The following are key conclusions and implications derived from this report:

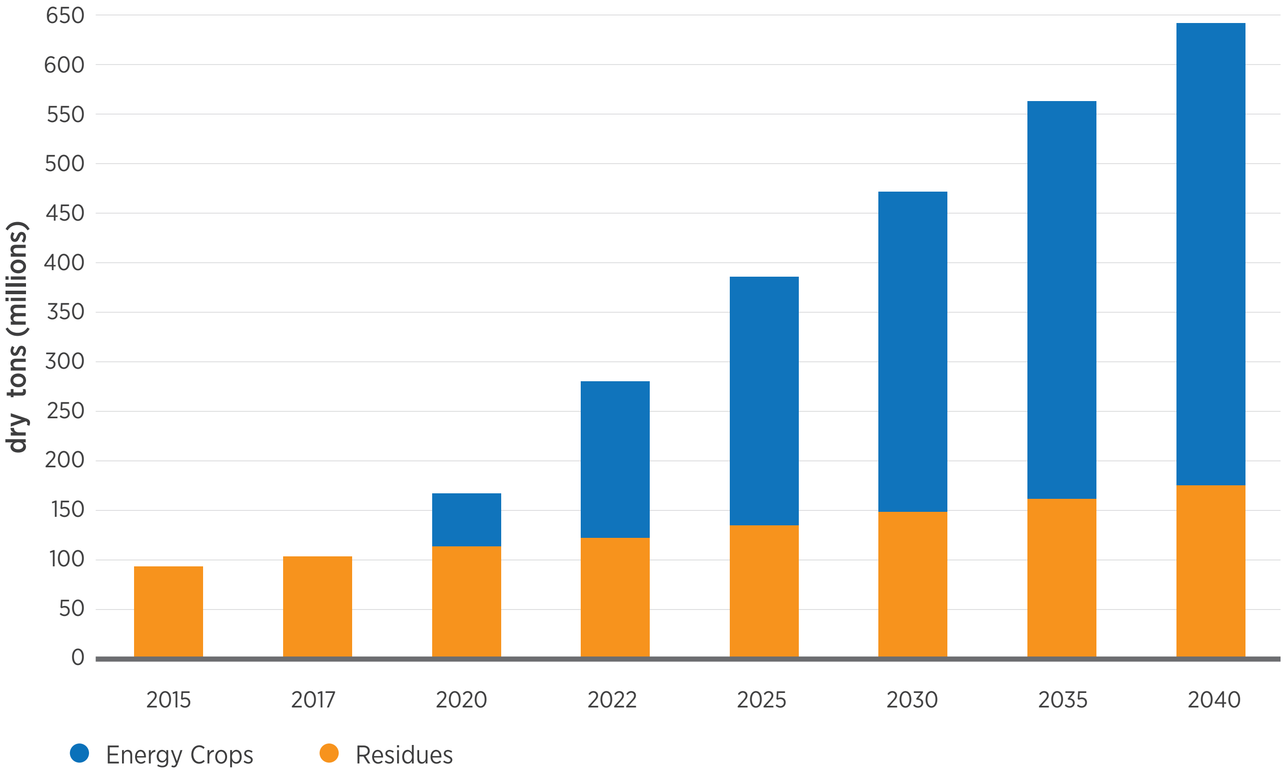
Residues and wastes are available now; energy crops offer growth potential

At prices up to $60 per ton, 104 million tons of crop residues, 18 million tons of logging residues, and 137 million tons of waste biomass are estimated to be available in 2017. This combined 259 million tons of biomass supplements the 365 million tons of currently used biomass and is available for harvest in the near term, even in the absence of biomass markets. At an assumed 80 gallons per dry ton, this supply could theoretically produce up to 21 billion gallons of advanced biofuels per year. As demonstrated by pioneer biofuels projects, biomass residues and waste resources offer an opportunity to gain a foothold in the commercialization of advanced biofuels. In contrast with residues, energy crops are virtually non-existent in the near term, but they can expand rapidly in response to market demand. A market price of $60 per dry ton starting in 2019 could spur energy crop availability, providing 78, 239, and 411 million tons of energy crops in 2022, 2030, and 2040, respectively, in the base case. A high-yield scenario could produce 736 million tons by 2040 at the same price. Thus, energy crops offer the prospect of great growth potential, complementing the near-term availability of biomass from residues and wastes. This relationship is illustrated in figure 8.5 and described in text box 4.4 in chapter 4.

Forestry resources are regionally specific and subject to macroeconomic and local market forces

As with conventional forest products, macroeconomic changes and local markets impact harvest scheduling, silvicultural practices, timber stand age class distribution, and future resource availability. For example, the slump of new housing starts from approximately 2008 to 2013 slowed harvesting of sawtimber stands in the South, shifting the stand age class distribution to older stands. The future economic availability of woody biomass is impacted by the rate of recovery from that market shift. A rapid recovery in housing starts would produce low-cost logging residues and rotate mature stands into new plan-

Figure 8.5 | Growth of energy crop and crop residue resources over time (base case, 1% productivity growth, $60 per dry ton)



tations, which could produce small-diameter trees that could be used for biomass. Conversely, a slow recovery in housing starts could reduce harvesting of sawtimber, increasing the proportion of plantations in mature stands. If such reduction in sawtimber harvest is coupled with increased demand for pulp and paper products in a shifting retail environment, competition for small-diameter trees could increase, depending on local mill operations. A key constraint in the analysis in chapter 3 is that naturally regenerated stands are not permitted to convert to plantations. However, silvicultural intensification could increase per-acre woody biomass yields.

Prices for delivered supplies are largely accessible; more research is needed

Under all three scenarios of near-term, long-term base case, and long-term high yield, over half of roadside supplies considered in the delivered analysis are available at weighted-average delivered prices of \$84 per ton or less. For 2040, 467 and 825 million tons of biomass are reported available at this price under the base-case and high-yield scenarios, respectively. However, these engineering costs assume investment in logistics systems capable of delivering at costs as specified in chapter 6. Further, significant proportions of feedstocks are only accessible at higher prices, or are assumed inaccessible due to losses or required supply buffers. Market, profit, investment, and innovation are needed to realize these delivered supplies at economically accessible delivered costs.

Algae has potential, but prices will need to decrease for that potential to be realized

Algae biomass potential for co-location strategies evaluated here range from about 23 to 84 million tons per year, comprising a small portion of what could be biophysically available. However, the biomass for use in the algal biofuel pathways discussed here is not yet economically viable. Prices for algae biomass from open ponds at future productivities range from just under \$500 per dry ton to more than \$2,000 per dry ton, depending on productivities, the requirement for minimal or full liners, and whether saline or freshwater strains are used. Co-location of facilities with a CO_2 source can provide cost savings; but other advances, such as increases in productivity, are necessary for an economically viable industry. Many technological advances, such as provision for stored CO_2 or pathways where algae serve as a “biocatalyst” (for example, whereby ethanol and/or hydrocarbons are secreted by cyanobacteria), are not considered. Nor are photobioreactors considered for any pathway. In order to make appropriate cost comparisons between algae and terrestrial feedstocks, fuel costs will need to be estimated, because algal biomass has potential for significantly higher fuel yields than energy crops.

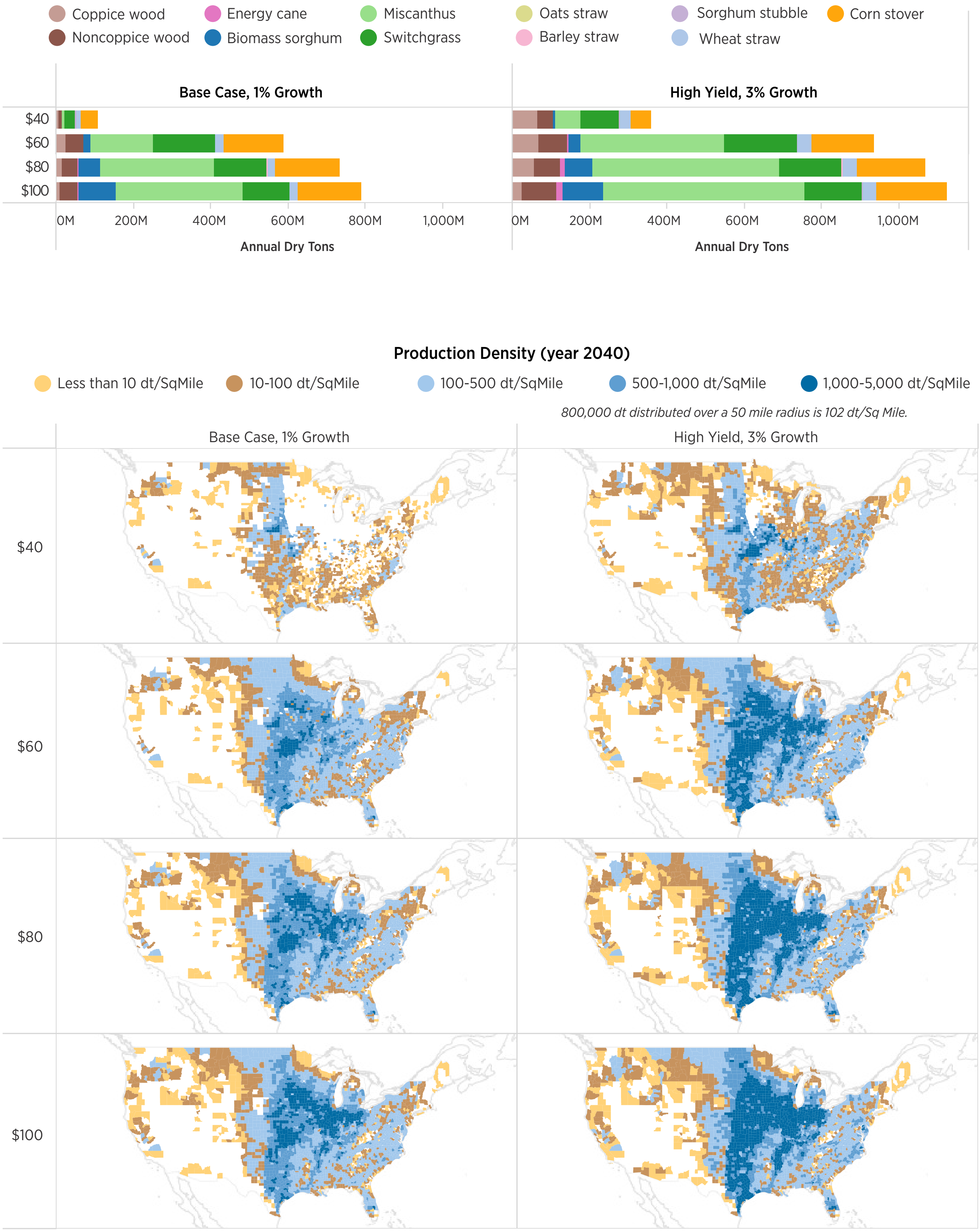
Feedstock availability is a function of market, innovation, and time

Future biomass availability is largely determined by potential profitability to biomass producers. This profitability increases with higher market prices and with innovations that reduce costs or improve efficiency. Innovation is demonstrated in this report in the form of high-yield scenarios, where higher per-acre yields lead to reduced per-ton costs, higher profit margins to biomass producers, and, in turn, increased biomass production. Figure 8.6 illustrates this interaction in the case of agricultural resources in 2040.

Potential supplies are contingent upon prices

It must be emphasized that these results represent potential supply. They are not predictions, but rather estimates of biomass availability at specified prices (i.e., markets exist from 2015 to 2040 for agricultural residues and forestry resources, and from 2019 to 2040 for energy crops). Thus, as in *BTS* and *BT2*, the results from these simulations represent potential supply.

Figure 8.6 | Potential agricultural resources by yield improvement scenario and farmgate price, 2040



Energy crops, in particular, require a sustained market to incentivize establishment and production. For example, the 411 million tons of energy crops available at $60 per ton (base-case scenario) in 2040 will not exist if the $60 per ton market begins in 2040. Rather, the ramp-up to this potential 411 million tons is contingent upon the $60 per ton market price offered to all producing counties in all years throughout the two decades of 2019 to 2040 (after the energy crops are planted in 2018). These considerations highlight the essential role of markets needed to realize the potential biomass supplies quantified in this report.

8.3 Looking Forward and Future Research Needs

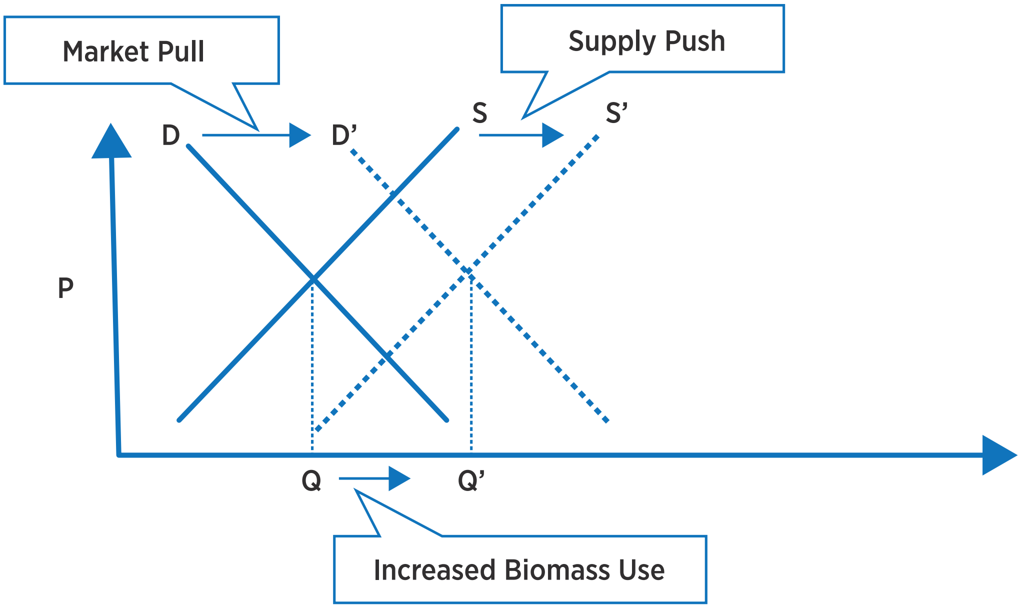
BT16 models the potential availability of agricultural, forestry, and algae resources. As with all modeling efforts, the richness and accuracy of the data are fundamental to a quality product. Both agricultural and forestry models use publicly available data from USDA. These USDA data sets need continued development and improvements to biomass resources. Also, the inputs used in the models, such as landowner payments, stumpage fees, and equipment costs, are always subject to updating; many costs are inflated using price indices, as production and cost information on biomass harvesting machines is not readily available. More research is needed on production costs, management treatments, and yields of energy crops. This report makes great strides toward more accurate regional yield values using a climate model, but even more focus is required to understand the impacts of crop management options on yield, at greater spatial and temporal resolution. As stated earlier, the complex relationships among the various parameters in the models and the outputs need more scrutiny and investigation.

The chapters identify specific research needs focused on reducing uncertainties in assumptions, updating assessments with new information, and identifying key implications of the biomass estimates:

- **Energy Crops**
    - Continued development of energy crops and logistics systems (the key opportunity to reach one billion tons of biomass is through energy crops; therefore, continued development of these crops and logistics systems is critical to reaching a billion-ton bioeconomy)
    - Modeling for comparative risk and required risk premiums for energy crops (this is required to foster commercialization and widespread adoption by growers)
    - Focus on key areas of research needs, primarily market development (i.e., farmgate price) and energy crop yield improvement, as indicated by the sensitivity analysis in chapter 4
- **Forestry**
    - Additional regional verification of the ForSEAM model
    - Impacts of converting natural stands to plantations and silvicultural strategies to provide biomass while contributing to other forest management objectives
- **Agricultural resources**
    - Periodic updates of biomass estimates to keep pace with advances in agricultural innovation and changing markets
    - Future changes in demand from international sources, including fluctuations arising from domestic and foreign policy shifts
    - A continued shift from estimating potential farmgate supplies to potential delivered supplies, as discussed in chapter 6 of this report

    - A shift of focus from potential biomass availability, to better understanding of factors influencing that potential
    - Focus on key areas of opportunity, primarily market development (i.e., farmgate price) and energy crop yield improvement, as indicated by the sensitivity analyses in chapter 4
- **Waste**
    - MSW sorting and recovery methods and costs
- **Analysis of biomass delivered to the biorefinery**
    - Costs of risk (e.g., feedstock supply security and consistency) and quality
    - Economic benefits that may be achieved through improved supply reliability, quality, and handling characteristics of advanced logistics systems
    - Effect of regional variation in moisture content at time of harvest on logistics cost estimates
    - Opportunities of multimodal transportation
    - Lower-cost, higher-efficiency densification and drying systems
    - Multi-feedstock, multi-product depots that share expensive depot infrastructure and energy requirements among a range of merchandisable intermediates
    - Feedstock blending strategies to optimize biomass quality while making best use of local resources
    - Improvements in harvest efficiency and cost to increase the profitability of producers and encourage higher rates of energy crop production
- **Algae**
    - More strategies for co-location with sources of waste CO_2, heat, and nutrients
    - New production technologies (e.g., photobioreactors and nighttime CO_2 storage)
    - Valuation of greater convertibility, co-products, and environmental services associated with algae production
    - Influence of production scale on maximum potential supply.

Figure 8.7 | Illustration of technology push and market pull interactions to increase biomass utilization



The biomass resources identified in this report will not be produced and utilized in the absence of market demand. Approximately 1/3 of the billion-ton potential in 2040—in the form of residues, wastes, and forestland resources—will exist in the field or forest, but it will not be harvested without adequate market signals. Another 1/3 of this billion-ton potential, in the form of energy crops, will not exist unless adequate prices are offered. The scale of potentially available biomass resources has been established in this report, building on *BTS* and *BT2*. Looking forward, we propose a focus on research that can inform strategies to realize this potential availability.

Strategies to foster market development can be characterized as "supply push" and "market pull." Broadly, strategies and technologies that increase biomass supply, decrease biomass price, or increase biomass value, can be considered as supply push. Strategies that increase market demand, in terms of supply or price, can be characterized as market pull. In economic terms, the intersection of supply and demand defines the quantity and price of market clearing (i.e., the point where the quantity supplied equals the quantity demanded). If advancements can be made in some combination of supply push (a shift in the supply curve to the right) and market pull (a shift in the demand curve to the right) then an increase in biomass production and utilization will be realized (fig. 8.7).

Supply push benefits can be realized by a combination of agricultural and logistics innovations across the feedstock supply chain. In chapter 4, a technology push effect is simulated with the high-yield scenarios, where crop yield improvements over time result in increased feedstock availability, all other factors being equal. This effect is illustrated by comparing the base-case and the high-yield scenarios in figure 8.6.

Market pull can be created with any innovation that adds products or value to the end use, or policies that may be applied to compensate for non-market benefits associated with biomass production and use. In this report, market pull is simulated as variation in farmgate prices, where higher prices result in greater supply availability. This effect is illustrated in the rows in figure 8.6. The causes of the demand side, market pull effects are beyond the scope of this report but are simulated by prices as described below.

Figures 8.6 and 8.7 illustrates how a combination of supply push and market pull developments can interact over time, offering multiple pathways to maximize market growth and realization of a billion-ton bioeconomy vision. This vision can be realized with investments in technology push (i.e., the 3% growth column in fig. 8.6), market pull (i.e., the $80 or $100 price scenario in fig. 8.6), or some combination of the two. The following are supply push and market pull research needs that have surfaced in the development of this report and with interactions with related efforts within BETO and the broader biomass and bioenergy stakeholder community. These research contributions would draw on capabilities from multiple agencies and institutions.

Future Research Needs, Supply Push

- *Crop improvement:* Increased yields increase supply and reduce per/ton production costs. Crop development can offer added value, increasing process-specific convertibility.
- *Advanced logistics:* Offer promise for benefits of risk reduction, improved handling characteristics, and improved convertibility, which lead to reduced risk and increased profit.
- *Precision agriculture:* Improved profits to the producer and enhanced production that can support sustainable production criteria.

Future Research Needs, Market Pull

- *Biofuels research:* Drop-in biofuels offer the possibility of vast new biofuel markets. Additional efforts seek to co-optimize the development of vehicle and low-carbon fuels, which could be a substantial new market for biofuels.

- *Bioproducts:* Technologies that can produce value-added intermediates, co-products, and high-value bioproducts can enable and expand biofuel markets.
- *Aviation biofuels:* The aviation market provides a unique and promising opportunity to increase the use of biofuels. These fuels must undergo substantial certification testing before they can be used in aircraft.
- *International markets:* U.S. access to international markets would offer an opportunity to stabilize and moderate biofuel production.

From a systems perspective, the cheapest feedstock may or may not be the most cost-effective. Algae biomass is more expensive than terrestrial feedstocks but is more readily convertible to a biofuel; biomass energy crops are generally more expensive than crop residues but may be lower in ash and more spatially concentrated; biomass delivered from an advanced logistics system may be more expensive than from a conventional system but may offer economic benefits of supply reliability, consistency, improved handling, and other benefits. This study is limited by product-agnostic assumptions and thus excludes these types of benefits, but future analyses with better information about conversion needs and optimization across the supply chain should incorporate them.

Considering the role of markets in realizing the potential biomass supplies quantified here, these results can be used to inform strategies to mobilize these markets and the biomass resources they will require. We can look to the history of commoditization of conventional crops for insight into interrelationships among supplies, markets, and technologies. R&D can improve profits and incentivize investment, which in turn, can grow market demand. Growing market demand can lead to increased feedstock supplies and more R&D. This cycle of investment, market growth, and feedstock supply expansion has become self-sustaining in commodity crop markets. DOE investments to date (e.g., the Regional Feedstock Partnership, biorefineries constructed by Abengoa and POET-DSM, and high-tonnage feedstock logistics projects) have started this cycle. Sensitivity analyses in chapter 4 indicate that, within the modeling assumptions used here, the greatest sources of variability in potential future feedstock availability are associated with yield improvement scenario and price. Pathways toward realizing the high levels of feedstock supply presented in this report include decreasing feedstock cost (simulated by high-yield scenarios), increasing feedstock price (simulated by higher market prices), time (simulated in annual time steps), or some combination of these. Combinations of these attributes can lead to a specified level of potential future production.

In summary, results in this report indicate the United States holds great potential for production of biomass feedstocks. In broad terms, a diversity of biomass resources could be tapped that could double or triple current levels of biomass use for bioenergy, producing approximately 1.0–1.5 billion tons of biomass annually for energy and co-products. Realization of this potential is contingent upon a mix of economic factors not considered here, such as markets, investment, and innovation, as well as economic research that supports the commercial development of biofuel supply chains. An assessment of the environmental sustainability of the biomass potential described here is presented in volume 2 of this report.

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