2016 BILLION-TON REPORT

Advancing Domestic Resources for a Thriving Bioeconomy

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Advancing Domestic Resources for a Thriving Bioeconomy

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Bioenergy Technologies Office

Volume 1:
Economic Availability of Feedstocks

July 2016

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UT-Battelle, LLC
for the
U.S. DEPARTMENT OF ENERGY

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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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.

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.

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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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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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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.

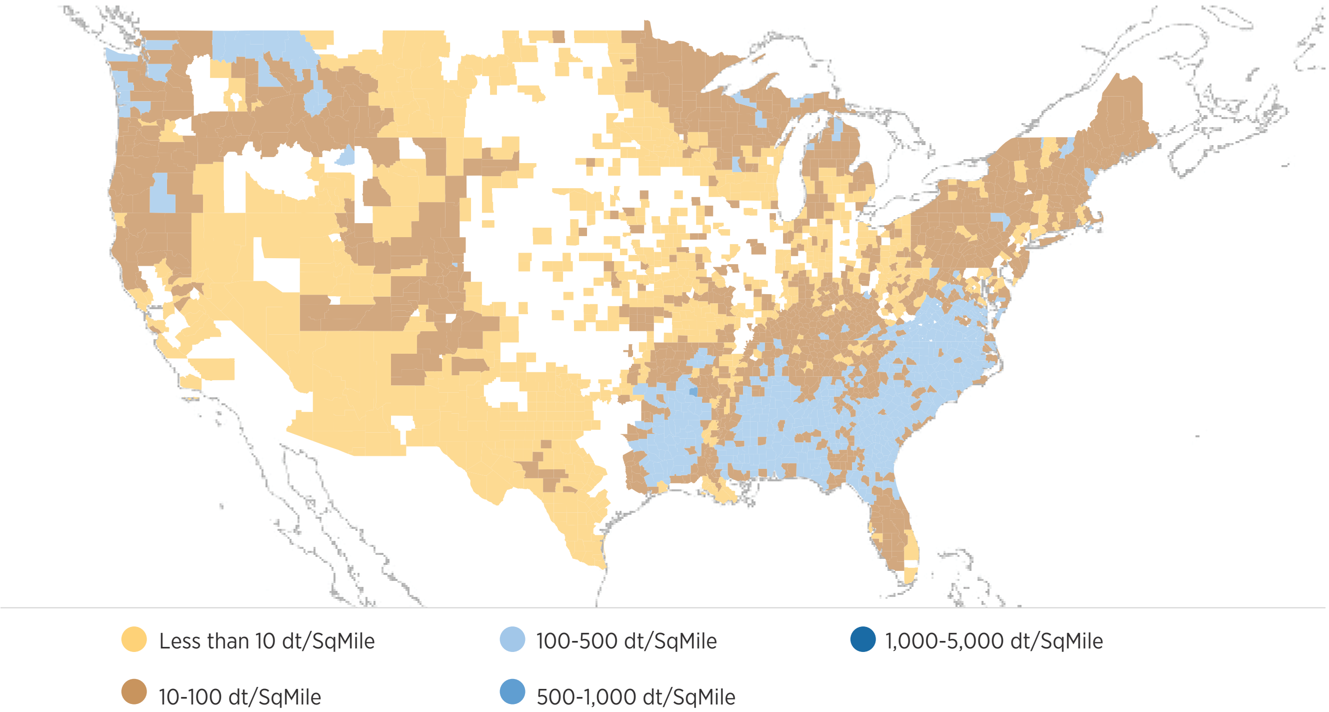
Roadside: Forest Resources and Urban Wood Waste

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]

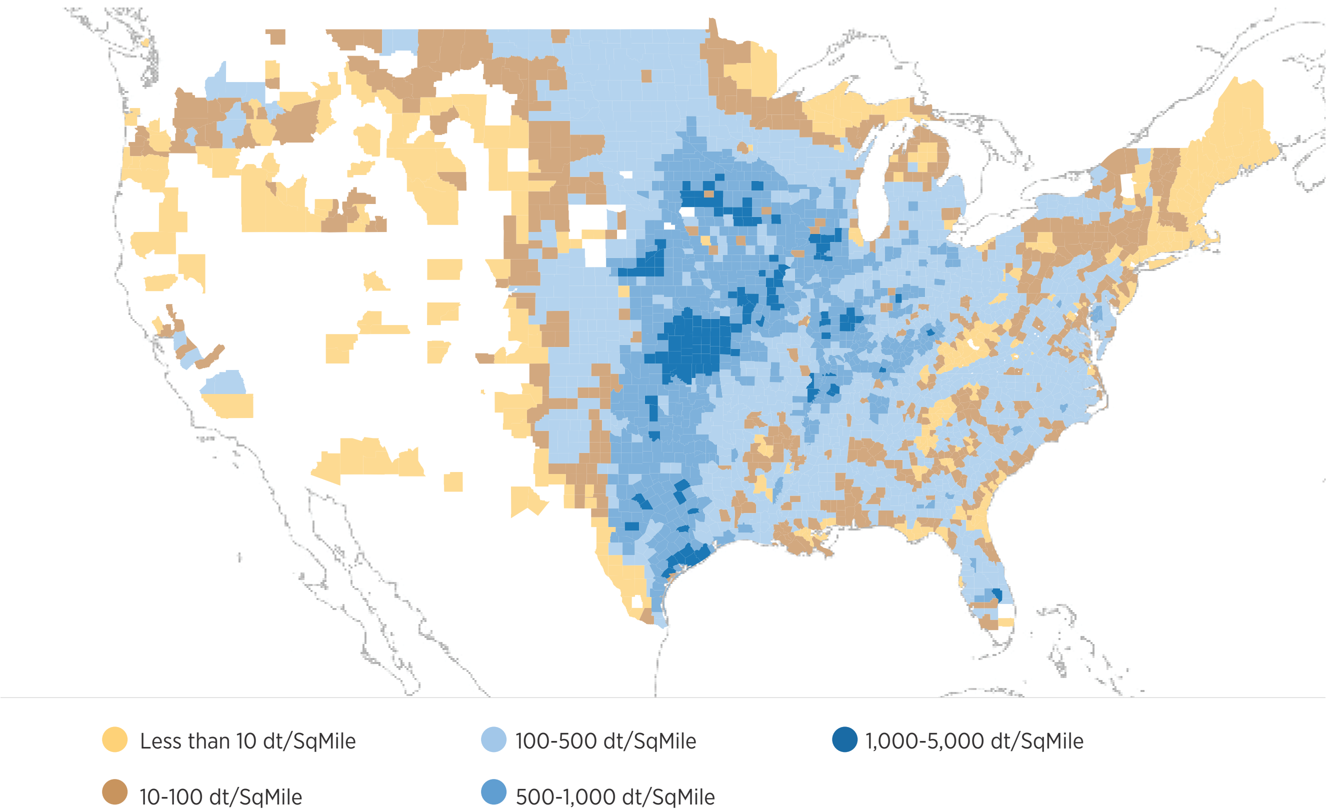
[1] Interactive visualization: https://bioenergykdf.net/billionton2016/1/3/tableau

[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]



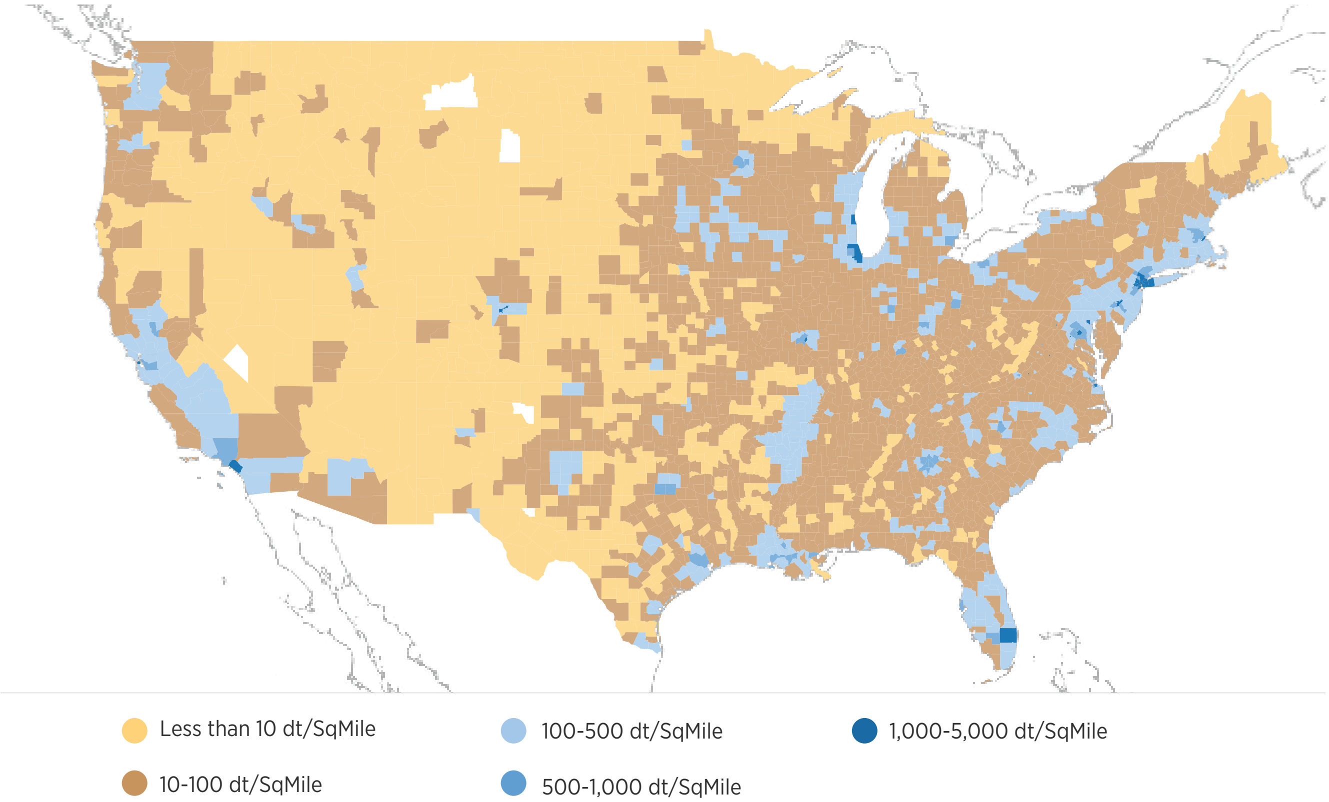
Wastes

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]

[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.

[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.

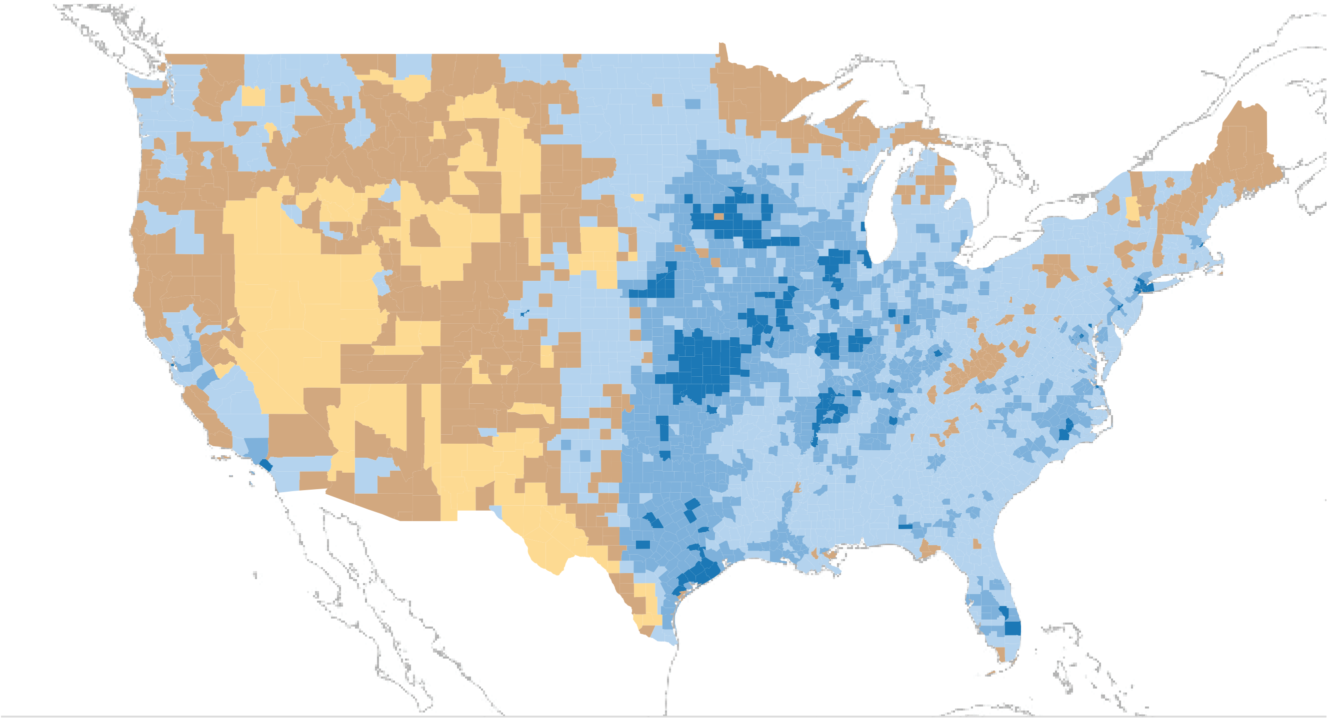
[d] The potential biogas from landfills is estimated at about 230 billion ft^3 per year as shown in table 5.12.

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

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

[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]



Less than 10 dt/SqMile

10-100 dt/SqMile

100-500 dt/SqMile

500-1,000 dt/SqMile

1,000-5,000 dt/SqMile

[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)

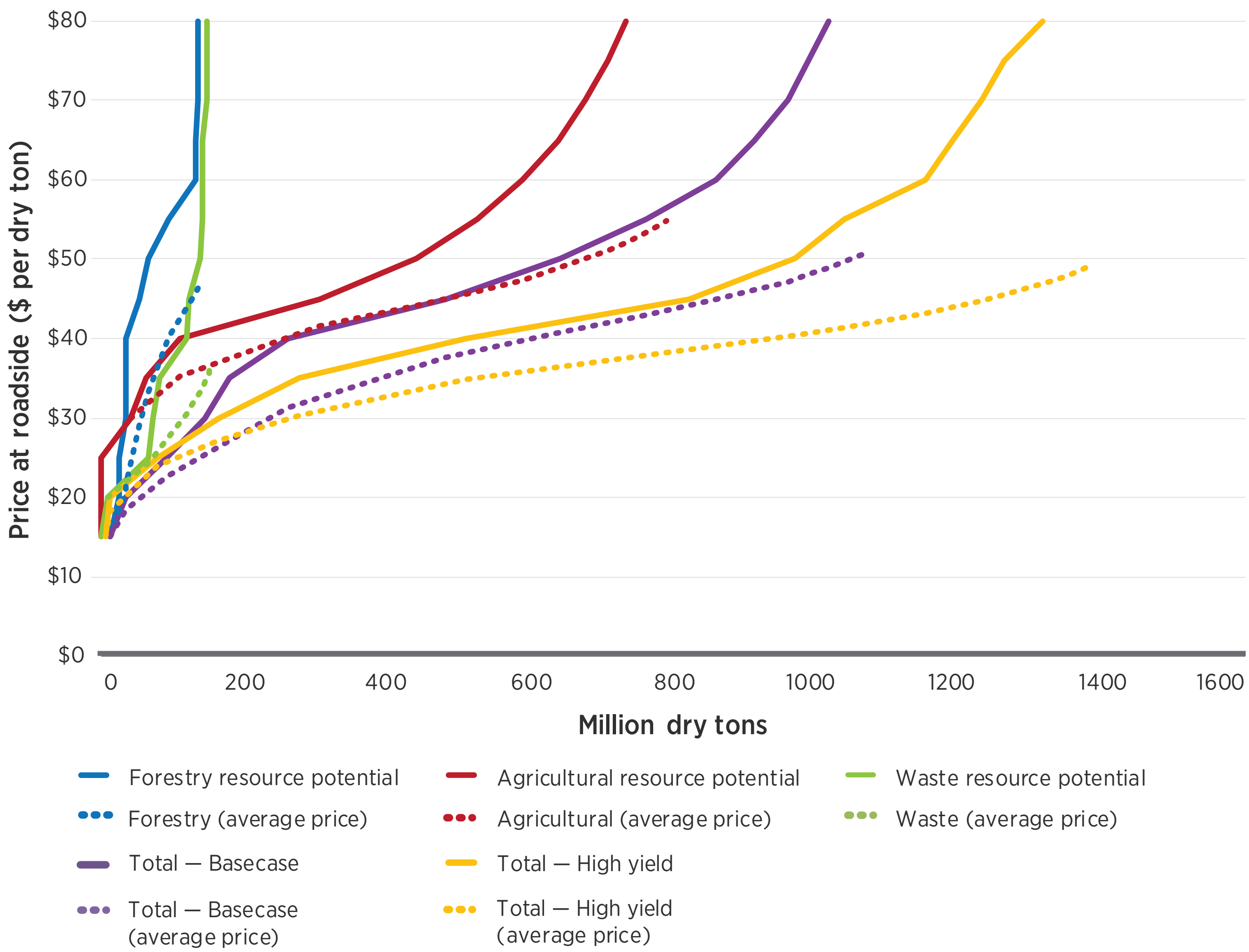
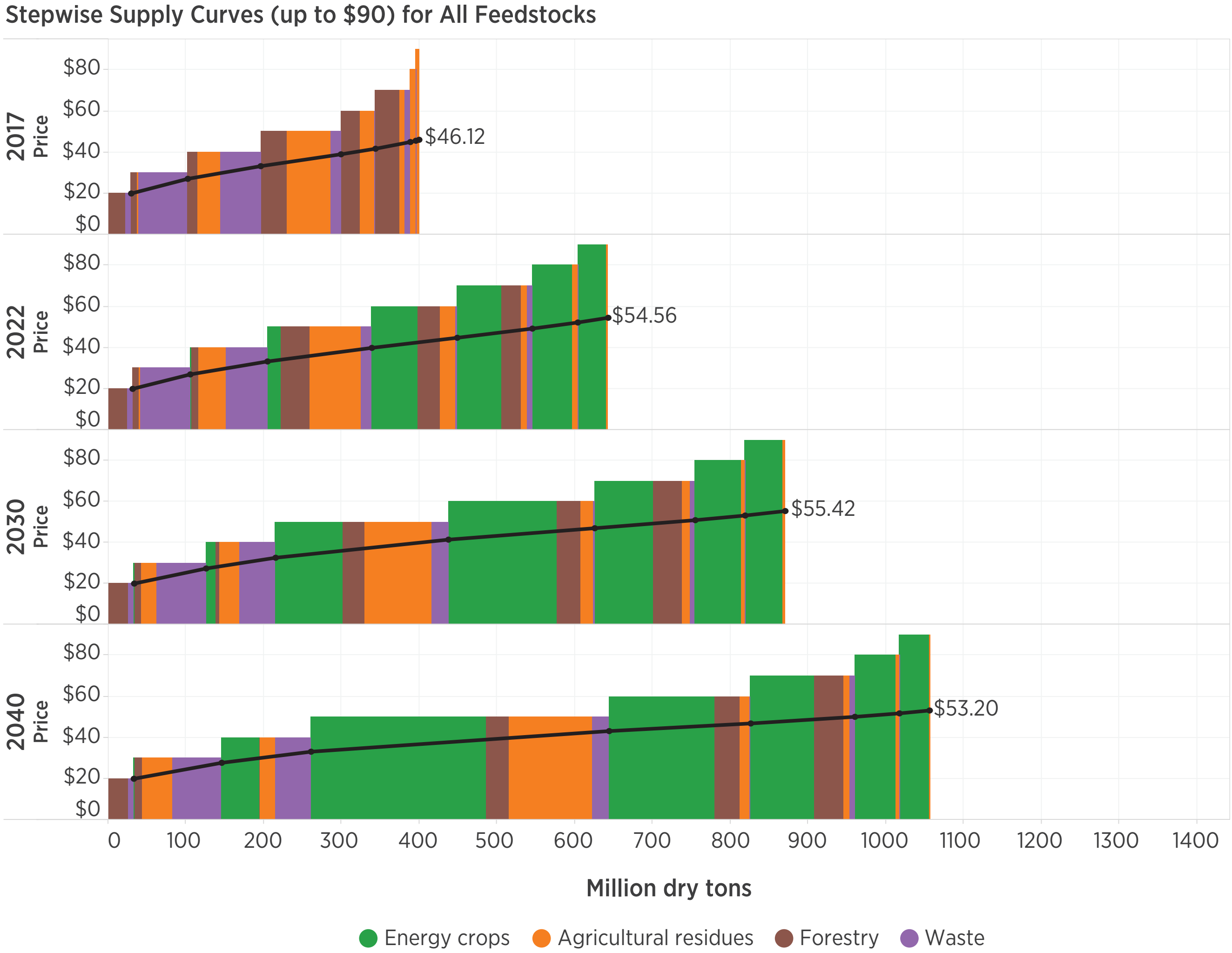


Figure ES.6 | Combined potential forestry, agricultural, and waste biomass resources shown as a function of marginal and average prices at the roadside for select years (base case)[11]



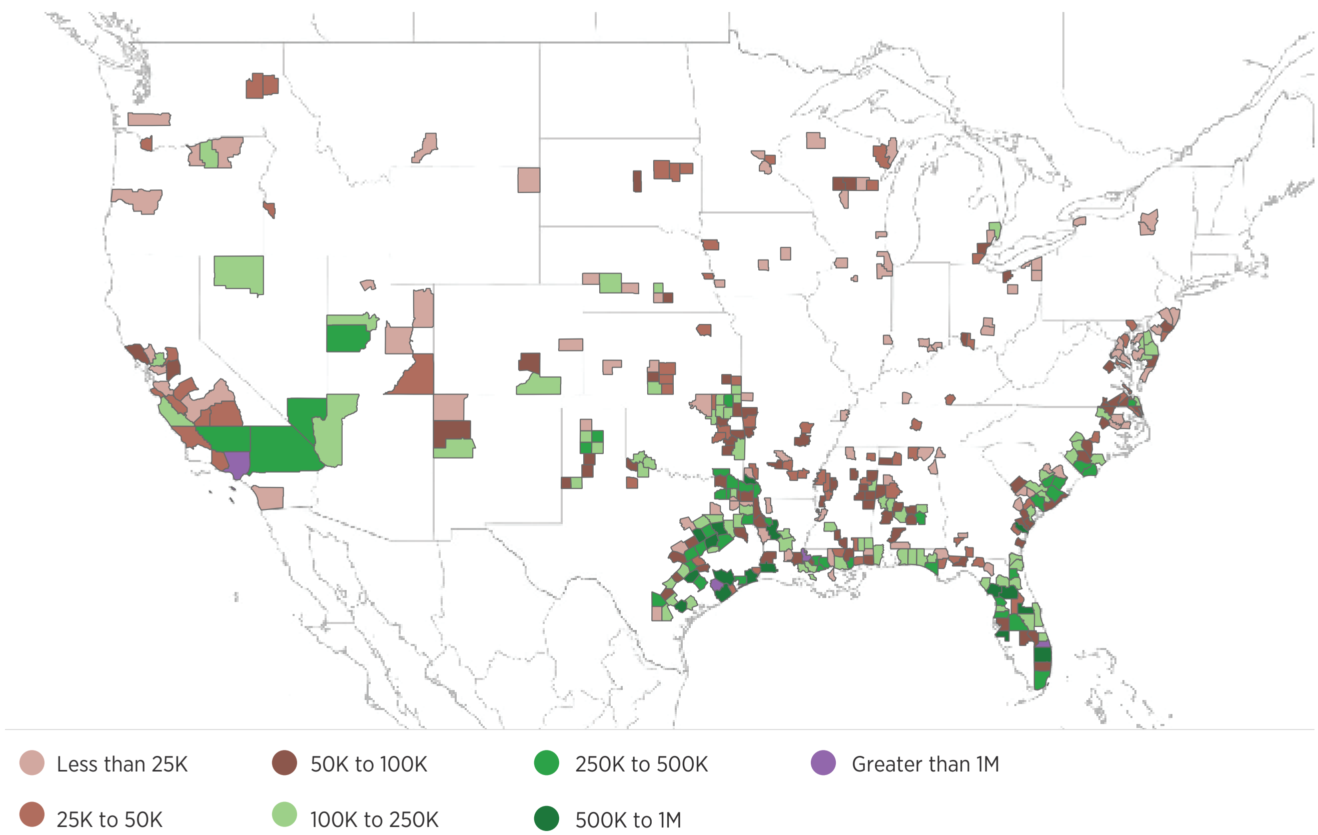
Algae

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

[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]



[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.

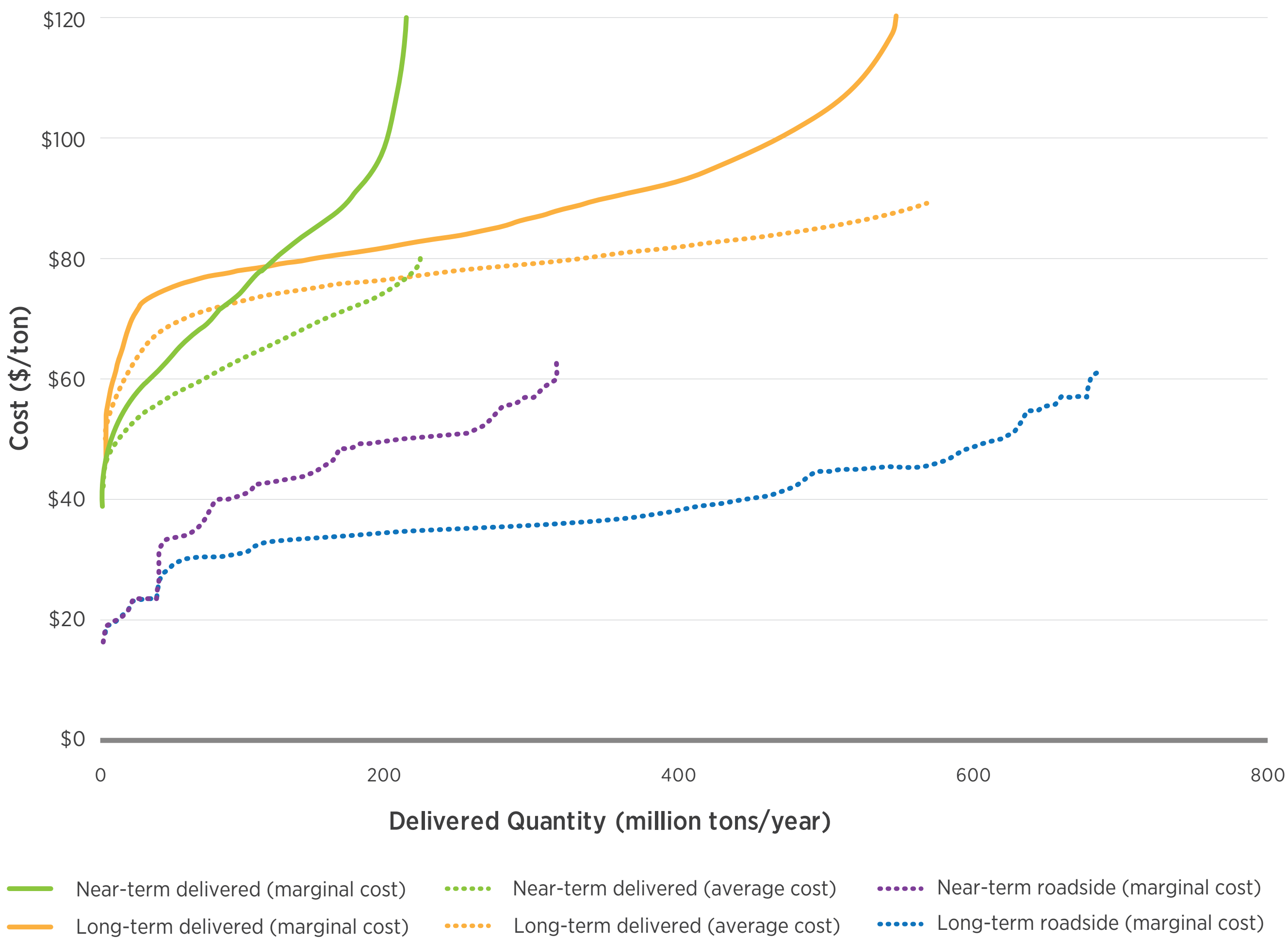
[b] For *Nannochloropsis salina*, the range of minimum prices includes both minimally lined ponds and lined ponds. For C*hlorella sorokiniana*, the range of minimum prices includes only minimally lined ponds.

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.

[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, commercial-ization, and markets.

References

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

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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).

[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

[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.

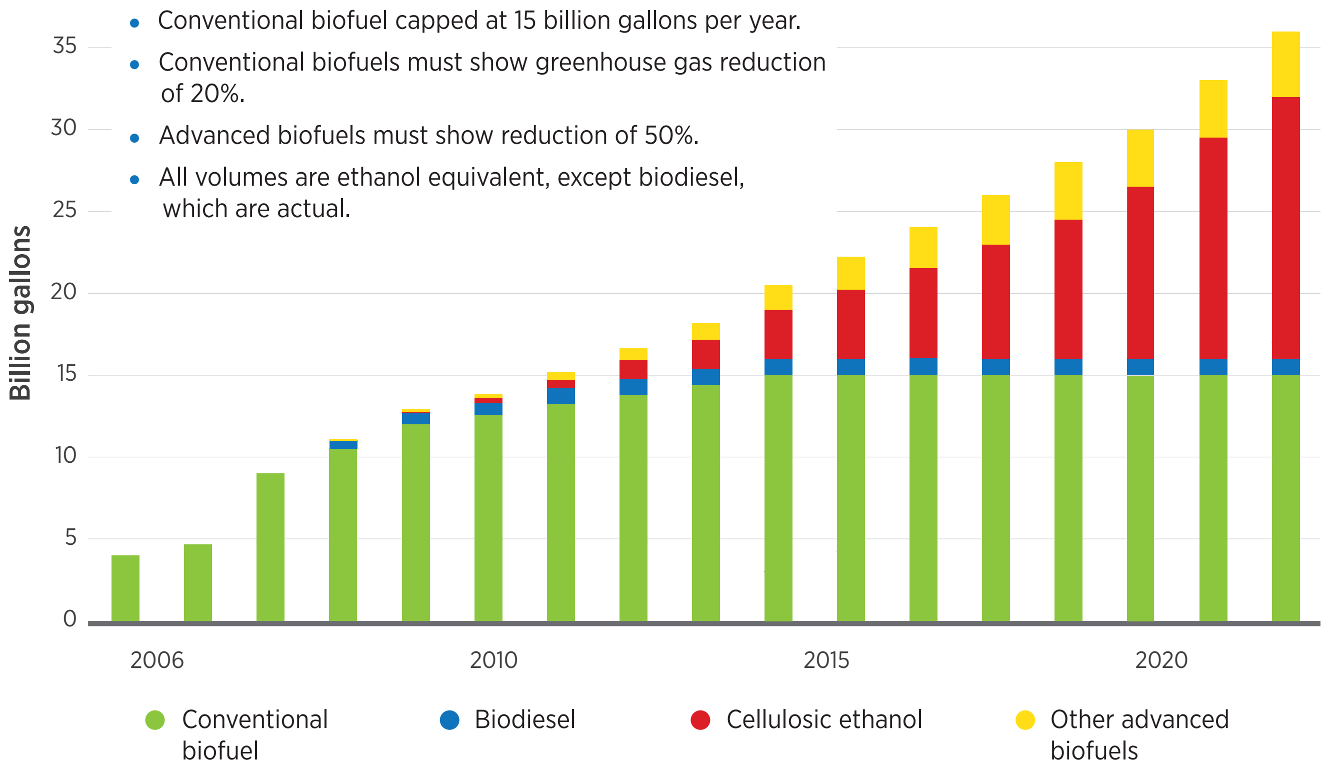
The vast majority of ethanol consumption is through the use of E10 (10% ethanol in gasoline), and virtually all motor gasoline sold in the United States is E10 (EIA 2015a) (see also chapter 2, section 2.3). Both E15 and E85 have been available in the market since the early 2000s but with limited use. 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*

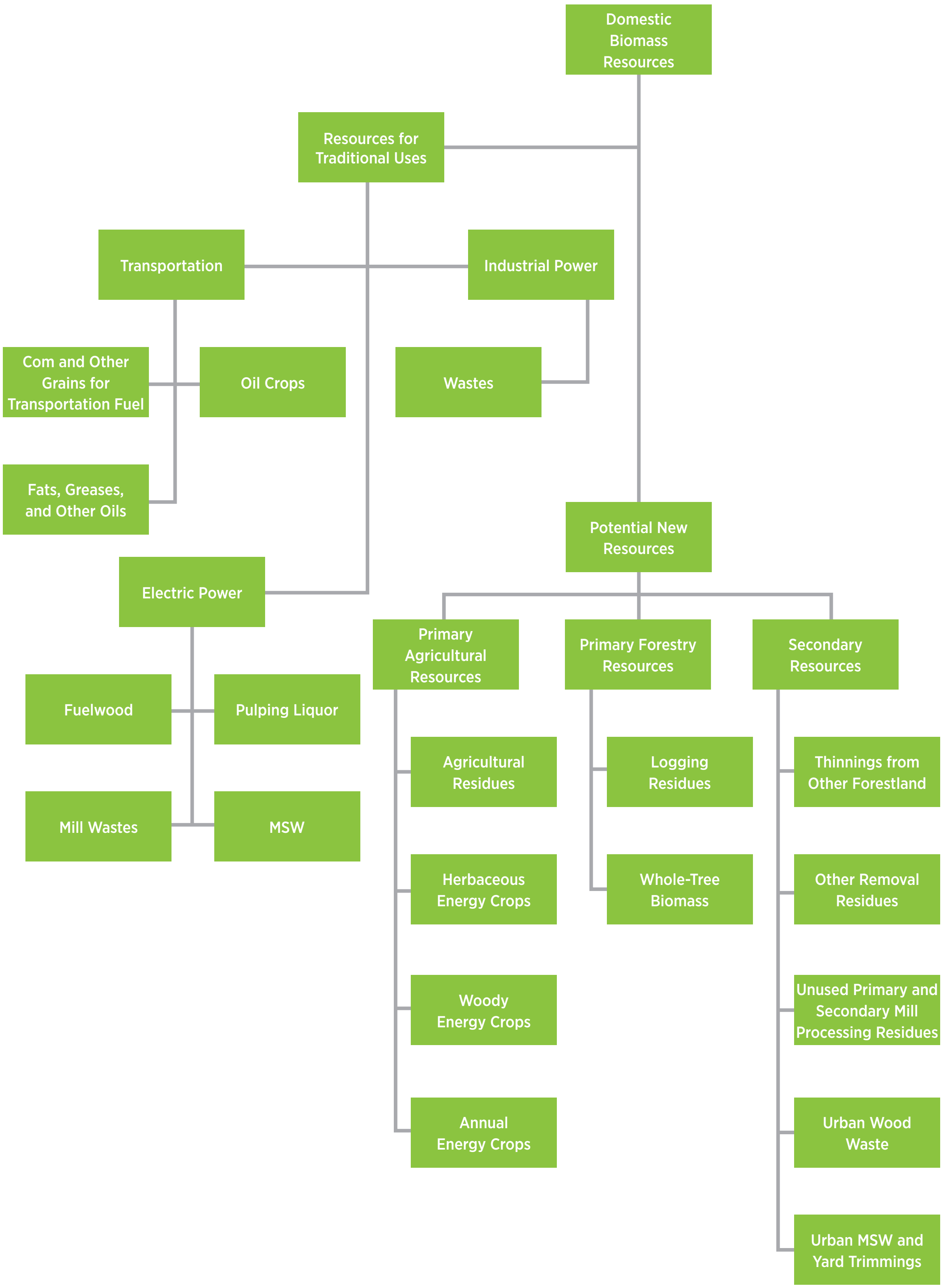
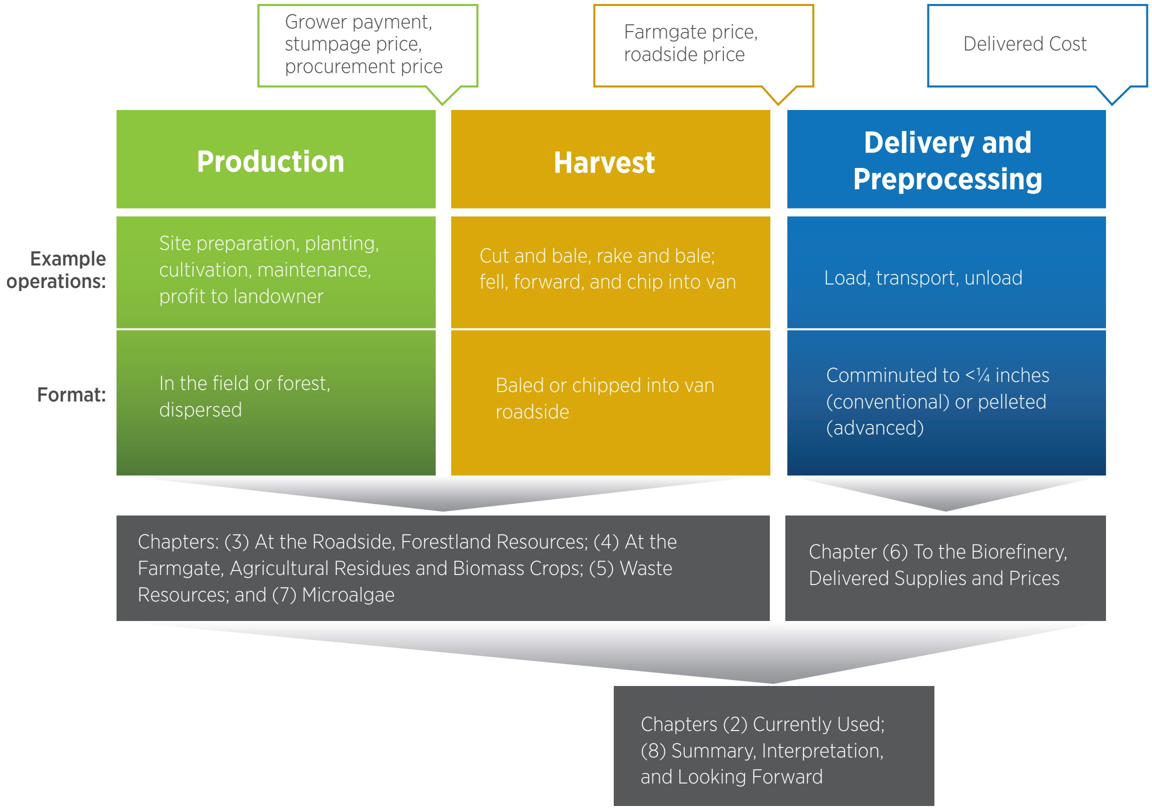


Figure 1.3 | Schematic of biomass resource supply chain, example operations, feedstock condition, cost stages, and chapter scopes



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.

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02 | Biomass Consumed in the Current Bioeconomy

2.1 Introduction

This chapter reviews and expands upon the large variety of biomass-based resources identified in the 2005 *BTS* and 2011 *BT2* that are currently used for fuels, heat, and power production. Biomass is a feedstock for a broad range of primary and secondary energy applications, from home heating to industrial power generation. This section will review primary energy consumption, along with a compilation of estimates of secondary biomass consumption, with attention to the quantification of biomass as a feedstock for energy uses.

Text Box 2.1 | Data Sources and Definition of Currently Used Resources

In this chapter, 2014 values of biomass energy consumption are used as much as possible; however, the wood-derived energy, MSW, and landfill gas values from EIA's 2015 *Electric Power Annual* are from 2013. These values were chosen as the best and most current source of data.

The *Electric Power Annual* was selected, as opposed to EIA's *Monthly Energy Review*, because it breaks down the feedstock categories to a more granular level and attributes energy to both electric and thermal end uses (unlike the *Monthly Energy Review*). The *Electric Power Annual* also provides information regarding MSW and landfill gas in thousand dry tons and million cubic feet, respectively.

In the 2011 *BT2*, projections of biomass consumption from EIA's *Annual Energy Outlook* provided the basis for growth in supply for existing biomass-to-energy pathways (EIA 2015a). This report deviates from this approach using two simplifying assumptions about future demand and supply. First, it is assumed that demand is constant for all existing uses identified in this chapter throughout the projection period to 2040. Second, future supply of biomass to meet existing uses equals demand. The representation of "currently used resources" in reporting the billion-ton potential is reported alongside potential future supply to highlight the growth in biomass potential supply without confounding estimates of growth in demand from biomass energy.

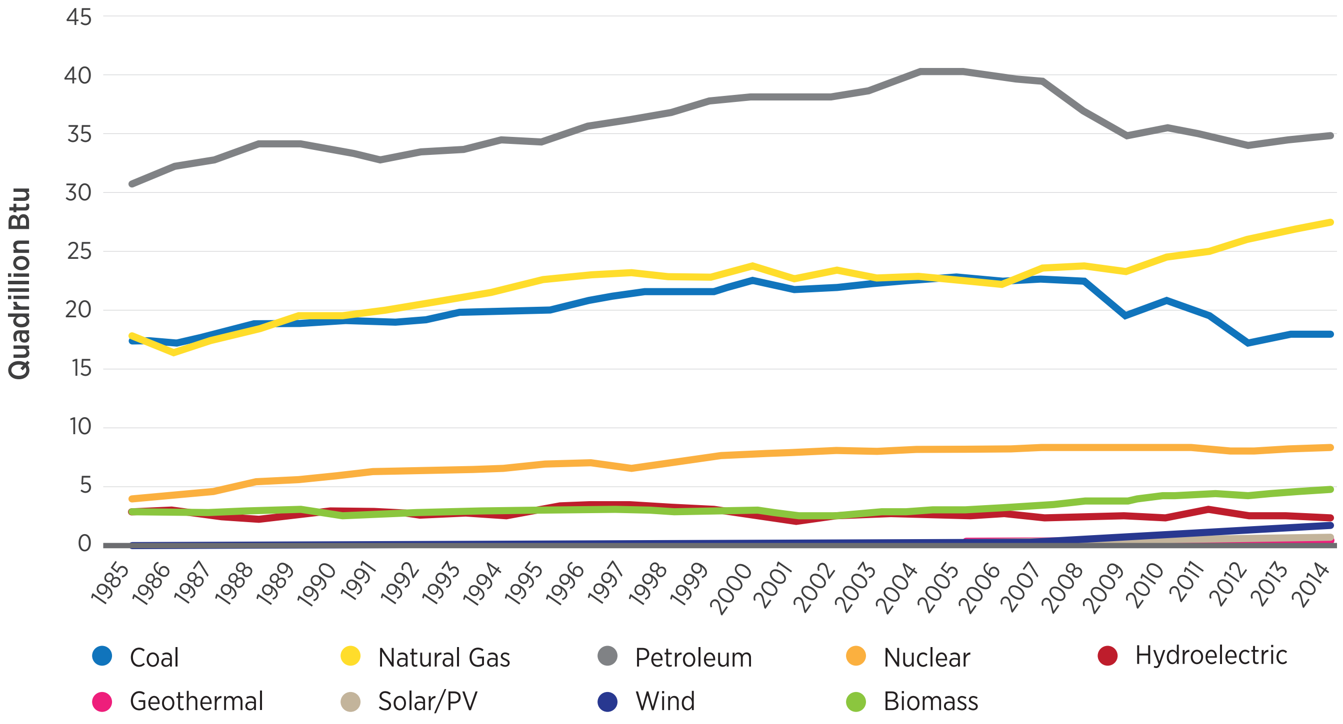
2.2 Primary Energy Consumption

According to EIA, combined energy consumption rose from a low of 76 quadrillion Btu in 1985 to a high of 101 quadrillion Btu in 2007 (EIA 2015b; see fig. 2.1). Around 2006, there is a clear inflection point marking downward trends in the use of coal and petroleum. Natural gas has shown the largest growth, although biomass, wind, solar, and other renewables are also trending upward. The use of renewable energy will continue to increase as the United States attempts to meet emissions reduction targets and transition toward a more diverse energy portfolio.

As shown in figure 2.2, cumulative renewable energy consumption has increased steadily since 2001, driven by growth in biofuels, wind, and solar production. It is interesting that the composite renewable energy total correlates closely with the largest sources, hydroelectric and biomass, up until 2001; after that, it grows according to the expansion of biofuels production from 2001 to 2014. Figure 2.3 provides a view of the 15-year historical consumption levels for the major components of renewable energy and a cross section of 2014 consumption by source.

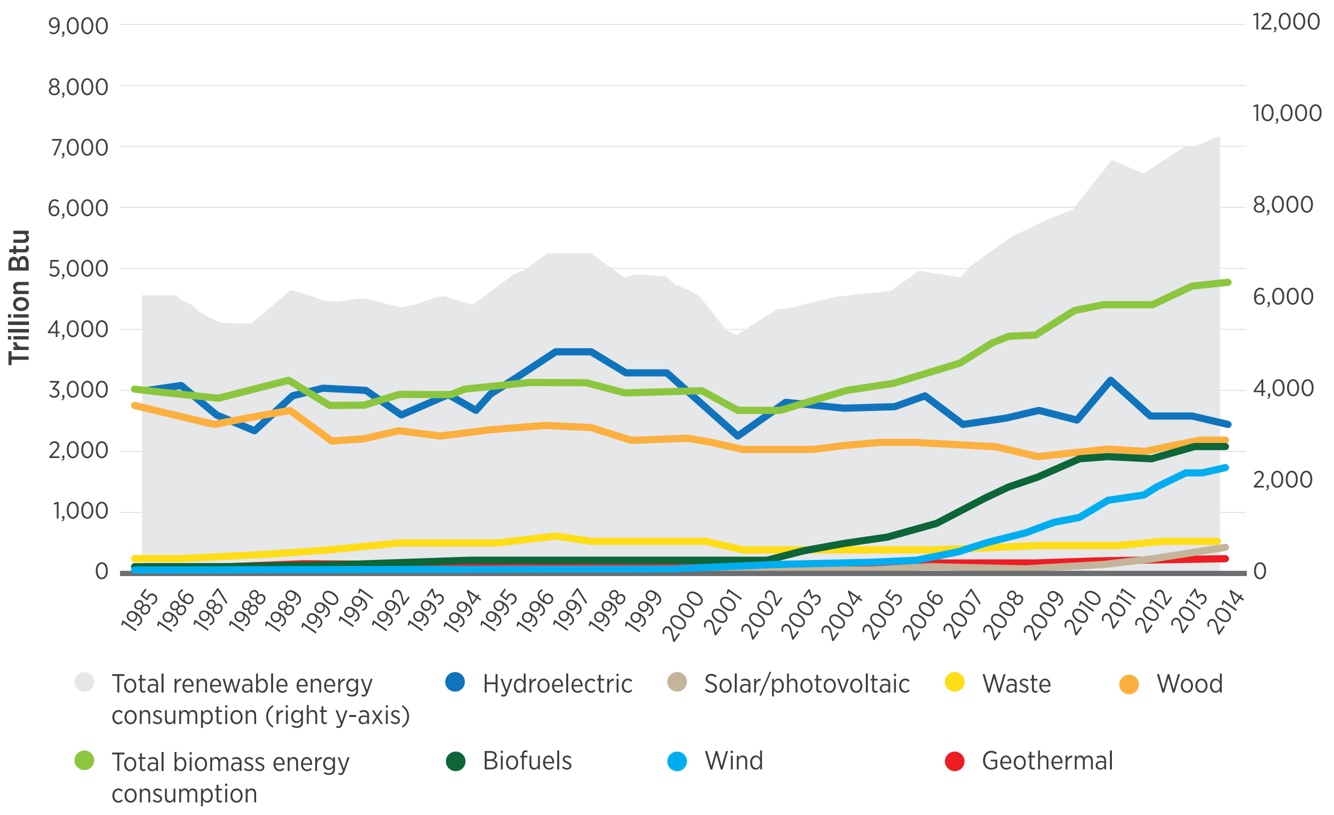
Biomass-based energy as a composite category of wood (23%), waste (5%), and biofuels (21%) contributes 50% of 2014 consumption.

Figure 2.1 | Primary energy consumption by source (1985–2014)



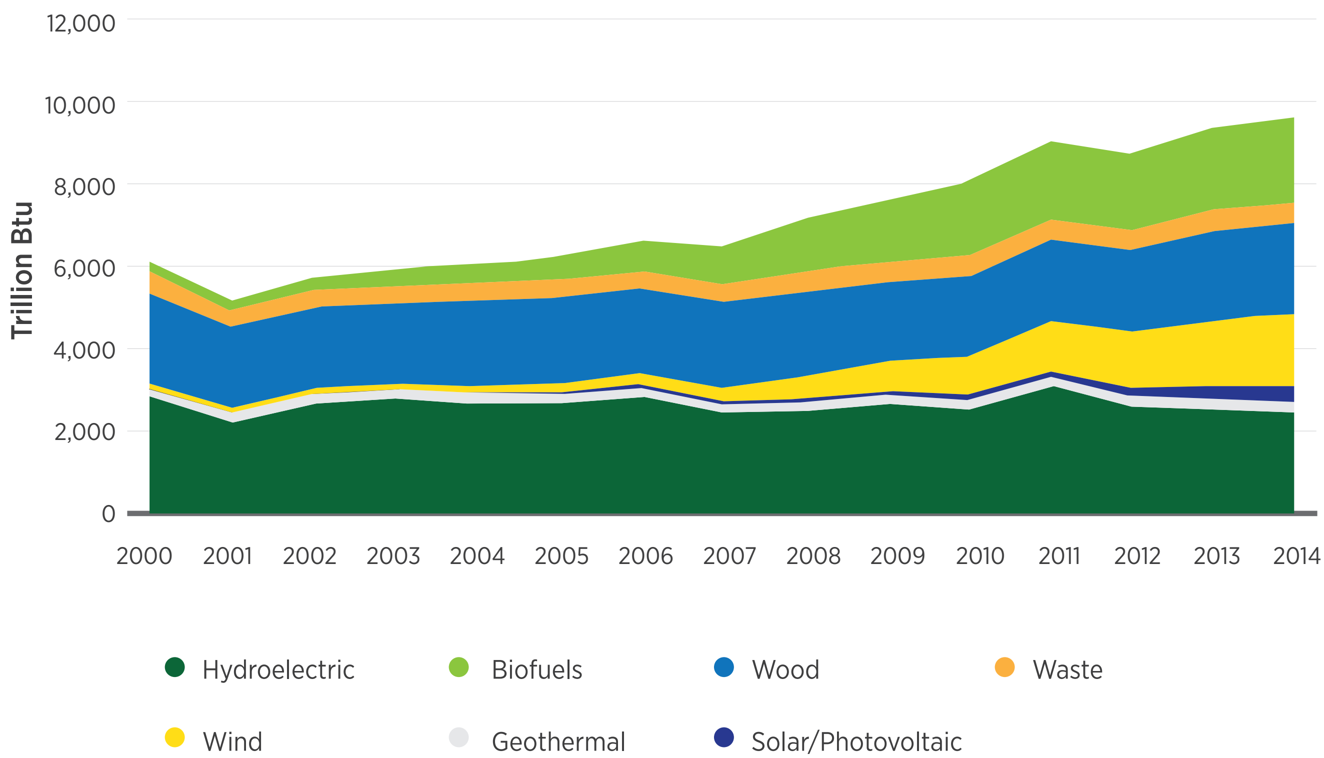
Source: Data from EIA (2015d).

Figure 2.2 | Primary renewable energy consumption by source and total consumption (1985–2014)



Source: Data from EIA (2015d).

Figure 2.3 | Primary renewable energy consumption by source (2001–2014)



Source: Data from EIA (2015d).

Hydroelectric energy consumption follows with 26% of renewable energy consumption, followed by wind (18%), solar (4%), and geothermal (2%). Current consumption will be explained in more detail in the following sections.

2.2.1 Estimates from Previous Assessments

The 2005 *BTS* reports domestic biomass consumption for energy at 184 million dry tons per year based upon 2004 energy consumption. In the 2011 *BT2*, biomass consumption for energy increased to 214 million dry tons, with the increase largely attributed to biomass for ethanol as a transportation fuel.

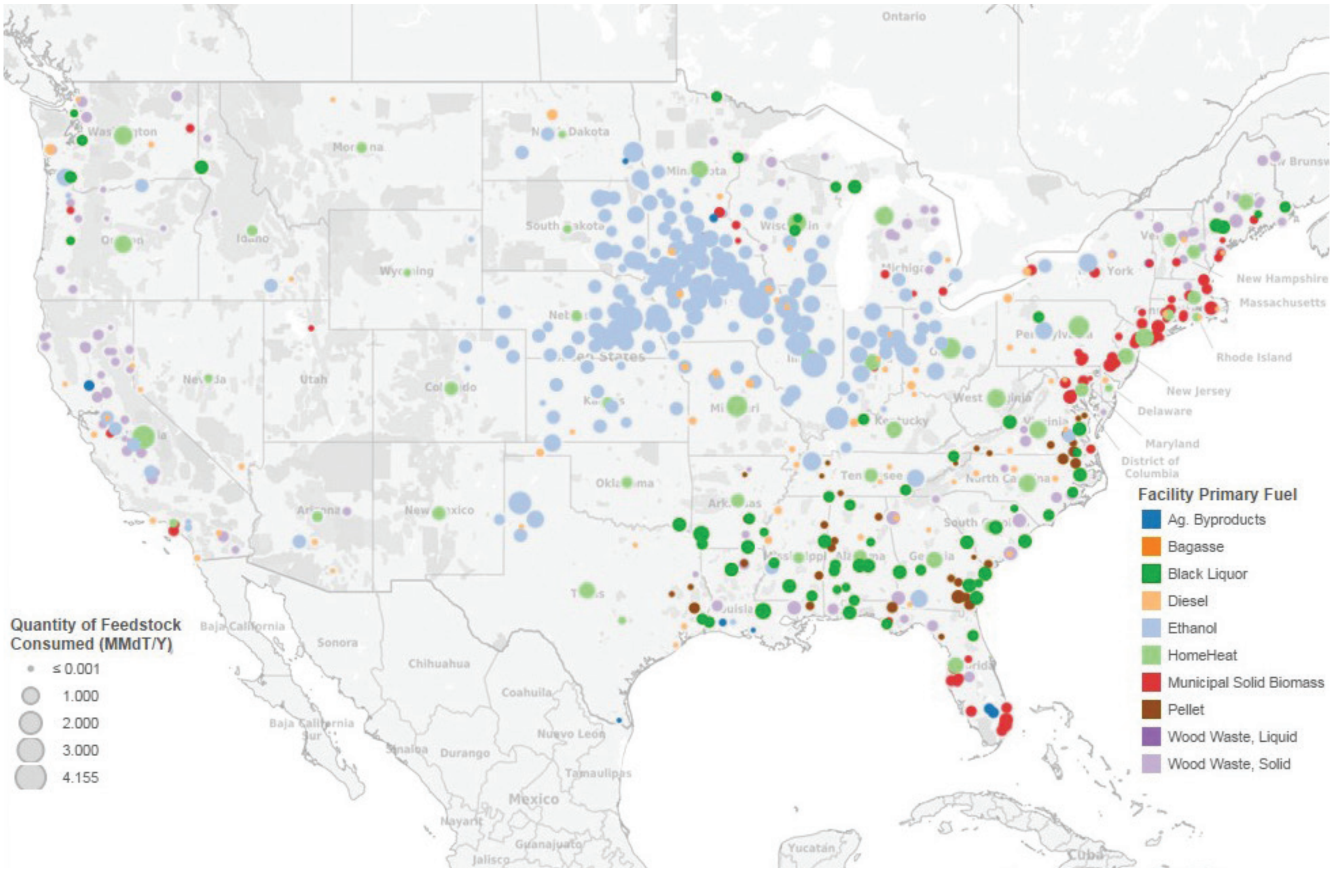
These estimates understate the amount of biomass for energy as a result of incomplete reporting of all biomass-to-energy pathways. In this report, the approach to estimating the currently used sources of biomass for energy has been expanded and improved to include greater detail for biopower and secondary feedstocks contributing to energy generation in the industrial sector. Additionally, greater detail is included based on publicly available bioenergy feedstock production and energy use statistics, particularly for emerging consumption classes. In each section, the amount of product is reported from an estimated biomass feedstock quantity. In many cases, conversion factors are assumed based upon technical values from industry, academic literature, and generally accepted renewable energy modeling assumptions. In this approach, the estimates are "bioenergy equivalent" amounts. All conversion factors to support the reported bioenergy production amounts are listed in appendix A.

2.2.2 Spatial Distribution of Biomass Consumption

The current locations of facilities using biomass for energy and energy products are tightly coupled with the locations of the raw biomass sources (fig. 2.4). The current bioenergy economy is the most efficient in history, yet the majority of commercial applications reflect conventional systems based largely upon starch and waste resources with passive feedstock quality controls. The largest industry consumers of biomass are producers of corn-grain-based ethanol located throughout the Corn Belt, Northern Plains, and Southern Plains. The second-largest biomass use is production of electric and industrial power from wood and wood waste. Wood waste consuming facilities are clustered within the Southeast region, but facilities that consume woody biomass are located across the Lake States, Northeast, and Pacific.

The greatest distribution of incinerators burning MSW occurs near population centers predominantly in the Northeast, where most of the 84 current facil-

Figure 2.4 | Spatial distribution of facilities that consume biomass for energy or energy products, by nameplate capacity in million bioenergy equivalent dry tons per year[1]



Source: Data from EIA (2015d); Forisk Consulting (2014); Biodiesel Magazine (2015); EIA (2015e); EPA (2015a); Renewable Fuels Association (2015).

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

ities exist (ERC 2014). Smaller classes of biomass consumption are bagasse from sugar cane processing, agricultural byproducts, and a rapidly growing sector of wood pellets for export (wood pellets are discussed in detail in chapter 3). Figure 2.4 includes a nationwide map showing the major facilities that consume biomass for energy or energy products. The points representing facilities vary in size by the annual nameplate generation capacity in tons of bioenergy equivalent biomass per year.[2] The methodology used to generate the capacity is described in appendix A.

2.3 Transportation Fuels

The current primary biomass sources for liquid transportation fuels are predominantly corn grain for ethanol and soybean oil for biodiesel. In general, technologies that convert accessible sugars via fermentation for corn grain and transesterification for soybean oil to transportation fuel for blending are referred to as “first generation.” Ethanol is consumed primarily as motor fuel in the form of E10 (10% denatured ethanol by volume, 90% petroleum), and E15 (15% denatured ethanol) in 2001 and newer light-duty vehicles only. Flex-fuel vehicles can also take E85 (up to 85% ethanol). However, the overwhelming majority of ethanol (more than 99%) is sold as E10. E10 is essentially ubiquitous; so for more ethanol to enter the market, blends higher than 10% would need to be sold. The most common forms of biodiesel blends are B5 or B20 (5% and 20% biodiesel blended with petroleum); however, B100 (100% biodiesel) can be used by certain vehicles.

Under RFS2, EPA provides aggregated monthly data on RIN transactions and renewable fuel volume production. These data are used to determine current actual volumes for the production of ethanol, biobased gasoline blendstocks/naphtha, biobased jet/aviation fuels, biobased diesel and heating oil, and biogas/compressed natural gas (CNG)/liquefied natural gas (LNG). These biofuel volumes are converted to tonnage and cross-referenced with reported information based on the USDA Feed Grains Database (USDA 2015) and the EIA Monthly Biodiesel Production Report to estimate the biobased fuel production by feedstock category, as shown in tables 2.1 and 2.2.

The following sections discuss current biobased fuel production and describe the references and assumptions used to estimate the amount of biomass resources consumed in conversion.

2.3.1 Fuel Ethanol

The rise in ethanol as a liquid transportation fuel in the early 2000s was due to its replacement of MTBE (methyl tert-butyl ether) as an oxygenate. The 2005 Energy Bill (including the RFS1) and EISA (including the RFS2) mandated an increase in the amount of corn grain-derived ethanol in fuel mixes. About 90% of corn ethanol is produced by the dry milling process (the other 10% comes from wet milling). In the past, the starch fraction was used to produce ethanol and the residual fractions were used to produce distillers grains (an animal feed). Preliminary reports as of November 2015 from the Agricultural Marketing Resource Center at Iowa State estimate that 43.64 million dry tons of dried distillers grains were produced in 2014 (Hoque and Hart 2015).

In 2014, renewable fuel ethanol production was 14.1 billion gallons. Mueller and Kwik (2013) report that dry mills produce an average of 2.82 gallons of ethanol per bushel of corn. At 56 lb of shelled corn per bushel and a 15.5% moisture content, this equates to 118 gallons/dry ton of corn (Rankin 2008). Thus, 14.1 billion gallons of ethanol at 118 gallons/dry ton represents about 120 million dry tons of corn (EPA 2015b). The USDA Feed Grains Database reports 5.2 billion bushels of corn were consumed in 2014 to

[2] Note that each state has one point representing residential power generation in the form of home heating. Facility data is represented for the most recent year of reporting, either 2014 or 2015.

Table 2.1 | Biobased Fuel Production in the Current Bioeconomy (million gallons)

Biomass resource category	Ethanol	Gasoline blendstock/ naphtha	Jet/ aviation fuels	Diesel/ heating oil	Biogas, CNG, and LNG	Total
Corn grain	14,106.81	–	–	–		14,106.81
Vegetable oils	–	–	–	1,471.12		1,471.12
Other fats, oils, and greases	–	–	–	505.42		505.42
Feed for gasoline blendstock/ naphtha[a]	–	12.09	–	–		12.09
Landfill gas	–	–	–	–	52.95	52.95
Total	**14,106.81**	**12.09**	**–**	**1,976.54**	**–**	**16,095.44**

[a]Gasoline blendstocks and naphtha can be produced from a variety of feedstocks, including agricultural residues, forest residues, biogenic MSW, yard wastes, biogas, energy grasses, oil seed plants, and other cellulosic materials.

Table 2.2 | Biomass Consumed for Fuel Production in the Current Bioeconomy (million bioenergy equivalent dry tons)

Biomass resource category	Ethanol	Gasoline blendstock/ naphtha	Jet/ aviation fuels	Diesel/ heating oil	Biogas, CNG, and LNG	Total
Corn grain[a]	119.55	–	–	–	–	119.55
Vegetable oils	–	–	–	5.51	–	5.51
Other fats, oils, and greases	–	–	–	1.89	–	1.89
Feed for gasoline blendstock/ naphtha[b]	–	0.22	–	–	–	0.22
Landfill gas[c] **(bcf)**	–	–		–	9.1	9.14
Total	**119.55**	**0.22**	**–**	**7.40**	**–**	**127.17**

bcf = billion cubic feet

[a]Corn grain consumed for ethanol production also creates 43.64 million dry tons of dried distillers grains (Wisner 2015).

[b]Gasoline blendstocks and naphtha can be produced from a variety of feedstocks, including agricultural residues, forest residues, biogenic MSW, yard wastes, biogas, energy grasses, oil seed plants, and other cellulosic materials.

[c]Bioenergy equivalent dry ton contributions from landfill gas are not added into the totals shown.

produce alcohol for fuel use, which at 56 lb of shelled corn per bushel and a 15.5% moisture content equates to 123 million dry tons of corn (USDA 2015). This value results in a slightly lower ethanol yield of 2.71 gallons per bushel, or 115 gallons of ethanol per dry ton. The 2% discrepancy between the number of dry tons of corn calculated from the RFS and that reported from the USDA Feed Grains Database is attributable to real-life variability in the assumed conversion efficiencies and feedstock moisture contents. Conversion efficiency has been rising over time, but there is an upper limit on the conversion rate based on the carbohydrate fraction of corn. Dry mills have also become more sophisticated, and most now also extract corn oil, which is used for either biodiesel production or animal feed.

Advanced technology now enables the production of ethanol from cellulosic biomass, including crop wastes, woody biomass, grasses, sorted MSW, and other sources. From 2013 to 2014, three pioneering facilities came online as first-of-a-kind integrated biorefineries capable of efficiently converting a broad range of biomass feedstocks into commercially viable second-generation biofuels, biopower, and other bioproducts. INEOS Bio's Indian River Bioenergy Center near Vero Beach, Florida, converts yard and wood waste into cellulosic ethanol.[3] POET-DSM's Project LIBERTY in Emmetsburg, Iowa, converts corn stover into cellulosic ethanol. Abengoa Bioenergy's biorefinery in Hugoton, Kansas, converts agricultural waste into cellulosic ethanol and renewable electricity.[4] In 2014, RFS2 reported the production of 728,000 gallons of cellulosic ethanol biofuel, which at 85 gallons per ton equates to about 10,000 tons of biomass. Combined, the three facilities mentioned are expected to take in up to 860,000 tons of agricultural residues and wood wastes to produce up to 53 million gallons of cellulosic ethanol and 27 MW of renewable electricity per year. These facilities may pave the way for additional investments in cellulosic ethanol, helping to advance U.S. competitiveness in clean energy technology while providing American farmers with an additional revenue stream.

2.3.2 Biodiesel

The second-largest type of liquid transportation fuels is biodiesel from vegetable oils, fats, and greases. Soybean oil makes up a little more than 50% of the feedstock for biodiesel. At present, about 25% of U.S. soybean oil production is used for biodiesel. Other feedstocks include yellow grease, canola oil, corn oil, white grease (lard), tallow, other recycled oils, poultry fat, other vegetable oils, palm oil, and miscellaneous other sources (EIA 2015c). Production in 2014 was 1.24 billion gallons, and the production capacity by the end of 2014 rose to 2.1 billion gallons (EIA 2015c). Although, historically, biodiesel has been produced via a chemical transesterification process, other technologies are also being used, such as enzymatic transesterification and hydrotreating. Hydrotreated oils and fats are called "renewable diesel," as opposed to biodiesel. Although biodiesel and renewable diesel can be made from the same feedstocks, biodiesel is chemically different from petrodiesel and renewable diesel because it contains oxygen atoms.

In 2014, EPA reported the production of 1,489 million gallons of biodiesel, 488 million gallons of non-ester renewable diesel, and 5,000 gallons of cellulosic diesel. Additionally, EPA reported 71,000 gallons of renewable heating oil and 50,000 gallons of cellulosic heating oil (EPA 2015b). Depending on the feedstock and conversion technology, the conversion rate may vary. We assume a conversion rate of 7.5 lb of oils/fats per gallon of biodiesel (or 267 gallons per ton) for biodiesel, renewable diesel, and

[3] Biofuels policy at the federal level dictates the eligibility of fuels to qualify for various subsidies and credits, such as RINs for advanced biofuels. Qualification is based upon a host of environmental performance and quality characteristics, one of which is the definition of eligible feedstocks.

[4] At the time of report publication, this plant was idle.

renewable heating oil, and 56 gallons per ton for the conversion of cellulosic biomass to diesel or heating oil. Based on these assumptions, it is estimated that more than 7.4 million tons of soybean oils, animal fats, and waste oils and nearly 1,000 tons of cellulosic biomass were consumed in 2014 for the production of fuel and heating oil. Cellulosic diesel production is entering the fuels market in small amounts. In 2014, the combined production of cellulosic diesel (for electric vehicle applications), renewable heating oil, and cellulosic heating oil was approximately 126,000 gallons from an estimated 2,265 dry tons of biomass.

2.3.3 Renewable Gasoline Blendstocks and Naphthas

Renewable gasoline blendstocks and naphthas represent a small but promising source of liquid transportation fuels. Renewable gasoline can be made from a variety of feedstocks, including agricultural residues, forest residues, biogenic MSW, yard wastes, biogas, and other cellulosic materials. Naphthas can also be made from a variety of biomass resources, including energy grasses such as miscanthus, switchgrass, and energy cane or oil seed plants such as *Camelina sativa*. Renewable gasoline and naphthas can be produced via hydrotreating and gasification processes. Renewable gasoline can also be produced by other thermocatalytic processes, pyrolysis, and direct biological conversion.

In 2014, EPA reported 29,000 gallons of cellulosic renewable gasoline blendstock and 12 million gallons of naphthas (EPA 2015b). Depending on the feedstock and conversion technology, the conversion rate may vary; however, we assume a conversion rate of 56 gallons per ton for the conversion of biomass to drop-in hydrocarbons.[5] Based on these assumptions, we estimate that more than 216,000 tons of biomass were consumed in 2014 for renewable gasoline blendstocks and naphthas.

2.3.4 Biogas

Biogas is produced from a variety of sources including landfills, municipal wastewater treatment facility digesters, and agricultural digesters. Biogas can be upgraded to renewable natural gas, which is comparable to conventional natural gas and can be injected into the pipeline network or used as an alternative fuel for natural gas vehicles. Renewable CNG and renewable LNG are both suitable for use in vehicles and can be used for light-, medium-, or heavy-duty applications. Although natural gas is a clean-burning alternative fuel, only about 0.1% is used for transportation fuel in the United States (DOE 2015b). Biogas may help to expand the natural gas vehicle fueling infrastructure in the United States.

In 2014, EPA reported the equivalent of nearly 53 million gallons of biogas and renewable natural gas were produced—more than 20 million gallons of biogas, 15 million gallons of renewable CNG, and 17 million gallons of renewable LNG.[6] By applying the lower heating value of propane as a proxy, 84,250 Btu/gallon, and a conversion factor of 0.488 trillion Btu (TBtu)/bcf, we estimate that the 53 million gallons is equivalent to 9.1 bcf of biogas.[7] Although biogas is produced from landfills, municipal wastewater treatment facility digesters, and agricultural digesters, a simplifying assumption is made that biogas used in transportation applications is currently from landfills.

[5] The estimated product yield for cellulosic biomass conversion to drop-in hydrocarbons of 56 gallons per dry ton is conservative relative to published values from National Renewable Energy Laboratory and Pacific Northwest National Laboratory design reports.

[6] 2014 RFS2 Data, https://www.epa.gov/fuels-registration-reporting-and-compliance-help.

[7] Conversion factor of 0.488 TBtu/billion cubic feet calculated using the 2015 EIA *Electric Power Annual* 2013 (EIA 2015f), tables 5.6 A–F.

2.4 Heat and Power

The current primary biomass sources for heat and power are predominantly woody biomass and wood waste for home heating and for industrial use as fuel. Woody biomass/wood waste, the biogenic portion of MSW, and landfill gas also make contributions to the electricity sector. Animal manure can also be collected and converted to biogas via anaerobic digestion. This gas is recovered, treated, and used to generate energy for farm and wastewater treatment applications.

The 2015 EIA *Electric Power Annual* (EIA 2015f, tables 5.5, 5.6, 5.7, and 5.8) provides energy values by sector for the wood/wood waste, biogenic MSW, other waste biomass, and landfill gas consumed for electricity generation and useful thermal energy. The value for thermal energy consumed in the residential sector is obtained from table A17 of the EIA *Annual Energy Outlook*. The AgSTAR Anaerobic Digester Projects Database provides basic information on anaerobic digesters on livestock farms in the United States (EPA 2015c). Estimates are extrapolated based on the digester type, end-use application, animal type, and animal population supplying the digester (using only reported values with no co-digestion). Table 2.3 shows the energy content of the biomass resources consumed to produce heat and power by end-use sector.

Several electrical and thermal conversion efficiencies are applied to the values in table 2.3 to estimate the useful electrical (in billion kWh) and thermal energy (in TBtu) output of each biomass resource by sector (shown in table 2.4). Depending on the technology and combustion method, electrical and thermal conversion efficiency may vary. Conservative estimates are used as much as possible when calculating estimates for the electrical and thermal energy output of the current bioeconomy.

Table 2.3 | Inherent Energy of Biomass Resources Consumed for Heat and Power in 2013 (Tbtu)

Biomass resource category	Electricity		Industrial		Commercial		Residential		Farm use	Total		
	E	T	E	T	E	T	E	T	Total	E	T	Total
Wood/wood waste[a]	187.1	20.3	210.3	898.3	0.5	1.0	–	582.5		397.9	1,502.1	1,900.1
Animal manure[b]	–	–	–	–	–	–	–	–	34.8	–	–	34.8
Biogenic MSW[a]	115.9	4.1	0.1	1.5	19.8	9.5	–	–	–	135.8	15.2	150.9
Other waste biomass[a]	16.1	6.8	8.3	54.4	5.0	1.3	–	–	–	29.4	62.4	91.8
Landfill gas[a]	119.1	0.1	2.3	0.1	11.3	0.2	–	–	–	132.8	0.4	133.2
Total	**438.2**	**31.4**	**221.0**	**954.3**	**36.6**	**11.9**	**–**	**582.5**	**34.8**	**695.8**	**1,580.2**	**2,310.8**

Note: *E* represents biomass consumed for electricity generation, and T represents biomass consumed for thermal energy output.

[a]The EIA *Electric Power Annual*, tables 5.5, 5.6, 5.7, and 5.8 provide energy values for biomass consumed for electricity generation and useful thermal output by sector in billion Btu. Residential values are from table A17 of the 2015 EIA *Annual Energy Outlook*.

[b]Based on biogas estimates from the AgSTAR Anaerobic Digester Projects Database. Values were extrapolated based on the digester type, animal type, and animal population supplying the digester (using only reported values with no co-digestion).

Table 2.4 | Useful Energy Output from Biomass (Forestry/Wood) Resources Consumed for Heat and Power in 2013

Biomass resource category	Electricity		Industrial		Commercial		Residential		Farm use		Total	
	E BkWh	T TBtu	E BkWh	T TBtu	E BkWh	T TBtu	E BkWh	T TBtu	E BkWh	T TBtu	E BkWh	T TBtu
Wood/wood waste[a]	13.7	12.2	15.4	539.0	–	0.6	–	349.5	–	–	29	901
Animal manure[b]	–	–	–	–	–	–	–	–	3.2	10.9	3	11
Biogenic MSW[c]	8.5	1.9	–	0.7	1.5	4.3	–	–	–	–	10	7
Other waste biomass[c]	1.2	3.0	0.6	24.5	0.4	0.6	–	–	–	–	2	28
Landfill gas[d]	10.5	0.1	0.2	0.1	1.0	0.2	–	–	–	–	12	0
Total	**33.9**	**17.2**	**16.2**	**564.2**	**2.8**	**5.6**	**–**	**349.5**	**3.2**	**10.9**	**56**	**947**

Note: Assumes a general conversion factor of 3,412 Btu/kilowatt hour (kwh). E denotes electric power generation; T denotes thermal power generation. BkWh = billion kilowatt hours. TBtu = trillion British thermal units.

[a]Wood/wood waste: Electric conversion efficiency of 25% and thermal conversion efficiency of 60%.

[b]Biogas from animal manure: 31.7% to electricity, 31.3% thermal energy, 37.0% loss based on AgSTAR end-use analysis.

[c]Biogenic MSW and other waste biomass: Electric conversion efficiency of 25% and thermal conversion efficiency of 45%.

[d]Landfill gas: Electric conversion efficiency of 30% and thermal conversion efficiency of 78%.

The tonnage (or billion cubic feet) of each biomass resource category by heat and power end-use sector is shown in table 2.5. The 2013 values for the biogenic portion of MSW and landfill gas are reported in thousand tons and million cubic feet by the 2015 EIA *Electric Power Annual* (*Electric Power Annual*, tables 5.6 and 5.7, respectively). Several conversion factors (described in the footnotes of table 2.5) are used for the remaining biomass resource categories.

The following sections discuss current heat and power production and describe the references and assumptions used to estimate the amount of biomass resources consumed in those processes.

2.4.1 Woody Biomass and Wood Waste

Woody biomass and wood waste is reported as a single category—“Wood/Wood Waste”—by the 2015 EIA *Electric Power Annual*. Wood and wood-derived fuels include wood/wood waste solids (including paper pellets, railroad ties, utility poles, wood chips, bark, and wood waste solids), wood waste liquids (red liquor, sludge wood, spent sulfite liquor, and other wood-based liquids), and black liquor. Wood and wood-derived fuels are used primarily as thermal energy inputs for the industrial sector; however, they are also used in electric power production, in the commercial sector, and for residential purposes.

Table 2.5 | Biomass Resources Consumed for Heat and Power in the 2013 Bioeconomy (million bioenergy equivalent dry tons)

Biomass resource category	Electricity	Industrial	Commercial	Residential	Farm use	Total
Wood/wood waste[a]	15.96	85.28	0.11	44.81	–	146.16
Animal manure[b]	–	–	–	–	10.50	10.50
Biogenic MSW[c]	15.03	0.20	3.65	–	–	18.87
Other waste biomass[d]	2.86	7.84	0.78	–	–	11.48
Landfill gas[e]	239.46	4.77	28.57	–	–	272.80
Total	**33.85**	**93.32**	**4.54**	**44.81**	**10.50**	**187.00**

[a]Wood/wood waste: 13 MMBtu/ton was selected as a conservative estimate based on various sources (EPAd 2015; DOE 2015a; INL 2014; NREL 2011).

[b]Animal manure: Applied GREET biogas assumptions applied by animal type to calculate 3.32 MMBtu/ton of total solids for manure digested in the current bioeconomy.

[c]Biogenic MSW: Reported directly from table 5.6 of the 2015 Electric Power Annual.

[d]Other waste biomass: 8 MMBtu/ton based on the values for biogenic MSW reported in the 2015 Electric Power Annual.

[e]Landfill gas: Reported directly from table 5.7 of the 2015 Electric Power Annual. Bioenergy equivalent dry ton contributions from landfill gas are not added into the totals shown.

In the projected bioeconomy, contributions from these individual wood resources are estimated at a more granular level.

Wood/wood waste, the largest category of biomass resource used for heat and power generation, is primarily used for residential heating and industrial use as fuel. Estimates from the 2015 EIA *Electric Power Annual* indicate that in 2013, the industrial sector consumed nearly 85.3 million dry tons of wood/wood waste to produce 15.4 billion kWh of electricity and 539.0 TBtu of thermal energy. In 2013, the residential sector consumed 44.8 million dry tons of wood/wood waste to produce 349.5 TBtu of thermal energy.

The two largest industrial consumers of biomass are the paper and wood products industries. In 2010, the latest year available, the Manufacturing Energy Consumption Survey reported a consumption amount of 824 trillion Btu, or 63.4 million bioenergy equivalent tons per year, assuming 13 million Btu per ton (EIA 2013). In the 2012 Resource Planning Act database, the amount of mill residues reported as being consumed for fuel was 26 million tons, down from 36.7 million dry tons in the 2007 assessment (USDA-FS 2014). Most of the material (51%) consumed is bark, and the remainder is composed of fine (36%) and coarse (13%) materials by weight. As reported, these two categories contribute 89.3 million tons per year to the industrial use estimate of 93.2 million tons per year. However, because of the calculation approach taken to disaggregate EIA national statistics, additional assumptions would need to be applied to attribute pulp liquor and mill residues categories more precisely to the industrial use category.

2.4.2 Biogenic MSW

Biogenic MSW consists of organic nonfossil material of biological origin that is a byproduct or a discarded product. Biomass waste includes MSW from biogenic sources, landfill gas, sludge waste, agricultural crop byproducts, straw, and other biomass solids, liquids, and gases. It excludes wood and wood-derived fuels (including black liquor), biofuels feedstocks, biodiesel, and fuel ethanol.[8]

Biogenic MSW is primarily used in the electrical and industrial sectors. Estimates from the 2015 EIA Electric Power Annual (table 5.7 and table 5.8) indicate that in 2013, the electricity sector consumed more than 15.0 million dry tons of biogenic municipal waste to produce 8.5 billion kWh of electricity and 1.9 TBtu of thermal energy. The industrial sector was the largest consumer of waste biomass for thermal energy in 2013, using more than 8.0 million dry tons of various types of waste biomass to produce 25.2 TBtu of thermal energy.

Tables 5.6*A* through 5.8*F* of the 2015 EIA *Electric Power Annual* break down biogenic municipal waste by the electrical, thermal, and total contributions of landfill gas, other biogenic MSW, and other waste biomass. A conversion factor of 8 MMBtu per dry ton was calculated using tables 5.7*F* and 5.7*C* of the 2015 EIA *Electric Power Annual*. Electrical and thermal conversion efficiencies of 25% and 45%, respectively were applied to the energy content of the biomass to obtain estimates for the electrical and thermal energy output.[9]

2.4.3 Landfill Gas

Landfill gas is generated by decomposition of organic material at landfill disposal sites. The average composition of landfill gas is approximately 50% methane and 50% carbon dioxide and water vapor by volume. The methane percentage, however, can vary from 40% to 60%, depending on several factors, including waste composition (e.g., carbohydrate and cellulose content).

The methane in landfill gas may be vented, flared, or combusted to generate electricity or useful thermal energy on-site, or injected into a pipeline for combustion off-site. Landfill gas is primarily consumed in the electric sector. Estimates from the 2015 EIA *Electric Power Annual* indicate that in 2013, 239.5 bcf of landfill gas produced 10.5 billion kWh of electricity in the electric sector. Table 5.6 of the 2015 EIA *Electric Power Annual* provides the energy content (in billion Btu) and amount (in million cubic feet) of landfill gas consumed by the electricity, commercial, and industrial sectors. These reported values were used to calculate a conversion factor of 488 Btu/standard cubic foot (scf). Electrical and thermal conversion efficiencies of 30% and 78%, respectively, were applied to the inherent energy content of the landfill gas to obtain estimates for the useful electricity and thermal energy output.[10]

2.4.4 Anaerobic Digestion

Anaerobic digestion is a biological process that occurs when organic matter (in liquid or slurry form) is decomposed by bacteria in the absence of oxygen (i.e., anaerobically). The decomposition process releases biogas consisting of approximately 60% meth-

[8] EIA biomass waste data also include energy crops grown specifically for energy production, which would not normally constitute waste.

[9] Depending on the technology and combustion method, electrical and thermal conversion efficiency may vary. See appendix A for more information.

[10] Depending on the technology and combustion method, electrical and thermal conversion efficiency may vary. See appendix A-2 for more information.

ane and 40% carbon dioxide. This gas can be recovered, treated, and used to generate energy, replacing traditional fossil fuels. Anaerobic digester systems can be installed successfully at operations that collect manure as a liquid, slurry, or semi-solid. Existing farms use a variety of different types of digester designs—such as anaerobic sequencing batch, complete mix, covered lagoon, fixed film, induced blanket, and plug flow reactors, and energy use technologies—such as boiler or furnace fuel, cogeneration, electricity generation, or flaring.

As of January 2015, AgSTAR estimates there are approximately 247 anaerobic digester systems operating at commercial livestock farms in the United States (EPA 2015c). Gas production estimates are available for only 94 of the operational systems reported in the AgSTAR database. Estimates for the remaining 153 digesters are made by extrapolating based on the digester type, animal type, and animal population supplying the digester (using only reported values with no co-digestion). Nearly 80% of these operational digesters are projects at dairy farms and 13% are at swine operations. Other digesters consist of mixed influent, beef, and poultry projects. An analysis of the AgSTAR database indicates that biogas is used for electricity generation (42%), cogeneration (41%), and boiler or furnace fuel (10%); is flared (2%); or is unknown/not reported (5%). Using these reported end uses, we calculate the energy distribution of the biogas to be 31.7% electricity, 31.3% thermal energy, and 37.0% loss.

Overall, the 247 operational anaerobic digesters are estimated to produce 3.2 billion kWh of electricity and 10.9 TBtu of thermal energy from 10.5 million tons of biomass (see appendix A for more information). Additionally, it is estimated that nearly 1.5 bcf of digester gas is flared each year. Using this gas for cogeneration could produce an additional 0.8 billion kWh of electricity and 0.4 TBtu of thermal energy.[11]

2.5 Biobased Chemicals

Biomass resources represent an important (and, in some cases, the only) option for sustainably replacing many of the petroleum-derived chemicals, plastics, and products relied upon today. Established by the Farm Security and Rural Investment Act of 2002 and strengthened by the Food, Conservation, and Energy Act of 2008, the USDA BioPreferred Program is charged with transforming the marketplace for biobased products and creating jobs in rural America. The 2015 USDA BioPreferred Report, *An Economic Impact Analysis of the U.S. Biobased Products Industry: A Report to the Congress of the United States of America*, provides an analysis of specific biobased segments within the U.S. economy (Golden et al. 2015). The report evaluates agriculture and forestry, biorefining, biobased chemicals, enzymes, bioplastic bottles and packaging, forest products, and textiles as the seven major biobased product industries contributing to the U.S. economy. It specifically excludes contributions from energy, livestock, food, feed, and pharmaceuticals.

The BioPreferred program database includes about 20,000 biobased products; however, it does not include many forest products and traditional textile fiber products. The BioPreferred program estimates that because the latter two sectors have only recently been included, the actual number of biobased products is dramatically higher than the USDA BioPreferred report indicates, and 40,000 products would be a conservative estimate. Direct sales of biobased products in 2013 are estimated to total nearly $126 billion.

The USDA BioPreferred report estimates that the starch produced from corn biorefineries in 2013 represented about 2% of the entire corn crop. In 2014,

[11] Cogeneration conversion efficiency: assumed energy outputs for cogeneration are 40% electrical energy, 50% thermal energy, and 10% loss (Clark Energy 2013).

according to the U.S. Feed Grain Database, 281.2 million dry tons of corn were produced for domestic use.[12] Assuming that the 2% relationship held true in 2014, and that this starch was used to manufacture biobased products, it is estimated that approximately 5.6 million dry tons of corn was consumed in 2014 to produce biobased products. Additionally, the BioPreferred report estimates that 0.6% of soybean and other oilseed processing was used to produce biobased products. Based on U.S. production and use forecasts for 2014, from table 3 of the 2015 *USDA Oilseed Yearbook* (ERS 2015), an estimated 0.32 million dry tons of soybeans were consumed in 2014 to produce biobased products.

Sufficient data to estimate the total number of individual "units" of biobased products is currently not available, and contributions from other feedstocks are not included within this report. We anticipate that the growth of these biobased sectors will continue to create both economic and environmental benefits for the United States.

2.6 Wood Pellets

Statistical information from the Forest and Agricultural Organization of the United Nations was used to estimate that 7.6 million dry tons of wood pellets were produced in 2014. Wood pellets are primarily produced for export to markets in the United Kingdom and Europe, which are strongly influenced by regulatory and political factors. Reports from the U.S. Forest Service (Abt et al. 2014) and the U.S. International Trade Commission (Goetzl 2015) anticipate that wood pellet export demand will plateau by 2020.

2.7 Emerging Sources of Biomass

Opportunities for near-term expansion of biomass resources for energy are found in waste streams, primary agricultural and forestry residues, and energy crops. This section explores in some detail commercialization of these resources for energy production across consumption sectors.

2.7.1 Biosolids and Wastewater Treatment

Wastewater treatment plants (WWTPs) represent another high-potential source of biogas. EPA reports that 1,484 WWTPs digest sludge to produce biogas (Bastian et al. 2011). Anaerobic digestion is a common technology for sludge treatment at WWTPs in the United States. The Water Environment Federation (WEF) released a phase 1 database that provides information about 1,241 U.S. WWTPs that operate anaerobic digestion systems and their biogas utilization (WEF 2014). WEF estimates that about 48% of the total wastewater flow in the United States is treated with anaerobic digestion (WEF 2013). However, less than 10% of facilities employ biogas for beneficial uses. Most biogas is flared, and only a small portion is used for on-site process heat and power production.

New technologies and digestion techniques are increasing the feasibility of transforming WWTPs into energy-positive water resource recovery facilities. One approach to enhancing anaerobic digestion at these facilities is through the co-digestion of biosolids with organic waste, resulting in higher methane yields, more efficient digester volume utilization, and reduced biosolids production. Combined heat and power (CHP) technologies such as internal combustion engines, microturbines, gas combustion turbines,

[12] 11,883.34 million bushels at 56 pounds of shelled corn per bushel and 15.5% moisture

and fuel cells may help to maximize the electrical and thermal energy output from a water resource recovery facility. Alternatively, biogas can be upgraded to renewable natural gas and can be injected into the pipeline network or used as an alternative fuel for natural gas vehicles.

A 2011 EPA report estimated that as of June 2011, CHP systems using biogas were in place at 104 WWTPs, representing 190 megawatts (MW) of electric power capacity and 18,000 MMBtu/day of thermal energy (Bastian et al. 2011). A March 2015 analysis from Argonne National Laboratory classifies the 1,241 WWTPs identified in the WEF phase 1 database into four categories based on average flow rates: plants with an average flow rate of 100–1,000 million gallons per day (MGD) (29 plants), 10–100 MGD (276 plants), 1–10 MGD (690 plants), and less than 1 MGD (96 plants) (Shen et al. 2015). Each rate category is broken down by biogas utilization, and biogas CHP technologies are further categorized by CHP technology type and whether there is power export. Overall, the Argonne analysis identified 282 operational CHP systems and 69 water recovery facilities that are exporting electric power to the grid.

Of the 29 facilities that process 100–1,000 MGD, Argonne found that 26 use biogas; 13 of those employ CHP technologies for energy generation, 6 export electric power to the grid, and 3 inject upgraded gas into natural gas pipelines. Of the 276 facilities that process 10–100 MGD, Argonne found that 238 use biogas; 123 of those employ CHP technologies for energy generation, 32 export electric power to the grid, and 12 inject upgraded gas into natural gas pipelines. Of the 690 facilities that process 1–10 MGD, Argonne found that 505 use biogas; 125 of those employ CHP technologies for energy generation, 30 export electric power to the grid, and 10 inject upgraded gas into natural gas pipelines. Of the 96 facilities that process <1 MGD, Argonne found that 55 use biogas; 21 of those employ CHP technologies for energy generation, 1 exports electric power to the grid, and none inject upgraded gas into natural gas pipelines. Of the CHP technologies, the majority, 54%, are internal combustion engines. Microturbines make up 10%, fuel cells 2%, and gas combustion turbines 1%; 33% are categorized as "other."

Both the 2011 EPA report and the Argonne analysis of the WEF phase 1 database indicate that there is significant potential to increase the utilization of biogas produced by WWTP digesters.

2.7.2 Biomass Crop Production

The commercialization of biomass crops for energy has increased since 2011, with deployment reaching up to 20,000 acres. Statistics for herbaceous energy crops are collected beginning with the 2012 census. The acreage is reported in table 2.6. These acres are underestimated; producers often do not report plantings of unique crops because they are not enrolled in federally subsidized programs, or the crops are grown on non-private agricultural lands (e.g., public universities, regional extension farms).

The regional statistics from the 2012 USDA census reported in table 2.6 represent production of switchgrass and miscanthus to supply multiple markets, such as power, fuels, and animal bedding; and they probably underestimate the gross production of all energy crop species. The data continue to improve for biomass production and consumption by use, reflecting the time lag due to the perennial nature of many of the dedicated species. Barriers to adopting these crops are being addressed through risk reduction measures such as crop insurance. Reporting of hybrid poplar acres in production increased from 211 acres in August 2014 to 2,554 acres in November 2014. In 2014 energy statistics, the use of dedicated herbaceous biomass for energy was reported in a mixed-waste category and is reported in the aggregated production amount. As of 2014, commercial primary crop residue collection for energy consumption is not reported in the USDA Census of Agriculture.

Table 2.6 | 2012 USDA Census Data for Herbaceous Energy Crop Production by Region

Farm production region	Acres harvested	Number of operations	Production (dry tons)
Appalachia	1,801	23	8,644
Southern Plains	979	4	1,178
Northeast	119	8	1,442
Other	0	13	0
Total	**2,899**	**48**	**11,264**

2.8 Summary

The total consumption of biomass resources for energy, including transportation, power, and heat, is reported in table 2.7. The primary sources of biomass in the current bioeconomy are agricultural resources and forestry/wood. The agricultural biomass is used predominantly for fuels and biobased chemicals. The woody biomass is used to produce heat and power for the electrical, industrial, commercial, and residential sectors. Animal manure is digested to produce heat and power for farm use. The biogenic portion of MSW and other waste biomass is consumed to produce heat and power for various sectors. The flow of these resources from feedstock to end product energy is described in the Sankey diagrams in figure 2.5.

Table 2.7 | Total Current Consumption of Biomass (2014) for Energy and Energy Products (million bioenergy equivalent dry tons per year)[13]

Biomass resource category	Fuel	Heat and power	Biobased chemicals	Wood pellets	Total utilized biomass	Supply chain losses	Total biomass
Agricultural	127.18	10.50	5.94	–	143.30	13.91	157.21
Corn grain[a]	119.55	–	5.62	–	125.17	13.91	139.08
Vegetable oils	5.51	–	0.32	–	5.83	–	5.83
Other fats, oils, and greases	1.89	–	–	–	1.89	–	1.89
Feed for gasoline blendstock/naphtha[b]	0.22	–	–	–	0.22	–	0.22
Agricultural residues	0.01	–	–	–	0.01	–	0.01
Manure	–	10.50	–	–	10.50	–	10.50

Table 2.7 *(continued)*

Biomass resource category	Fuel	Heat and power	Biobased chemicals	Wood pellets	Total utilized biomass	Supply chain losses	Total biomass
Forestry/wood	–	146.16	–	7.61	153.76	17.08	170.85
Wood/wood waste	–	146.16	–		146.16	16.24	162.40
Wood pellets	–	–	–	7.61	7.61	0.85	8.45
Energy crops	–	–	–	–	–	–	–
Herbaceous energy crops	–	–	–	–	–	–	–
Woody energy crops	–	–	–	–	–	–	–
MSW/other wastes	–	30.35	–	–	30.35	–	30.35
Biogenic portion of MSW	–	18.87	–	–	18.87	–	18.87
Other waste biomass	–	11.48	–	–	11.48	–	11.48
Landfill gas[c] (bcf)	9.14	272.80	–	–	281.94	–	281.94
Algae	–	–	–	–	–	–	–
Total Biomass	**127.18**	**187.00**	**5.94**	**7.61**	**327.73**	**30.99**	**358.73**

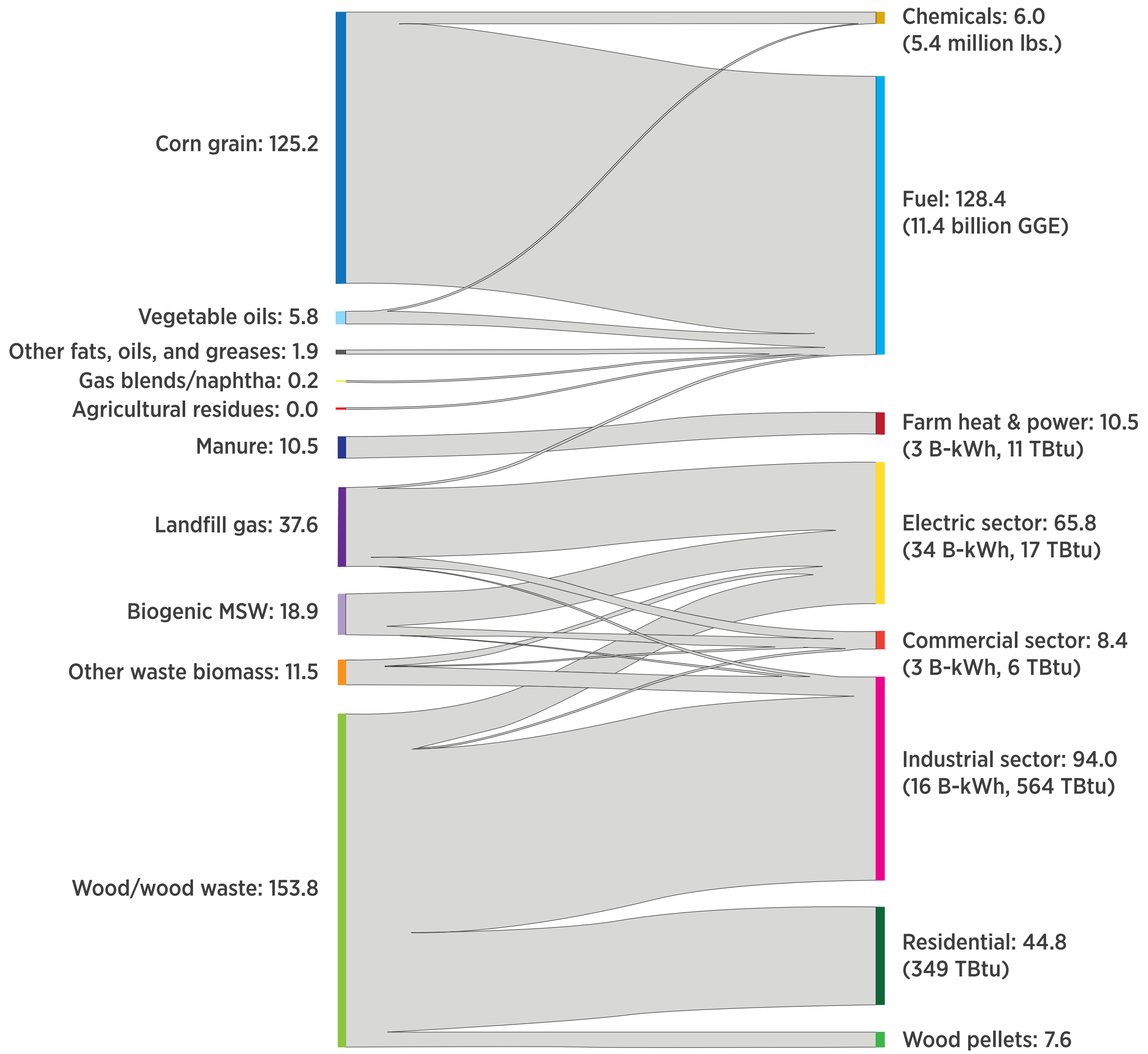
[a]Corn grain consumed for ethanol production also creates 43.64 million dry tons of dried distillers grains (Wisner 2015).

[b]Renewable gasoline blendstocks and naphtha can be produced from a variety of feedstocks, including agricultural residues, forest residues, biogenic MSW, yard wastes, biogas, energy grasses, oil seed plants, and other cellulosic materials. RFS2 does not provide clarity for the current sources of biomass.

[c]Bioenergy equivalent dry ton contributions from landfill gas are not added into the totals shown here but are represented in the Sankey diagram in figure 2.5 by applying a conversion factor of 0.2665 lb/scf.

[13] Interactive visualization: https://bioenergykdf.net/billionton2016/2/1/table

Figure 2.5 | Sankey diagram of feedstock, sector consumption, and final product distribution, in million dry tons per year[14]



Note: Biomass resources are shown on the left and their allocations are shown on the right. The size of the flow is representative of the amount of biomass allocated to that end use. For this figure, contributions from landfill gas are represented as tons of biomass equivalent by applying a conversion factor of 0.2665 lb/scf.

[14] Interactive visualization: https://bioenergykdf.net/billionton2016/2/3/sankey

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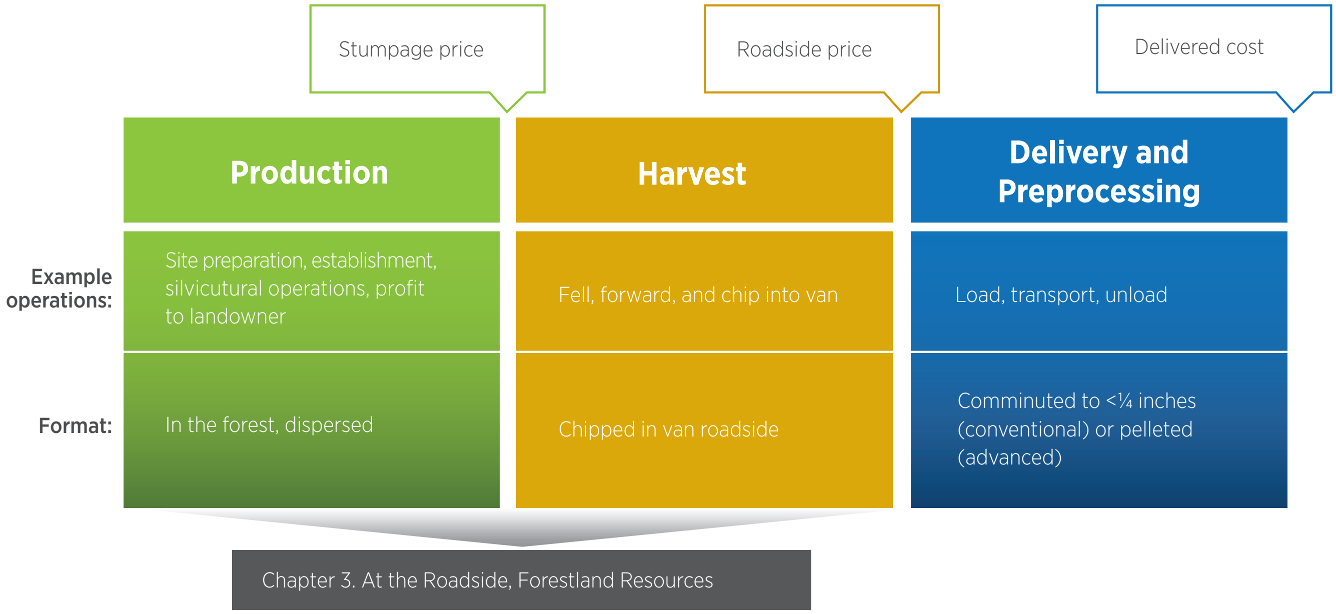
03 At the Roadside: Forest Resources



3.1 Background and Introduction to the Forest Resources Analyses

3.1.1 Chapter Structure

Chapter 3 assesses the availability of forest resources to the roadside. Not all woody feedstocks are discussed in this chapter. Logging residues and whole-tree biomass are included. Other feedstock categories have been moved to chapter 5 or are redefined to be included in the whole-tree biomass category. New methodologies and data are used in the assessment to estimate woody biomass as a function of price, year, and scenarios based on national wood demand.

This chapter has six major parts. Section 3.1 provides background and information useful to understanding the context for analyzing forestry resources. This section presents useful definitions as well as feedstock labels and types that have changed since the 2011 *BT2*. It also describes the underlying sustainability assumptions used in the model, and issues in federal land management. Although the model is only for the conterminous United States, the biomass potential in Hawaii and Alaska is also introduced.

Section 3.2 explains an important part of the model inputs. Descriptions of the underlying harvest systems, operational attributes, and costs are presented in this section. New costs were developed for this section, using a different method than in the 2011 *BT2*.

Section 3.3 explains conventional wood and biomass demand scenarios—another important aspect of the analysis. These scenarios are used from the U.S. Forest Products Module/Global Forest Products Model (USFPM/GFPM). The projected conventional products demands are used to estimate logging residue supply, and the biomass demands are used to develop supply curves.

Section 3.4 is the primary section that describes the new Forest Sustainable and Economic Analysis Model (ForSEAM) forestry model and its outputs. A very important aspect of the model is that it first solves for conventional timber demands (i.e., sawtimber and pulpwood). Logging residues are estimated as a function of the conventional timber production. Then the model solves for additional biomass from tree stands of designated sizes to meet the biomass demands in the selected scenarios. Shadow prices are used to determine the cost at which the demands will be met. These shadow prices and biomass demands are then used to develop cost curves that provide levels of biomass at selected costs. The outputs are shown for $40, $60, and $80 per ton but were also run at higher cost levels. The amounts of biomass estimated to be available by cost and year are reported as the forest resources to roadside in this report.

Section 3.5 is a unique addition to this report because it is a comprehensive market analysis. The Subregional Timber Supply (SRTS) inventory and harvest model for the U.S. South is used. This is added for several reasons:

- The newly developed ForSEAM had to be verified. A published model in use, SRTS, was adopted for that purpose.
- *BT16*, like the earlier reports, is a supply analysis; the forestry supply is now being modeled as a function of demand. Thus, a market assessment of the South was completed to demonstrate the interactions between market demands and supply.
- It is important to understand the impact of increased pellet production, especially in the southern United States, on both demand and future supply.

This section assesses the factors that influence the demand for and supply of wood for both energy and conventional products in the South. A partial equilibrium timber market model was used to evaluate a set of combinations of these factors to illustrate the impacts of the supply and demand factors on market outcomes. Using subregions of the U.S. Coastal South, evaluations were completed on (1) competing pulpwood demands, (2) declines in sawtimber harvest, (3) substitution of mill residues for small roundwood, and (4) changes in timberland area. The section discusses the simulations of market impacts on the prices, inventory, and removals of timber, as well as timberland area by management type.

Section 3.6 summarizes the available biomass from forest resources at roadside. Discussions of the results and their implications are included in this section. Finally, section 3.7 discusses additional research that would be useful in extending and improving the analysis of available biomass potential from U.S. forestland.

3.1.2 Chapter Summary

Chapter 3 provides estimates of primary biomass (removed from the land) from timberland-only forest resources at selected costs to roadside. Total costs to the conversion throat that include transportation and preprocessing are described in chapter 6. It is important for the reader to understand that roadside costs are not the total cost of a feedstock at a conversion facility. Also when biomass availability is reported by roadside cost, the actual amount of biomass transported to and useable at the biorefinery may be less because of losses, screening and separation, and spoilage. In this chapter, the availability of logging residues from conventional harvest and from whole trees harvested explicitly for biomass are modeled. Two other primary forest biomass feedstocks, “other removal residues” and “thinnings on other forestland” are discussed in chapter 5 and are counted as wastes in *BT16*, unlike in the 2011 *BT2*. The estimates are developed for private (industrial, nonindustrial, and tribal) timberland and federal timberland. They are based on significant underlying assumptions regarding the available land base, ratios of types of harvest, residue retention rates, growth rates, land cover and use management, growth/harvest limits, and other implications that need to be understood. These estimates are conservative but provide a good basis for understanding forest biomass inventory and analyses. Hopefully, this assessment will be of value to others to further the work begun in this chapter.

In the newly developed forestry model, ForSEAM, the current Forestry Inventory and Analysis (FIA) database provides the basis for determining how demands for conventional products such as sawtimber and pulpwood will be met up to 2040. The demands are based on a set of projections for U.S. forests and forest products markets under varying market conditions. The USFPM/GFPM forest products market model—linked with the SRTS inventory and harvest model for the South—was used to project the harvest removals, inventory, price, and timberland area that result from three levels of wood biomass feedstock demands. The baseline scenario (Baseline_ML) represents the lowest level of wood energy demands. In the moderate and high wood energy demand scenarios, feedstock prices rise sufficiently to reduce paper and paperboard production levels by 1% and 3%, respectively, below baseline in 2040. In the high-demand scenario, impacts on prices are ameliorated somewhat by an assumed increase in investment in southern pine plantation management that would be expected as prices for softwood small roundwood increase. In addition, increases in timberland area (in USFPM/GFPM) are projected based on the assumption that increasing prices lead to increased land rents, and increasing land rents lead to increased conversion of marginal agricultural land to timberland.

The linear programming model ForSEAM was constructed to estimate forestland production for traditional forest products and to meet biomass feedstock demands. The supply component includes general forest production activities for 305 production regions or agricultural statistic districts and is placed in a national linear programming model. Each region has a set of production activities defined by the scenario demands. These production activities include sawtimber, pulpwood, and biomass (fuelwood is defined as biomass for this report). Sawtimber and pulpwood harvest activities generate forest residues that can be harvested for energy and bioproducts, and whole trees can be removed for biomass under some specific assumptions of size. High-value sawtimber is never harvested for biomass.

The model estimates biomass potential from timber stand information across the conterminous United States. An important variable is tree diameters that are classed as average stand diameter. Class 1 has a diameter of >11 inches, class 2 has a diameter of 5–11 inches, and class 3 has a diameter of <5 inches. The model estimates the costs, the locations, and the kinds of biomass available to meet a prescribed demand. The demands are derived from the Forest Product Demand Component. This component is based on six USDA Forest Service scenarios with estimates developed by USFPM.

Not all forestland in the United States is considered in the analysis; only the conterminous United States is included. All protected, reserved, and non-roaded forestland is excluded. The analysis is restricted to only timberland instead of all forestlands. Although conventional products are removed from slopes greater than 40% using cable systems, no logging residues are recovered, leaving 100% on the site. A major criterion is that the harvest in each state does not exceed annual growth. There is no road construction, as only forest tracts located within a half mile of the roads are harvested. The current-year forest attributes reflect previous years' harvests and biomass removals, which means that dynamic stand tracking of forest growth is incorporated into the model and the analysis. Another underlying assumption is the retention of biomass to protect the site and maintain soil carbon. Also, there was no conversion of natural stands to plantations.

A final major assumption is that there are no forestland losses over the modeling time period and no land cover changes in the model. This means that fast-growing plantations specifically for biomass are not established after the harvest of a natural stand. All harvested stands are assumed to regenerate back to, and according to, the original cover. Natural stands regenerate to hardwood, softwoods, or mixed, as they were previously. Plantations are regenerated as plantations. An unfortunate downside to this approach is that insufficient amounts of biomass are generated in the out years of the modeling period to meet the high-demand scenarios. These scenarios were developed based on the establishment of millions of acres of plantations to be grown for biomass. As will be discussed in more detail, there are several changes involved with using the model that are more restrictive in biomass availability than in the 2011 *BT2*.

Shadow prices[1] are developed for the demand scenario biomass amounts. The shadow prices and the associated acres for the scenario demands (dry tons of biomass) are reported by product type (logging residues or whole-tree biomass), as well as other parameters of the study, across selected years. Conventional timber products are not reported in this chapter but will be made available on the Bioenergy KDF. All the outputs will be made available in various forms and formats.

These shadow prices for the scenario demands are used to develop conventional supply curves to estimate biomass availability at roadside for a given cost. A summary of available biomass in the baseline scenario using an example cost of $60 per dry ton to roadside is shown in table 3.1. The out-year biomass availabilities are slightly reduced with the underlying assumption that no biomass plantations were established on forestland for the baseline example. In other scenarios, such as the supposedly highest biomass demand, there were even more significant reductions in out years, especially 2040, because biomass plantations were not established.

Table 3.1 | Summary of Forest Biomass of the Baseline Scenario by Ownership and Year at a Cost of $60 per Dry Ton to Roadside

Ownership	2015	2017	2020	2025	2030	2035	2040
	Million dry tons						
Private	66.5	68.1	73.6	64.9	61.6	66.4	64.5
Federal	15.8	19.8	20.5	20.4	19.6	19.5	17.0
Total	**82.3**	**87.9**	**94.1**	**85.3**	**81.2**	**85.9**	**81.5**

The market analyses show that the timber markets in the South are affected by the age class distribution and broad management types in the current forest, and these markets in turn affect future age class distributions and management types. The product markets for large- and small-diameter timber are linked, as they both are produced at each point in time on a single acre of timberland, especially in natural stands; trees on plantations are more uniform in size. The only way to get large-diameter trees for sawtimber is to allow small-diameter stands to age. Markets are linked to these changing diameters across the South.

Competition for pine small roundwood in some regions will likely intensify with increased demands for wood biomass feedstocks, leading to higher prices and some potential reductions in other uses, as shown in the Mid-Atlantic subregion. Past reductions in conventional demand for hardwood small roundwood imply that prices for this feedstock will likely not increase as rapidly as prices for pine small roundwood.

[1] In the strictest sense, a shadow price is any price that is not a market price, but the term usually also carries the connotation that it is an estimate of the economic value of the good or service in question. See http://web.stanford.edu/group/FRI/indonesia/documents/gittinger/Output/chap7.html.

An increase in demand for small-diameter roundwood alone, however, is not likely to affect the demand for sawtimber. The prices for sawtimber will likely continue to stay low in such areas as the Gulf Coast, reducing landowner incentives to replant, as well as reducing the availability of land for replanting. The harvest of mature trees provides stand regeneration opportunities. The amount of sawtimber harvest and the subsequent regeneration opportunities affect the availability of "thinnable" acres in the 10–15 years following the final harvest and thus affect the availability of the next generation of small-diameter softwood removals that can be used for biomass.

A potential recovery in the housing and lumber markets leading to renewed sawmilling has the potential to increase the availability of sawmill residues, which may ease the pressure on the small roundwood resources and thus ameliorate price increases. The impact is greatest in areas that have active sawmilling industries and smaller average-diameter sawmill inputs, such as the Southeast Coast region.

Finally, timberland has been shown to respond to land rents, and increased demand with a quasi-fixed inventory will lead to higher prices and thus higher land rents. In this way, increased demand for feedstock for wood energy can contribute to increased timberland area (or at least to smaller decreases in timberland area).

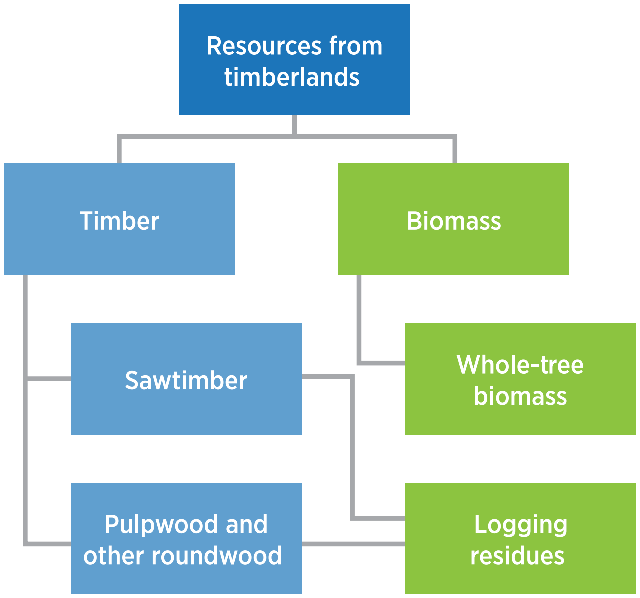
3.1.3 Introduction

This chapter provides forest biomass supply curves to estimate the available tonnages of forest biomass at given roadside costs, by county, by year, and by scenario. The content is similar to that in the 2011 *BT2*, but it differs in some major ways. Some of these changes are identified and discussed in previous chapters, and all are discussed as appropriate in this chapter. Generally, the changes are the following:

- Feedstock types are slightly modified.
- An economic model is used to develop supply curves for biomass for various timber and biomass demand scenarios.
- Some underlying assumptions and coefficients are modified.
- Wood waste resource analyses are now separate and discussed in chapter 5.
- Federal lands are included in the forest resource analysis.

Forest biomass as feedstocks includes (1) wood wastes in forests, at mills, and from landfills; (2) harvests from silvicultural treatments such as thinning, fuel reduction, and regeneration cuts; and (3) purpose-grown trees on plantations. Trees and tree components from land conversion practices such as urban expansion into woodlands or right-of-way clearing are also a source of wood waste. A more formal breakdown of forest wastes categories is shown in the feedstocks taxonomy of chapter 1.

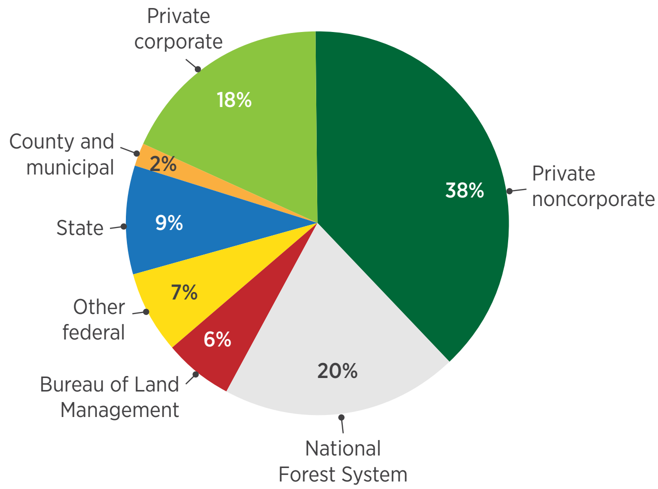
Figure 3.1 | Biomass resources from timberland



This chapter discusses only primary (direct from the land) biomass resources from timberland (fig. 3.1). Land type definitions are shown in text box 3.1 (Smith et al. 2009). The feedstocks included in this chapter are forest residues (i.e., logging residues) and whole trees cut explicitly for biomass uses (i.e., whole-tree biomass). Only biomass on timberland in the conterminous United States is used in this analysis. Table 3.2 shows the amount of land, forestlands, and timberlands in the United States and in the conterminous United States. Figure 3.2 details the ownership of forestlands. Section 3.4 reports the available acres in the model and then the number of acres treated each year. Some restrictions and underlying assumptions reduced the amount of available timberland in the model.

Two classes of forest feedstocks—"other removal residues" and "thinnings on other forestland"—have been moved to chapter 5 and are being considered as secondary resources. A new model used to estimate primary feedstocks was not capable of handling these two feedstock types, so the methodology used in previous versions of this report was applied to estimate the biomass availability for these feedstock types.

Figure 3.2 | Forestland ownership in the United States



Source: Data from USDA Forest Service (2012).

Text Box 3.1 | Definitions

- **Forestland**—Land at least 120 ft wide and 1 acre in size with at least 10% cover (or equivalent stocking) by live trees of any size, including land that formerly had such tree cover and that will be naturally or artificially regenerated.
- **Timberland**—Forestland that is producing, or is capable of producing, in excess of 20 ft^3 per acre per year of industrial wood and not withdrawn from timber utilization by statute or administrative regulation.
- **Other forestland**—Forestland other than timberland and productive reserved forestland.
- **Reserved forestland**—Forestland administratively removed from production.

Primary forest biomass resource categories have changed over time in the series of Billion-Ton reports, mostly because of the changing analytical methodologies. In the original 2005 *BTS*, the primary forest resources were (1) logging residues, (2) fuel treatments from timberland and other forestlands, and (3) fuelwood. In the 2011 *BT2*, primary forest biomass types were (1) fuelwood for current use only,

(2) composite operations—half logging residues and half thinnings from timberlands, (3) other removal residues, (4) thinnings from other forestlands, and (5) conventionally sourced wood (pulpwood).

The composite operations category was added in the 2011 *BT2* to handle the conceptual transition from a two-pass operation to an integrated operation. In a two-pass approach, logging residues are left at the stump during the stand harvest for later removal. In an integrated system, timber and biomass are harvested together. As it was difficult in *BT2* to model the transition from non-integrated to integrated systems, *BT2* makes an assumption to avoid counting the biomass as both logging residues and integrated thinning biomass. A conservative estimate was 50% of the logging residue supply estimates and 50% of the thinning supply estimates, which means that over the time of the projection, about half will come from the recovery of logging residues and half from thinnings.

Table 3.2 | Forestland and Timberland in the United States

Type of land	United States	Conterminous United States
Total land	2.3 billion acres	1.9 billion acres
Forestland	751 million acres	623 million acres
Timberland	514 million acres	475 million acres

Source: Data from USDA Forest Service (2012).

In *BT16*, the primary feedstocks from timberlands were again changed, as the new model can differentiate spatially and temporally between logging residues and the cutting of whole trees (table 3.3). The underlying assumption is that all harvesting of residues is integrated—the biomass portion (logging residues) is harvested at the same time as the conventional timber.

"Conventionally sourced wood" in the 2011 *BT2* is categorized as "whole-tree biomass" in *BT16*. The new whole-tree biomass category is commercial and noncommercial trees harvested for biomass from a stand in which no commercial trees are harvested for conventional products—all trees harvested go to

Table 3.3 | Forest Resources Feedstock Type Changes

Feedstock	2005 *BTS*	2011 *BT2*	*BT16*
Logging residues	•	•	•
Composite		•	
Thinnings (timberland)		•	
Thinnings (other forestland)		•	•
Other removals		•	•
Conventionally sourced wood		•	
Whole trees			•

Note: Thinnings (other forestland) and other removals are covered in chapter 5. Thinnings (timberland) are included as logging residues or whole-tree biomass.

biomass uses. The stand can be clear cut (all trees removed) or thinned (partial cut of trees in the stand). In the model, this biomass type was harvested only when there was not a sufficient amount of logging residues to meet the biomass demand in a scenario. (The process is explained in detail in subsequent sections of this chapter).

As trees grow and mature, their value usually increases greatly along with their size and form. The use of wood for energy purposes is not competitive in the market compared with the use of wood for paper, board, and lumber products. As a result, only younger stands and smaller-diameter stands are harvested as whole-tree biomass.

Logging residues are available only when trees are harvested for conventional timber markets; when those markets are saturated, logging residues are no longer available as a source of biomass. In this analysis, logging residues are assumed to be harvested as an integrated product, along with the conventional sawlogs and pulpwood, at a relatively low extra cost compared with whole-tree biomass. Therefore, all available logging residues are harvested first in the model to meet the biomass demands in the scenarios. When the demand is greater, then the model solves for the lowest-cost whole-tree biomass to supplement the demand.

Forest biomass (e.g., loblolly pine) is a unique resource as a biomass feedstock and an economically feasible alternative or complement to conventional forest product systems. The current resource, grown primarily for pulpwood and other traditional forest products, is the result of decades of research in plantation management. Because of its cultural acceptance, extensive management knowledge, established genetic improvements, and high yields, pine is a key candidate feedstock to support the emerging biomass industry at a feasible scale in the southern region. Kantavichai, Gallagher, and Teeter (2014) assessed the feasibility of loblolly biomass plantations and compared breakeven prices for a short-rotation biomass plantation with those for a traditional timber management plantation. For landowners, if biomass stumpage prices reached $10.50 per green ton (or higher), biomass plantations would be feasible; furthermore, biomass plantations can benefit landowners interested in diversifying their management portfolios. Munsell and Fox (2010) also examined the feasibility of increasing biomass production from harvested pine sites and idle farmland by looking at yield simulation models and financial analyses. Results suggest that with intensive management, a mixture of conventional and biomass pine (on harvested sites) could be profitable for landowners.

Land use change in forestry has consisted primarily of the conversion of forestlands to other uses such as residential and commercial infrastructure (Bentley and Steppleton 2012). In this report, there is no land use change from/to forestry and non-forestry use. Neither are there any exchanges between agriculture and forestry, as the ForSEAM and the POLYSYS models are not linked.

Another significant underlying assumption is that there are no changes in land cover (i.e., harvest was followed by reestablishment/continuation of the same cover type). There are no additional plantations established on natural stand sites for biomass. Current plantations are regenerated as plantations but are not necessarily harvested for biomass, as is explained in section 3.4. The assumption makes it difficult to meet future demands in this report.

As reported in the 2011 *BT2*, the component ratio method (CRM) was used for calculating the non-merchantable volumes of the merchantable trees (Heath et al. 2008). The method was again used in *BT16*. The FIA program of the USDA Forest Service adopted the CRM in 2009 for estimation of the above-ground live tree component biomass. The approach is based on (1) converting the sound volume of wood in the bole to biomass using a compiled set of wood specific gravities, (2) calculating the biomass of bark on the bole using a compiled set of percent bark and bark specific gravities, (3) calculating the biomass of tops and limbs as a proportion of the bole biomass based on component proportions, (4) calculating the biomass of the stump using equations, and (5) summing the parts to obtain a total aboveground live biomass. The CRM incorporates regionally specific volume models by species and species group (Domke et al. 2013).

The methodology has had some scrutiny. Domke et al. (2013) report that biomass and carbon stock estimates decreased, on average, by 16% for the 20 most common species across the 48 conterminous states. A similar volume-to-biomass conversion method significantly underestimates biomass from 6.3% to 16.6% for selected species (Zhou et al. 2011). Heath et al. (2008) report lower biomass estimates with the CRM. Mater (2015) reports that CRM underestimates for species outside the west range from 5% to 36%, with 15% a mid-range value for northern and southern species.

The CRM was used in *BT16* primarily for consistency with the 2011 *BT2* and compatibility with the FIA database. The CRM is consistently applied across the United States in the FIA (Woodall et al. 2011). As improvements are made in the CRM, such as developing a method of estimating merchantable bole biomass for the sawlog component and the component above the minimum sawlog top diameter for timber species in the FIA program, more accurate and better biomass estimates will be available in the database. Additional efforts are ongoing in the continued refinement of FIA's modeling/estimation procedures to estimate biomass in the future (Woodall et al. 2011).

Woody crops for energy are considered in chapter 4, as they were in the 2011 *BT2*. That is because the agricultural model uses agricultural land for energy crops. The forestry analysis used a new model (described in detail later in this chapter) that can look at land change; however, it is not yet capable of linking agricultural and forestry lands together to analyze land use change between the two sectors. Since there are no definitive data, and there are many uncertainties surrounding both technical and social aspects of land use decisions in forestry, a simplifying assumption used in this analysis was that land use in forestry did not change. All timberlands are assumed to remain in forestry over the analysis period. Furthermore, no intensification changes are made in the stand types. All stands regenerate back to the previous stand type. For example, natural pine or mixed stands are not put back into fast-growing plantations. Harvested plantations are assumed to be regenerated artificially as intensively managed plantations.

3.1.4 Federal Lands and Fire

In the 2011 *BT2*, biomass from federal lands was estimated separately from biomass from private lands for most feedstock types. Again, in this analysis, federal lands are estimated separately, but they are included in the model. The primary reason for separating them is that biomass from federal forestlands—the largest component of public lands—is excluded from being a qualifying renewable biomass under EISA.[2] Biomass is estimated for all private and federal ownership categories, even though federal lands do not currently qualify under the RFS. Federal lands are included because they are a valuable source of biomass, and because reducing and removing biomass is one way of improving the resiliency of federal lands under stress from droughts, pests, and fire.

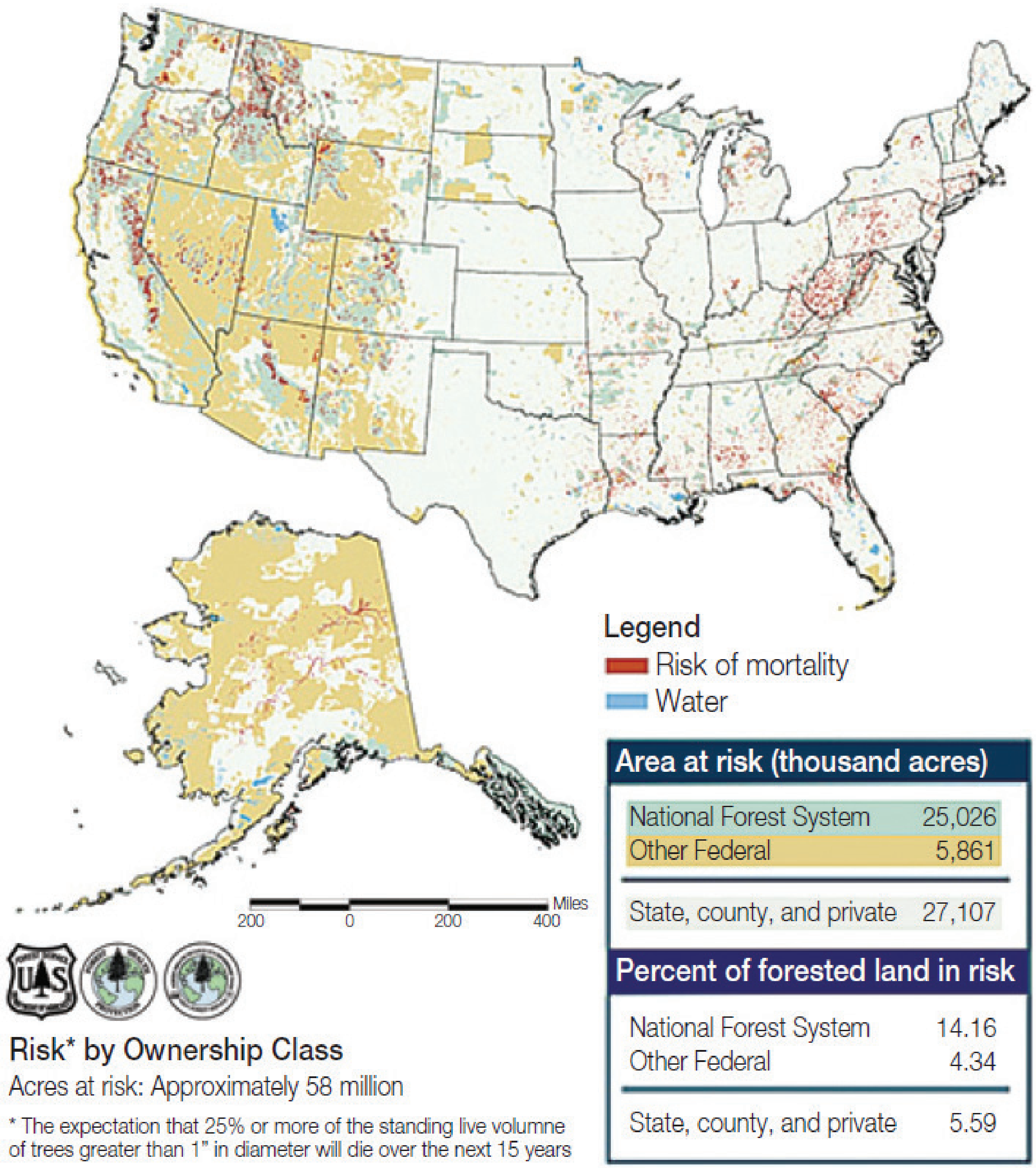
From 2005 to 2014, almost 628,000 wildfires consumed nearly 65 million acres in the United States, representing a serious environmental and economic threat that is extremely costly to battle (NIFC 2016). Although much of the annual variation in the number and size of wildfires (fig. 3.3) reflects climate variation, it is more generally an indication of poor forest health. Much of the fuel for wildfires results from overstocked forestland with small-diameter trees. Those conditions make trees generally more susceptible to attacks from insects and disease, which lead to

[2] Energy Independence and Security Act of 2007, Pub. L. 110–140, 121 Stat. 1492, http://www.gpo.gov/fdsys/pkg/BILLS-110hr6enr.

early mortality and create an ideal source of fuel. The problem is expected to intensify as weather patterns continue to change, with more severe droughts and precipitation shifts in the future (Bentley and Stepleton 2012). Figure 3.4 illustrates the vast land area where high tree mortality (>25%) from insects and diseases is expected. Note that the issue is not limited to the West but impacts forestland across the nation.

Figure 3.3 | Land area impacted by wildfires annually (2005–2014) in the United States

Figure 3.4 | Areas with potential risk of tree mortality greater than 25%



Source: USDA Forest Service, Forest Health Monitoring Program

Wildfire suppression costs routinely run in the billions of dollars every year, leading to intense interest in developing effective remediation approaches. Remediation would involve reducing stocking through various types of harvest operations. There are clear access challenges; however, a major issue is the absence of attractive markets for what ultimately is small-diameter, low-value trees. Although the Forest Service has sold a not insignificant tonnage of woody biomass over the last 5 years to address forest health concerns, the total amount has declined from 2.3 to 1.6 million dry tons (table 3.4). The decline can be attributed, in part, to the limited value of the raw material. The availability of new technology to effectively utilize this woody residue for the production of fuels and industrial chemicals would ultimately increase the value of the resource and expand the volume of the feedstock for the biomass industry. This outcome would have important ramifications for forest health across the country, as well.

Table 3.4 | Amount of Biomass Sold for Energy and Wood Products from National Forestlands, 2010–2014

Year	Biomass sold (dry tons)		
	Bioenergy	Bioproducts	Total
2014	1,099,527	500,126	1,599,653
2013	1,429,677	298,848	1,728,525
2012	1,398,284	535,500	1,933,784
2011	1,473,071	510,426	1,983,497
2010	1,651,419	643,635	2,295,054

Source: Data from NIFC (2016).

The Bureau of Land Management (BLM) manages 58 million acres of forest and woodlands. They include pinyon-juniper and western juniper woodlands, Alaska boreal forest, and 2.2 million acres of the Oregon and California Railroad Revested Lands in western Oregon, as well as forests in the Rocky, Sierra Nevada, and Cascade mountains (BLM 2014). In 2014, BLM sold about 116,559 green tons of biomass (including firewood permits and biomass chips from Stewardship contracts). In 2014, BLM completed 28,875 acres of thinnings. These acres contribute to the nearly 117,000 green tons sold, but not all thinnings result in a permit or contract to convey material.

3.1.5 Sustainability

In the 2005 *BTS*, an underlying principle was the sustainability of the selected feedstocks, which are known to be sustainable under proper production, harvest, and use regimes. The 2011 *BT2* took such assumptions further with supporting analyses and the incorporation of delimiters in land use, location, inputs, removal levels, systems, and operations with the goal of maintaining environmental quality. *BT16* volume 1 uses similar constraints and is followed by more in-depth environmental sustainability analyses in volume 2.

For forestry resources to roadside, assumptions used in the availability analysis of volume 1 are to

- Remove fragile, reserved, protected, and environmentally sensitive forestland
- Access stands without road building
- Use production and harvest systems specified for particular species, timber size, and land condition to minimize impacts
- Manage residue removal levels to protect the soil and water and to ensure long-term productivity
- Assume the use of best management practices (BMPs) and include in cost estimates
- Restrict harvest levels to ensure that timber growth always exceeds harvest at the state level
- Leave at least 30% of logging residues on-site to protection soil, provide habitat, and maintain soil carbon.

Compliance with BMPs is very important to forestry sustainability. BMPs are usually voluntary, but they can have some compliance enforcement or regulatory oversight. Many of the eastern states have compliance monitoring programs to assess the application of these BMPs or guidelines on public and private forestland (Phillips and Blinn 2004). The approaches among these states to collecting on-site monitoring data (measuring compliance) and evaluating sites are variable. A survey of eastern states found that almost all the southern states monitor the application of BMPs, but proportionally fewer of the northern states have established compliance monitoring programs. The state forestry agencies provide the leadership for these programs in most of the eastern states. States that monitor tend to evaluate all public and private forestland owner categories located within their states. In general, northern states monitor a broader array of site resources (e.g., cultural resources, visual quality) compared with southern states, which focus on water quality and wetlands protection. However, northern states focus their monitoring on timber harvesting, forest road construction, and maintenance.

Forestry BMPs usually focus primarily on forest water quality from timber harvesting, site preparation, forest road construction and maintenance, stream crossings, and other categories of forest operations. Cristan et al. (2016) reviewed the literature on BMP effectiveness and concluded the literature indicates that forestry BMPs protect water quality when measures are constructed correctly and in adequate numbers. Another literature review by Anderson and Lockaby (2011) concluded that a limited number of studies have quantified BMP effectiveness in reducing sediment runoff. Three paired studies of forested watersheds in the eastern United States found that BMP efficiencies ranged from 53% to 94% in sediment and nutrient loading reductions (Edwards and Willard 2010).

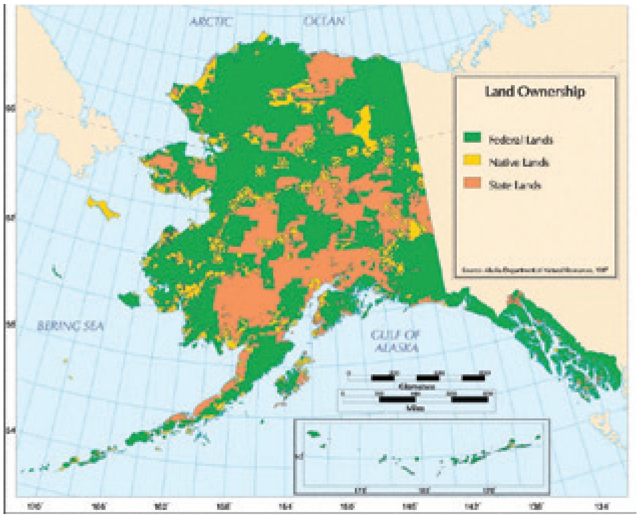
3.1.6 Alaska and Hawaii

Neither Alaska nor Hawaii is analyzed using the model because of the lack of data. Alaska has forest inventory data for portions of the state; Hawaii is now starting to conduct forest inventories.

The approximate forestland area of Alaska is 127 million acres. Alaska is the only state that has never had a complete forest inventory (PNW 2011). The southeast and south-central regions of Alaska are regularly inventoried. This area contains about half of the state’s timberland. Public agencies manage 88% of the 15.3 million acres of forestland in the coastal region of Alaska (PNW 2011). Private owners hold about 12% of the forested area in the region but about 24% of timberland. The same assessment of nearly 12 million acres of available forested land estimated only 3.7 million green tons of annual growth—a limiting factor for accessing biomass.

There is increasing interest in the use of biomass in southern Alaska, but use is constrained by high transportation costs, currently inadequate harvesting systems, and limited information on available biomass

Figure 3.5 | Lands in Alaska by ownership



supply. There are more than 1.3 billion tons of biomass stored within the live trees of coastal Alaska. Nearly 83% of the live forest biomass in coastal Alaska is on national forestland managed by the USDA Forest Service. How much of this standing biomass can be harvested is difficult to determine primarily because of lack of accessibility and the drop in timber sales. The harvest in southeast Alaska has dropped substantially in recent years because of lawsuits over sales of timber from the Tongass National Forest, lower timber inventories on some native corporation lands, high operating costs throughout the region, and shifting global markets and competition (Barrett and Christensen 2011). Assessment of the biomass potential in Alaska continues to be developed.

Hawaii has almost 2,000 acres of forest area that have about 48% forest cover (FIA 2012). However, the islands are just now being measured for the Forest Service FIA. Some old assessments have been completed for merchantable wood estimates that provide some level of biomass potential analysis (see Turn, Keffer, and Staackmann 2002). The Hu Honua bioenergy facility is developing a 30 MW power station that uses eucalyptus plantation and wood residues.

3.2 Timber and Biomass Harvest Costs

3.2.1 Methodology

For the 2011 *BT2*, harvest costs for simulated thinnings and conventionally sourced wood were calculated using an adapted Fuel Reduction Cost Simulator (FRCS) (Dykstra, Hartsough, and Stokes 2009; Fight, Hartsough, and Noordijk 2006). The FRCS estimates the biomass-to-roadside cost by three system types: (1) whole-tree harvesting with mechanical felling and ground-based extraction, (2) whole-tree harvesting with manual felling and ground-based extraction, and (3) whole-tree harvesting with manual felling and cable-yarding (DOE 2011). The cable-yarding system is used when the slope of the harvested land exceeds 40%. All biomass is chipped, and the chipping cost is added to the harvest cost for the thinnings. For logging residues, FRCS is used to calculate chipping costs only, as the underlying assumption is that logging residues are felled and extracted along with the merchantable trees; thus there is no harvest cost for biomass as a by-product. Fuel costs and labor rates are adjusted according to the region of the United States modeled. Stands over 0.25 mile from an established road for cable-yarding systems, and between 0.5 and 1.0 mile for ground-based systems, are too expensive to be considered, although they are not excluded.

A different approach is used to estimate harvest costs in this study. The harvest costs and chipping costs are estimated as input to ForSEAM (see section 3.4.). Specifically, input costs are derived for each of the following parameters:

- **U.S. region:** Northeast, North Central, South, Inland West, and Pacific Northwest
- **Stand type:** Upland hardwood, lowland hardwood, natural softwood, planted softwood, or mixed softwood/hardwood

- Stand diameter class: Class 1, diameter >11 inches; class 2, diameter 5–11 inches; and class 3, diameter <5 inches
- Cut (type of harvest): Clear cut or thinning (partial cut)
- Products: Timber (merchantable products of sawlogs and pulpwood), logging residues (forest residues), and whole-tree biomass
- Harvest method: Full tree or cut-to-length
- Ground slope condition: ≤40% or >40%.

A deterministic spreadsheet model developed by the Consortium for Research on Renewable Industrial Materials (CORRIM) was used to estimate the input harvest costs to ForSEAM. The CORRIM model calculates cost, fuel, and chemical outputs (Oneil et al. 2010; Johnson et al. 2004) and had been modified previously to estimate the costs of harvesting forest residues (Johnson, Lippke, and Oneil 2012). In this particular version, the spreadsheet model was used to calculate machine and labor costs, with fuel costs as a part of the machine rate.

3.2.2 Harvest Systems

The CORRIM spreadsheet provides individual machine costs by region and by equipment attributes such as engine horsepower, undercarriage (tracks or tires), capacity, and use (clear cut or thinning). These machines must be assembled into systems to determine total costs for the production of timber, logging residues, and whole-tree biomass.

In most cases, the system is full-tree (see text box 3.2), meaning the felled trees are taken to a landing to be processed. Processing could consist of removing the limbs and tops and then loading the stems onto trailers (timber harvest). The remaining biomass—limbs, tops, small and cull trees, and tree wastes (i.e., logging residues)—could then be chipped. In steep ground conditions, trees are usually processed at the stump, and only log sections or the tree bole is moved to the landing. For those systems, no biomass in the form of logging residues is recovered. The same is true of cut-to-length systems in which the felling and processing occurs at the stump and only clean, short boles of wood are extracted to the landing with no biomass recovery. Finally, in cases when whole trees are harvested for use as biomass and the merchantable timber is not sorted or removed, the full trees could be processed into smaller components such as chips or particles.

Conceptually, timber harvesting requires felling, extraction, processing, and loading functions that make up a system. Each of the functions has various alternative equipment types. Felling equipment can range from chainsaws to large-capacity, tracked swing feller-bunchers. Extraction equipment can be cable or grapple skidders, forwarders, or cable-yarding. Processing can be even more complex, occurring either at the stump or at the landing, with options that include chainsaws; various types of delimbers and buckers; and comminution machines such as grinders, hogs, and chippers. Figure 3.6 shows representative machines used in harvesting.

Text Box 3.2 | Harvest Methods

Cut-to-length: Trees are felled, delimbed, and bucked to individual product lengths directly in the stump area and then transported to the landing or roadside as log sections. In this study, only softwood species are harvested with cut-to-length methods.

Full-tree: Trees are felled and transported to the landing with the branches and top still intact. Transport to the landing is usually by skidder (cable or grapple). At the landing, the full trees are delimbed and bucked into individual products and components—sawlogs, pulpwood, limbs, and tops—or chipped as full trees.

Source: USDA Forest Service (2016).

Figure 3.6 | Machines for harvesting trees and forest residues

(Courtesy of U.S. Forest Service Southern Research Station)

In harvesting timber (e.g., merchantable sawlogs and pulpwood), the final product is usually delimbed and topped into tree-length roundwood or logs cut to specific lengths. In some cases, the pulpwood trees can be delimbed and debarked at the landing and chipped. This option is not considered in this study but could have wide application if the limbs, tops, and bark could be economically recovered for biomass. Then, if logging residues were recovered during the harvest or after the harvest of the roundwood timber, a chipper and usually another loader would be added to the timber harvest system.

The concept of integrated logging with the harvest of merchantable wood and biomass occurring at the same time is discussed in more detail in the 2011 *BT2*. Finally, if merchantable trees are not separated, and all the felled and extracted trees are used for biomass, then the system has the same machines used for timber harvest without any delimbing and bucking, but without an extra loader with the chipper. The key component in this study is that merchantable materials are assumed to be harvested as roundwood. If the logging residues are recovered, they are integrated into the system by adding a chipper and another loader. If only biomass is harvested as whole trees, then the system consists of felling, extraction, and chipping without any delimbing or bucking.

The systems are assembled specifically for the region (see text box 3.3), stand type, type of harvest (clear cut or thinning), products, harvest method, and ground slope. Regions have various systems based on the other parameters, e.g., systems for hardwood, planted softwoods, steep slopes. However, the region determines the harvest method—whether full-tree or cut-to-length. A regional logging analysis report is used primarily as the basis (Baker et al. 2013), along with professional judgments of associates. In the final analysis, 50% full-tree and 50% cut-to-length systems are assumed for the Inland West and North Central regions. The other regions are assumed to be 100% full-tree. In effect, the use of cut-to-length systems reduces the available logging residues by

Text Box 3.3 | Harvest Regions

Harvest costs are determined for five geographical regions of the United States (excluding Alaska and Hawaii). These regions, although not definitive in the inclusion/exclusion of specific states, were chosen to represent the types of stand or ground conditions. The five regions used in this study are similar to those reported by Johnson, Lippke, and Oneil (2012). The regions and states are listed in table 3.5.

approximately half, since it is assumed that the logging residues behind cut-to-length operations stay in the woods. Cable-yarding is included only on slopes greater than 40% and predominately in the Inland West and the Pacific Northwest regions. As with cut-to-length systems, no logging residues are harvested.

Using the literature and the professional opinions of associates, individual machines also are assembled for each region, stand type, type of cut, product, method, and slope. The type of equipment used in a particular system is based on the region and the stand type (Baker et al. 2013; Johnson, Lippke, and Oneil 2012; Wang, Hartley, and Liu 2013). For example, in the Northeast, most hardwood is still felled and delimbed with chainsaws (Wang, Hartley, and Liu 2013). This is also true of hardwoods and conifers in the Pacific Northwest. Larger feller-bunchers, skidders, cable-yarders, and loaders are used more for clear cutting than for thinning. Tracked swing feller-bunchers are used on hardwood stand types in lieu of chainsaw felling in the South, as reported.

Much effort went into equipment selection for a harvest system. The details are not reported in this section but will be reported in an ancillary paper in the near future. Since there are numerous types of machines and variations of systems, the systems used in this study are considered to be representative only of the various systems used across the United States or even in specific regions or stand types. The systems are aligned with states (see table 3.5) as a representative system, but the use does not infer that the system used is the only system in that state or the best representative of harvest systems in that state.

Table 3.5 | States in Forest Regions

Northeast	South	North Central	Inland West	Pacific Northwest
CT	AL	IA	AZ	CA
DE	AR	IL	CO	OR
KY	FL	IN	ID	WA
MA	GA	KS	MT	HI
MD	LA	MI	NM	AK
ME	MS	MN	NV	
NH	NC	MO	UT	
NJ	SC	ND	WY	
NY	TX	NE		
PA	VA	OK		
RI		OH		
TN		SD		
VT		WI		
WV				

Note: Alaska and Hawaii are not in the model.

3.2.3 Harvest Costs

A cost per dry ton is estimated for each component, and then the system cost is derived by summing these component costs. The model uses these systems to "seed" the economic analysis; therefore, the absolute costs are not as important as the relative differences. Care is taken to ensure consistency in underlying assumptions to generate the costs.

The CORRIM database is used to develop the systems and the costs per ton of the merchantable products and the biomass (Johnson, Lippke, and Oneil 2012). The database includes equipment cost, labor costs, and production levels (ton/hour) for a specific machine. These estimates cover a range of years, as the database is a composite of many published reports. The machine and machine costs are updated to a 2014 basis. The productivity levels are not changed, except for being crossed-checked as needed because of the appearance of outlier values.

The equipment costs are updated to 2014 using the producer price index for construction machinery manufacturing (Bureau of Labor Statistics 2015a). The costs had been last updated in 2004, so a multiplier is used to update the costs to a 2014 basis. All aspects of machine costs are included in these estimates—owning, operating, and fuel costs.

Logging wages are updated separately for each state and then averaged by region. The data are from the Bureau of Labor Statistics (2015b) for logging wages (North American Industry Classification System code 1133). A 35% loading factor for benefits and other payroll costs is added to the wage costs.

Two other modifications to the CORRIM costs are made: (1) adding part of the felling, extraction, and preprocessing (delimbing and bucking) to the logging residue costs and (2) adding an overhead cost. In earlier versions of this report, an assumption was that logging residues were integrated into the system and brought to the landing as part of the timber harvest. The working assumption had been that there were no costs for logging residues except for the chipping costs. All the costs for felling, extracting, delimbing, bucking, and loading were allocated to the timber, and none of these costs were allocated to the logging residues (Jernigan et al. 2013). That assumption is changed in *BT16* to allocate 10% of the timber harvest cost to the logging residues, in addition to the entire chipper and second loader costs.

Since no commercial timber products are recovered in whole-tree biomass harvest systems, all the felling, extracting, and chipping costs are allocated to the biomass costs. There are no timber delimbing and bucking costs, but a loader is also included to handle the biomass around the chipper.

Finally, there are overhead costs associated with a harvest system (e.g., a foreman, profit, tools and support equipment, and fueling systems). For this study, 15% of the total system cost is added to the total cost to cover these overhead costs. It is assumed that this added cost also covers the cost of BMP treatments, such as bridge and stream crossings, deconstruction of roads, and establishment of grass protection zones.

3.3 Projections of Wood Fuel Feedstock Supplies from U.S. Forests under Six Demand Scenarios

3.3.1 Introduction

The previous Billion-Ton reports, *BTS* and *BT2*, (Perlack et al. 2005; DOE 2011; Turhollow et al. 2014) estimate potential wood availability for a given price through 2030, but they do not consider competition for wood with conventional products such as lumber, paper and panels. We evaluate the use of small-diameter roundwood (softwood less than 9 inches in diameter at breast height [dbh] and hardwood less than 11 inches dbh) that is being harvested to supply wood biomass feedstocks in conjunction with conventional products; our analysis accounts for changes in standing timber inventories, net growth, and investment in tree plantations. Because small roundwood is (1) sold in a competitive market and used for paper and panel manufacturing and (2) harvested in conjunction with sawlogs that are used for lumber and plywood, the conventional and wood energy markets are linked and are modeled jointly in this analysis.

To incorporate wood energy markets into conventional wood products markets, this study develops six projection scenarios: a baseline scenario and five alternate scenarios that include three levels of increased national wood energy demand, two levels of increased housing starts (which lead to increased solid wood products demand), and increased intensity of forest plantation management (to meet high wood energy demand). The projections are made to 2040. For each scenario, we estimate wood fuel feedstock supply and conventional timber supply by U.S. region (North, South, and West) and source (logging residues, mill residues, small roundwood, large roundwood, and fuelwood) to meet national wood energy and conventional wood product demands.

The USFPM/GFPM (Ince et al. 2011a) is used to project wood energy supply and prices along with production, net imports, and prices for other wood products. To better project the impacts of increased wood energy demands on southern forests, a model is developed that combines the market projections of USFPM/GFPM with the forest inventory projections of the SRTS model (Abt, Cubbage, and Abt 2009). This combined model provides projections of regional wood fuel feedstock production and timber use in conventional products that are used in subsequent modeling efforts to estimate wood fuel feedstock supply by U.S. county (section 3.4).

This section discusses the wood energy and market scenarios, the USFPM/GFPM+SRTS modeling approach, and the projection results and summarizes the findings.

3.3.2 Wood Energy and Market Scenarios

Six scenarios are developed to evaluate U.S. forest product market outcomes for three levels of U.S. national wood biomass feedstocks demand, two levels of housing recovery, and two levels of southern pine plantation growth rates (table 3.6). In all scenarios, (1) U.S. demand for solid wood products is driven by projected growth trends in U.S. real gross domestic product (GDP) and single-family housing and (2) U.S. demand for paper products is driven by U.S. real GDP and by recent historical growth rates for advertising expenditures in print media and electronic media (Ince et al. 2011b). Net exports of U.S. forest products are influenced by projections of global demand for forest products and projections of global currency exchange rates. All scenarios used the 2012 USDA Economic Research Service global projections for GDP and currency exchange rates for all countries to 2030 (USDA-ERS 2015).

The baseline scenario in this study is derived from a baseline scenario developed by Ince and Nepal (2012) that assumes a moderate rebound in housing, with average single-family housing starts increasing to the long-run historical trend of 1.09 million per year by 2020 and following a slowly increasing trend thereafter (Ince and Nepal 2012). The baseline scenario also includes wood energy demand, which is determined by historical econometric relationships between fuelwood consumption and GDP growth (Simangunsong and Buongiorno 2001). In the baseline scenario, wood energy demand increases by about 26% between 2010 and 2040, from 58 to 73 million dry short tons. This scenario also includes a pine plantation growth rate determined from the most recent FIA data (USDA Forest Service 2015b).

The alternate scenarios vary with housing starts, wood energy demand, and pine plantation growth rates, as shown in table 3.6 and discussed in the following paragraphs.

Housing starts: For baseline housing starts, we assume a return to the long-term average of 1.09 million single family starts per year by 2020 as presented in Ince and Nepal (2012), then an increase of 0.4% per year after that. To generate a higher number of housing starts, we assume starts would be 10% higher by 2025 and would stay 10% higher throughout the projection. The top quartile of housing starts from 1959 to 2011 is at least 10% above the long-term average, indicating that a higher rate is achievable.

Wood energy: The baseline wood energy demand scenario is derived as shown in table 3.6. The moderate and high wood energy demand scenarios are assumed to represent increases in domestic and/or pellet export wood energy demands that are not captured in the estimated relationship between fuel wood use and GDP (fig. 3.7). Potential uses include the rapidly growing production of wood pellets for export (Abt et al. 2014). The moderate wood energy demand scenario is developed as a quadratic demand that encompasses the announced production facilities in the Forisk Consulting wood energy database through 2020 (Forisk Consulting 2014) and an assumed increase based on continued pellet exports. This results in a total wood energy demand in the moderate scenarios of 108 million dry short tons in 2040. The high wood energy demand scenario assumes that production in 2020 will be twice as high as in the moderate scenario. After fitting a quadratic through the 2015 and higher 2020 points, we end with a demand of 143 million dry short tons.

Pine plantation growth rates: The two high-demand wood energy scenarios are combined with the two housing scenarios, and both include an assumption that a timber supply response occurs from increased timber demand for use in conventional products or energy. We model this supply response by increasing the growth rates on new pine plantations in the South by 50%, which could occur from increased use of selected genetic stocks and/or best practices for plantation management. Recent research implies that under specialized conditions, growth rates could be two to five times higher than current levels (Fox, Jokela, and Allen 2007; Jokela, Martin, and Vogel 2010). We apply the 50% increase only on new plantations—well within the potential range identified in Fox and Jokela. In all other scenarios, the plantation growth rate is based on growth rates from the latest FIA data (USDA Forest Service 2015b).

Table 3.6 | Description of Wood Energy, Housing, and Plantation Investment Scenarios

Scenario[a]	Growth in housing starts[b]	Growth in wood biomass demand for energy[c]	New plantation management intensity in the South[d]
Moderate housing–low wood energy (baseline)	Returns to long-term average by 2025	Increases by 26% by 2040	Based on current FIA pine plantation growth rate
High housing–low wood energy	Adds 10% to baseline in 2025 and beyond	Increases by 26% by 2040	Based on current FIA pine plantation growth rate
Moderate housing–moderate wood energy	Returns to long-term average by 2025	Increases by 86% by 2040	Based on current FIA pine plantation growth rate
High housing–moderate wood energy	Adds 10% to baseline in 2025 and beyond	Increases by 86% by 2040	Based on current FIA pine plantation growth rate
Moderate housing–high wood energy (and high plantation growth)	Returns to long-term average by 2025	Increases by 150% by 2040	Increases by 50% over current FIA growth rate by 2040
High housing–high wood energy (and high plantation growth)	Adds 10% to baseline in 2025 and beyond	Increases by 150% by 2040	Increases by 50% over current FIA growth rate by 2040

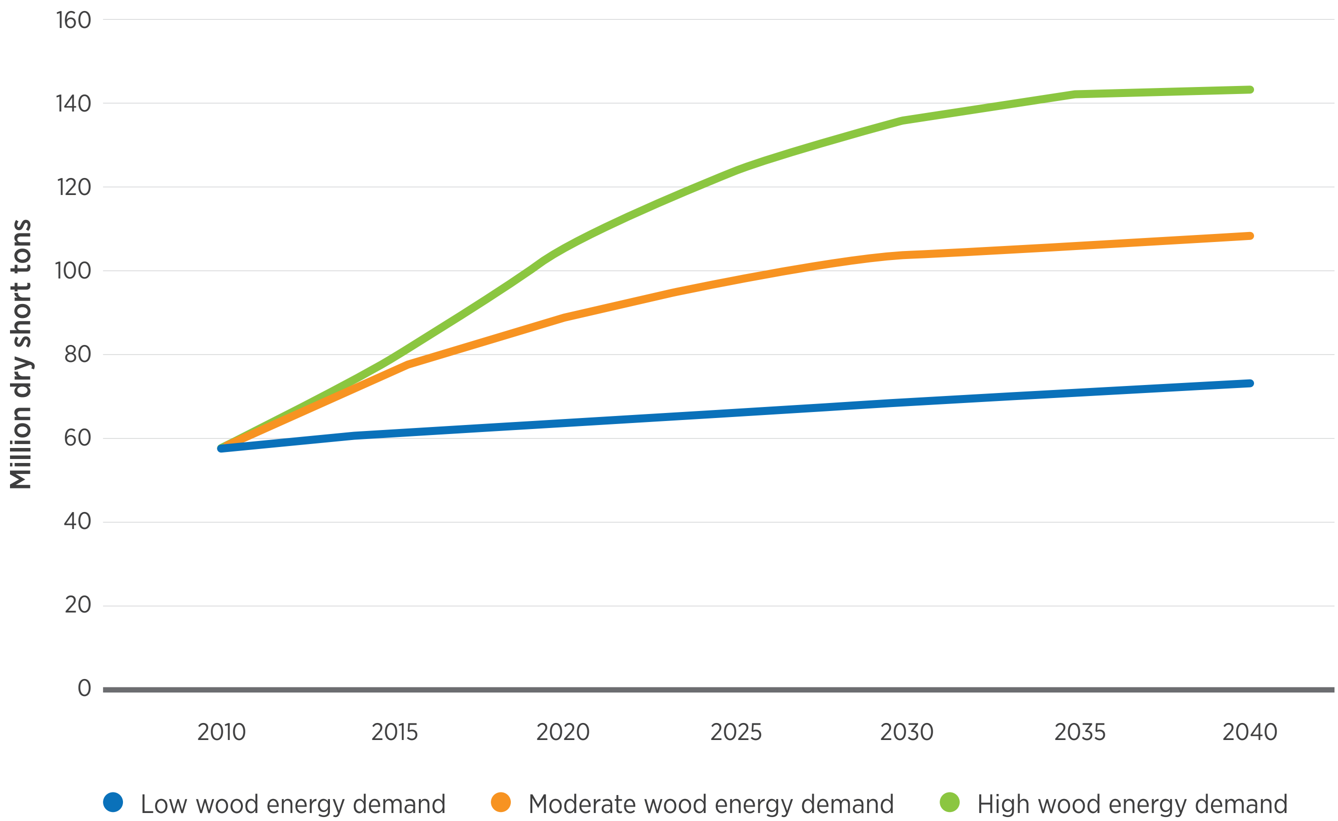
[a] All changes are to domestic production; assumptions regarding international trade are not varied from Ince and Nepal (2012); demand for paper and paperboard is consistent with Ince and Nepal (2012) assumptions.

[b] The long-term average of housing starts from 1959 through 2011 is slightly less than 1.1 million per year.

[c] Actual wood biomass production in 2010 was 58.2 million dry tons for all scenarios.

[d] Current average FIA growth rate on pine plantations across the South (all owners, all ages) is approximately 108 cubic feet/acre per year (1.6 dry ton/acre per year). Increasing management intensity by 50% only on new plantations results in an increase in the average South-wide growth rate over time up to 140 cubic feet/ac per year in 2040 (2.1 dry tons/acre per year).

Figure 3.7 | Assumed U.S. wood energy demands



3.3.3 USFPM/GFPM+SRTS Modeling Approach

The USFPM/GFPM is a global forest products partial equilibrium market model with detailed U.S. forest products production, trade, and prices. In USFPM/GFPM+SRTS, wood energy demand can compete for supply sources also used to make lumber, panels, and paper; forest inventory responds to harvest and growth; and timber prices drive timberland area in the South. U.S. demand for wood energy is specified in the USFPM/GFPM at the national level, and the model determines the fuel feedstock supply allocation among the North, South, and West regions by using the lowest-cost feedstock sources to meet the national demand. The U.S. demand for wood energy includes demands for residential and industrial fuel wood, as well as the potential for increased demand for wood pellets for export and/or assumed domestic demands for biopower and biofuels.

SRTS is used to project southern forest timber inventory as driven by timber harvests projected by USFPM/GFPM. In addition, SRTS provides estimates of timberland area in response to increases in projected timber prices. Timber inventory modeling in SRTS is done at the FIA survey unit level (or an area with a similar amount of timberland) because the FIA data used are statistically reliable only at that level of disaggregation. For the North and West, an endogenous timber inventory model (Nepal et al. 2012) and exogenous timberland area change (Ince and Nepal 2012) are used.

Two iterative procedures are used to develop projections from USPFM/GFPM and SRTS. The first iterative procedure matches SRTS projections of softwood sawtimber prices for the South with price projections from USFPM/GFPM. To do so, SRTS uses the USFPM/GFPM projected southern timber harvests for each scenario as a fixed exogenous harvest quantity. Projected timber prices from the SRTS run are compared with those from USFPM. Adjustments are then made to (1) SRTS timber supply price elasticities and (2) SRTS cull factors, which indicate what proportion of hardwood and softwood sawtimber harvest qualifies as small roundwood. SRTS is then rerun using the same harvest as before. This process is repeated until SRTS-projected softwood sawtimber prices matches projected prices from USFPM.

The second iterative procedure matches USFPM/GFPM harvest and inventory for the South to SRTS harvest and inventory. To develop a match, timber harvest projections from USFPM/GFPM are used in SRTS runs, and the resulting timber inventory from SRTS is used in the subsequent run of USFPM/GFPM as a shifter in the timber supply curves. The timber supply elasticity with respect to inventory is 1.0 for all products and species. This iterative procedure is continued until the projected timber harvest quantities from the USPFM/GFPM and the southern timber inventory quantities from SRTS do not change. At this point, the two models are considered to have converged and the modeling is considered complete for that scenario.

USFPM/GFPM projections use an exogenous national demand for fuel feedstocks to be used for wood energy. The feedstocks can be used to produce residential heat, industrial heat and power, commercial heat, electricity, biofuels, and wood pellets for export. The timber inputs that contribute to these feedstocks include logging residues, mill residues (used to generate on-site power or sold to others for power), small roundwood that can also be used to make paper and panels, and fuel wood. Both fuel wood and logging residues may be left on-site after a harvest if they are more expensive than other sources of fuel feedstocks.

The USFPM/GFPM model linked to SRTS provides projections of regional (1) timber supply for use in conventional wood products such as lumber, panels and paper products; (2) wood fuel feedstock supply by source (logging residue, mill residue, pulpwood, fuelwood); and (3) timber inventory.

3.3.4 Projection Results

Projected solid wood product consumption and wood fuel feedstock sources and prices are generally consistent with expectations based on assumptions about demand drivers and costs for supply sources in the models. For example, higher housing starts lead to higher softwood sawtimber harvest; higher wood energy demand leads to higher softwood non-sawtimber harvest; the South continues to provide the majority of wood used for energy; logging residue use increases with increased wood energy demand; and paper and paperboard production is lower with increased wood energy demand. This section presents a few highlights of the results of the six scenario projections. Additional model outputs and tables can be found online in the Bioenergy KDF.

As shown in figure 3.8*A* and *B*, higher numbers of housing starts lead to higher softwood sawtimber harvest in all scenarios. In addition, more housing starts also lead to higher softwood non-sawtimber harvests in response to increased demand for oriented strand board, as this production more than doubles over the projection period (fig. 3.8*B*). These increased harvests lead to increased prices and reduced timber inventory relative to the baseline, except under the high wood energy demand and high plantation growth rate scenarios, in which additional tree growth in the South begins to bring inventory back up to the baseline levels. Figure 3.8 also shows that increased wood energy demand results in slightly higher sawtimber and non-sawtimber harvest.

Figure 3.8 | Projected U.S. softwood harvest by scenario, 2015–2040. *A*, softwood timber. *B*, softwood non-saw timber (includes small roundwood and non-growing stock).

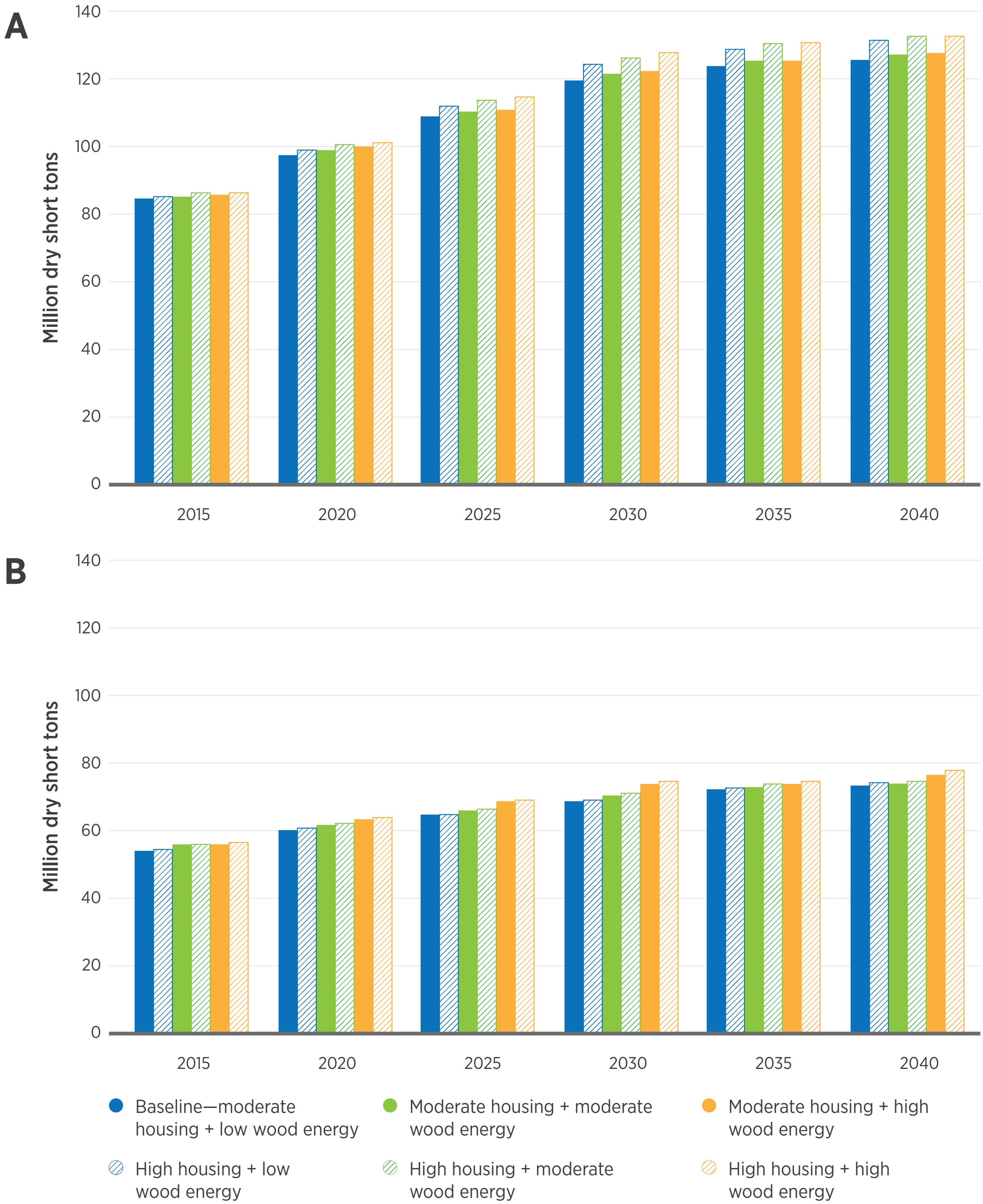
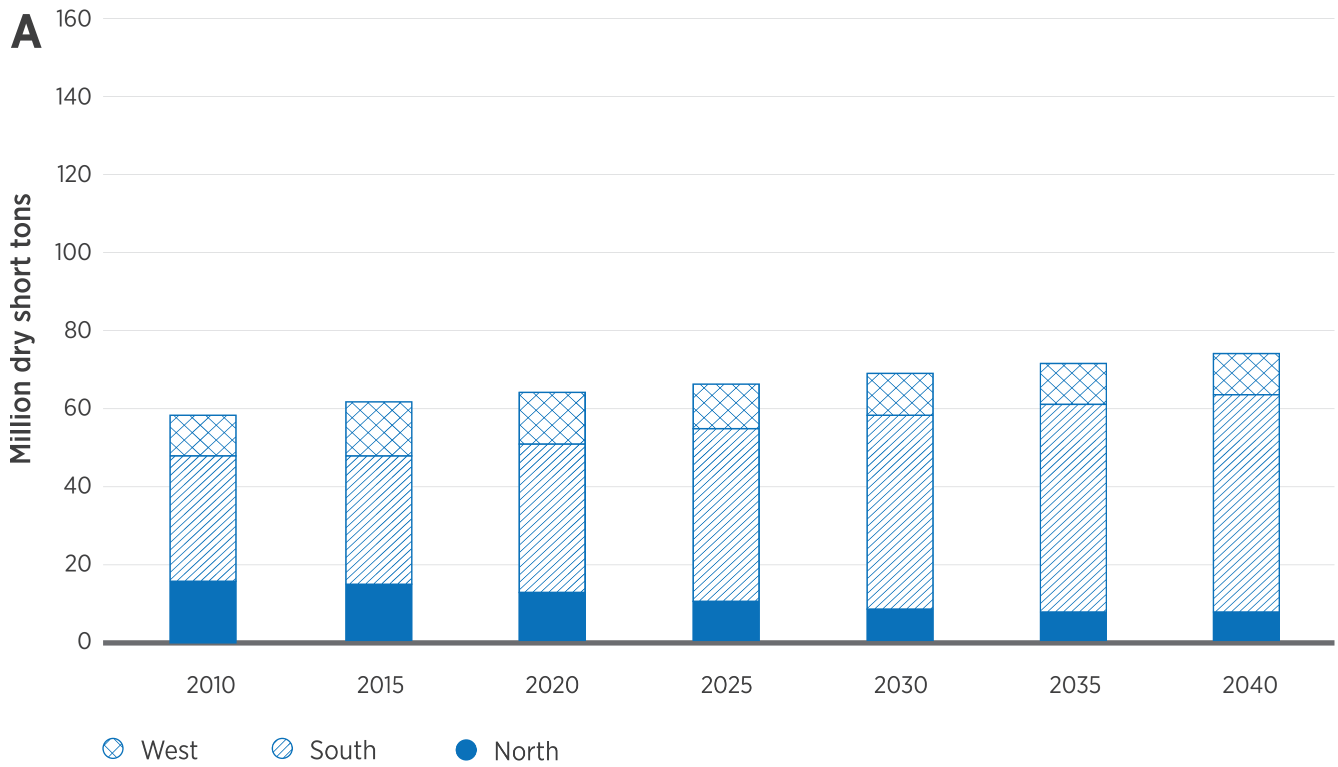
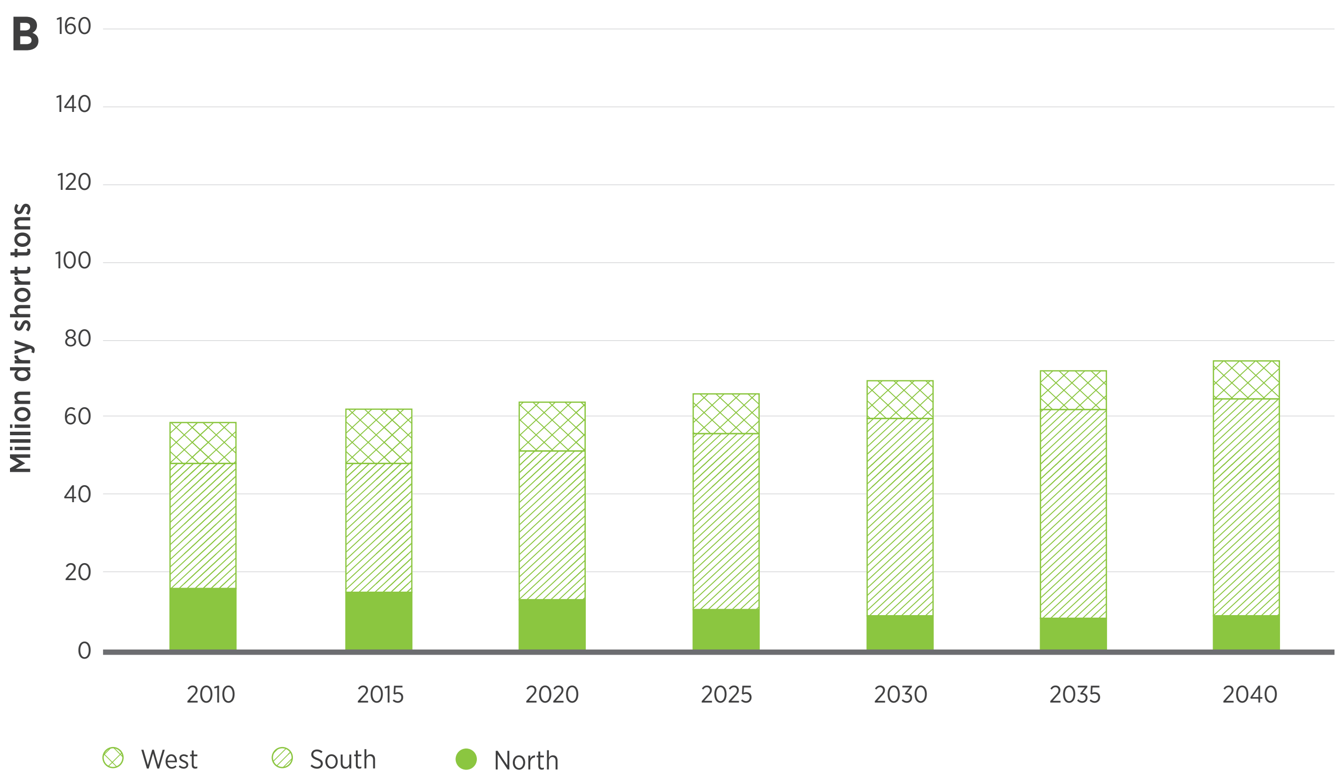


Figure 3.9*A*, *B*, and *C* show the source regions for the wood supplied for energy for a moderate housing recovery paired with low (baseline, moderate, and high demands for wood energy. In all three cases, the South continues to provide most of the wood for energy use, with the proportion increasing in the higher wood energy demand scenarios; starting at 55% in 2010, the South supplies more than 68% of wood for energy by 2040 in all six scenarios.

These aggregate outcomes obscure some of the detailed production trends. For example, there is a projected minor shift for U.S. small roundwood from conventional uses for paper or panels to use for wood energy under the higher wood energy demand scenarios (figs. 3.10 and 3.11). As some portion of small roundwood is used for wood energy in the moderate and high wood energy demand scenarios, less is available for the production of wood pulp for use in paper production; as a result, production of paper and paperboard is lower than the baseline (fig. 3.12). In the baseline or low wood energy demand scenario, paper and paperboard production increases by less than 550 thousand dry short tons from 2010 to 2040 (about 1%), which represents a slight recovery from the recession and then a decline that continues the previous historical trend. Adding additional wood energy demands leads to declines of 1% in the moderate wood energy demand scenario (a loss of about 300 thousand dry short tons of production compared with 2010) and 3% in the high wood energy demand scenario (a loss of about 1.2 million dry short tons of production compared with 2010). Newsprint production is least affected, as it uses recycled paper as a major input. The largest reduction occurs in other paper and paperboard, followed by printing and writing paper. Northern and western paper production is affected more than southern paper production, and the increase in housing starts has little impact on paper production.

Figure 3.9 | Projected U.S. wood energy production by region for low (*A*), moderate (*B*), and high (*C*) wood energy demand scenarios paired with moderate housing demand





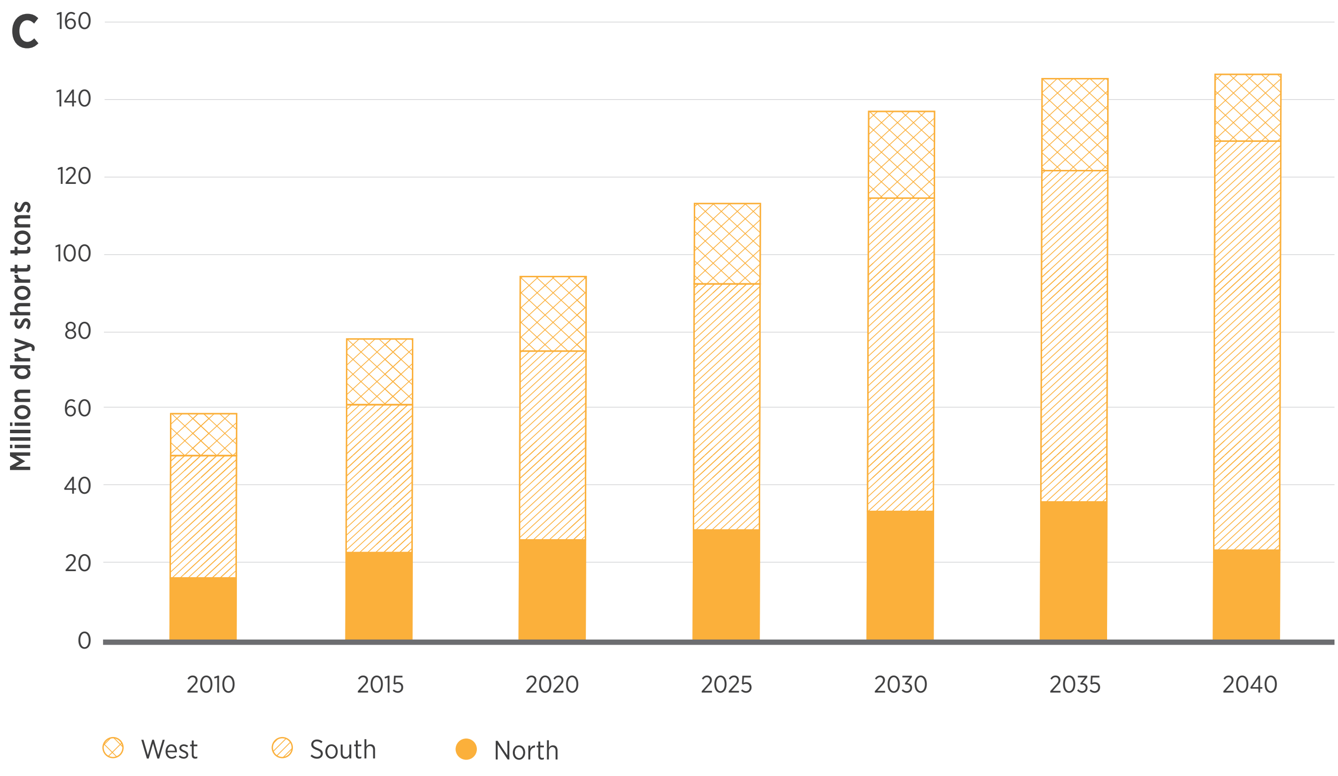


Figure 3.10 | Projected U.S. small roundwood production for use in conventional wood products, including use for pulp and paper products, paperboard and panels, by scenario, 2015–2040

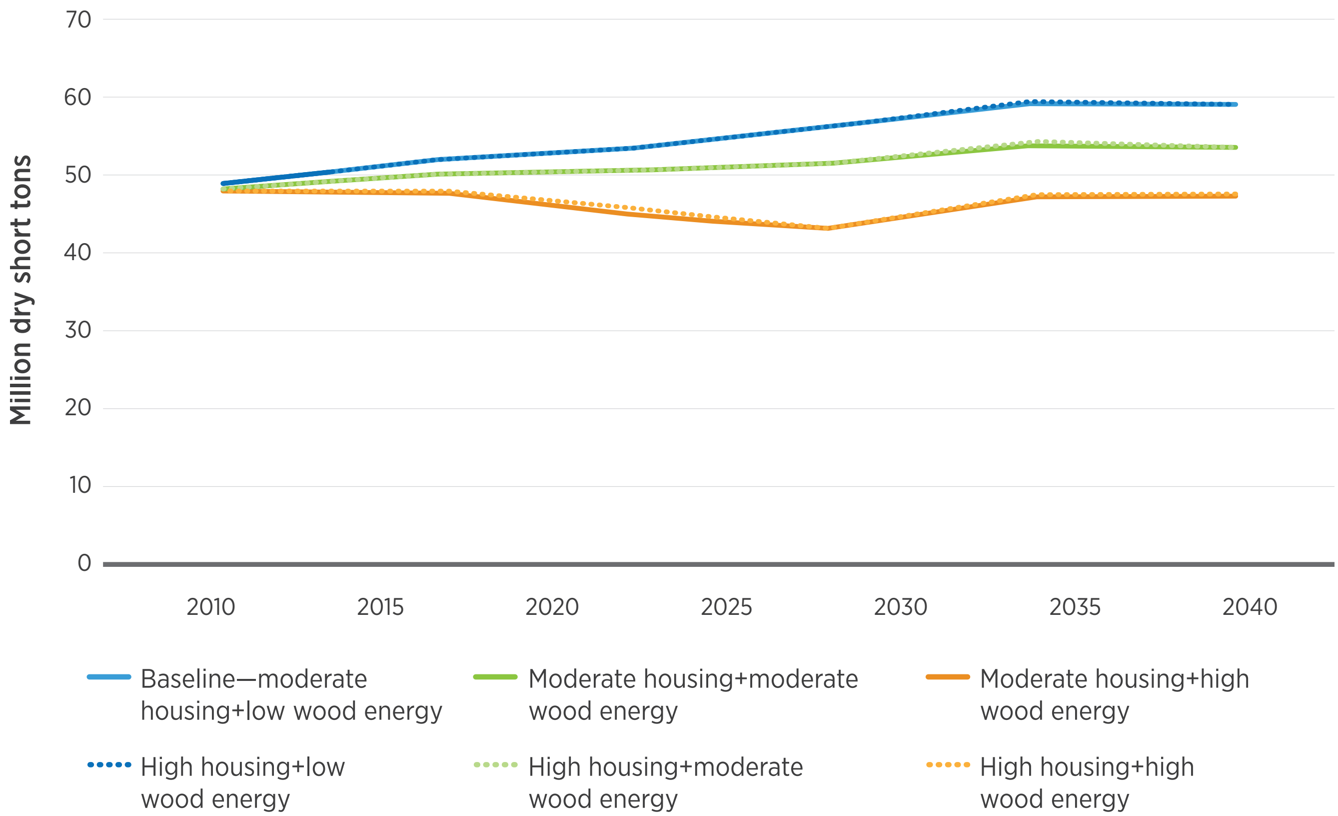
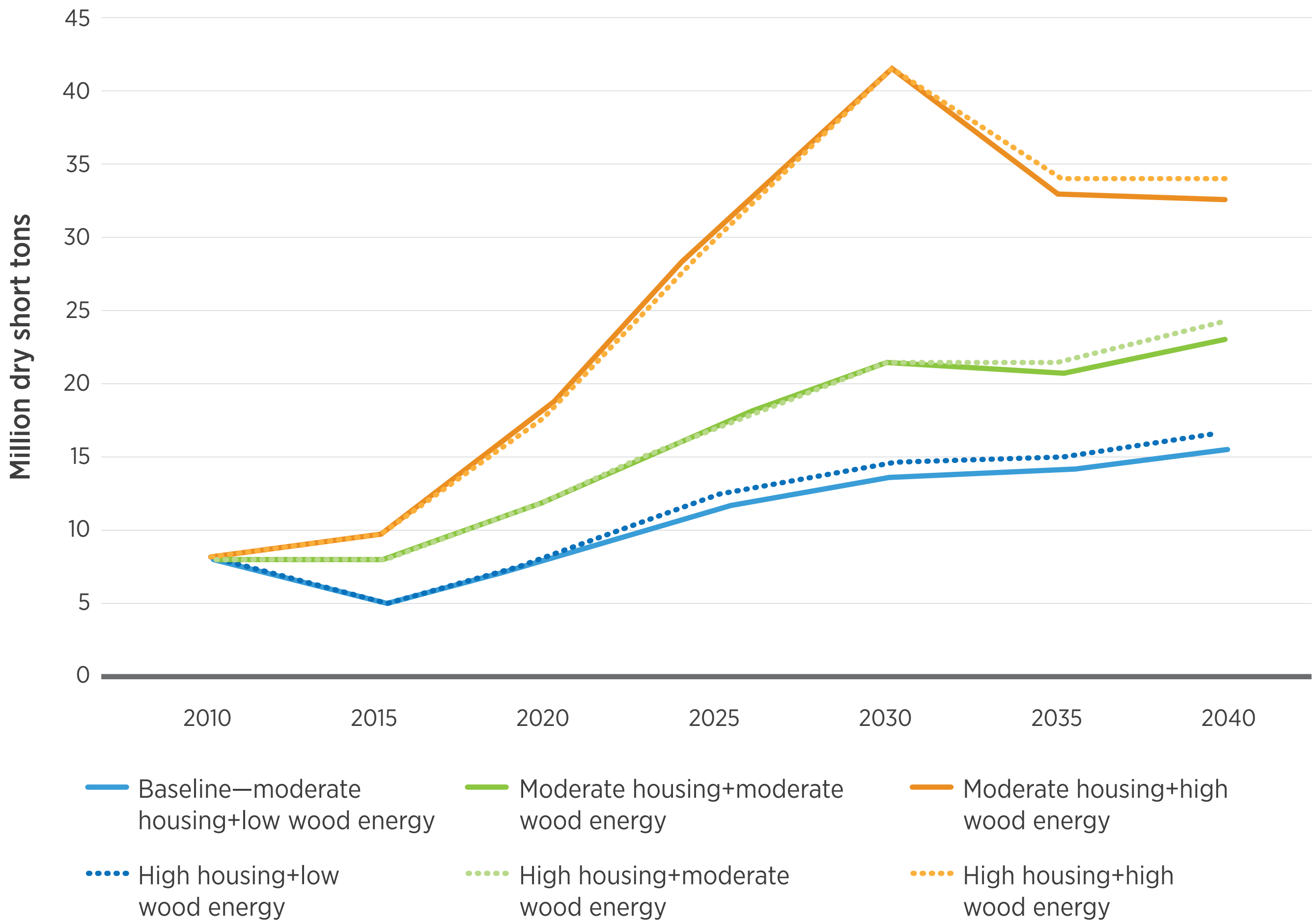


Figure 3.11 | Projected U.S. small roundwood production for wood energy use by scenario, 2015–2040

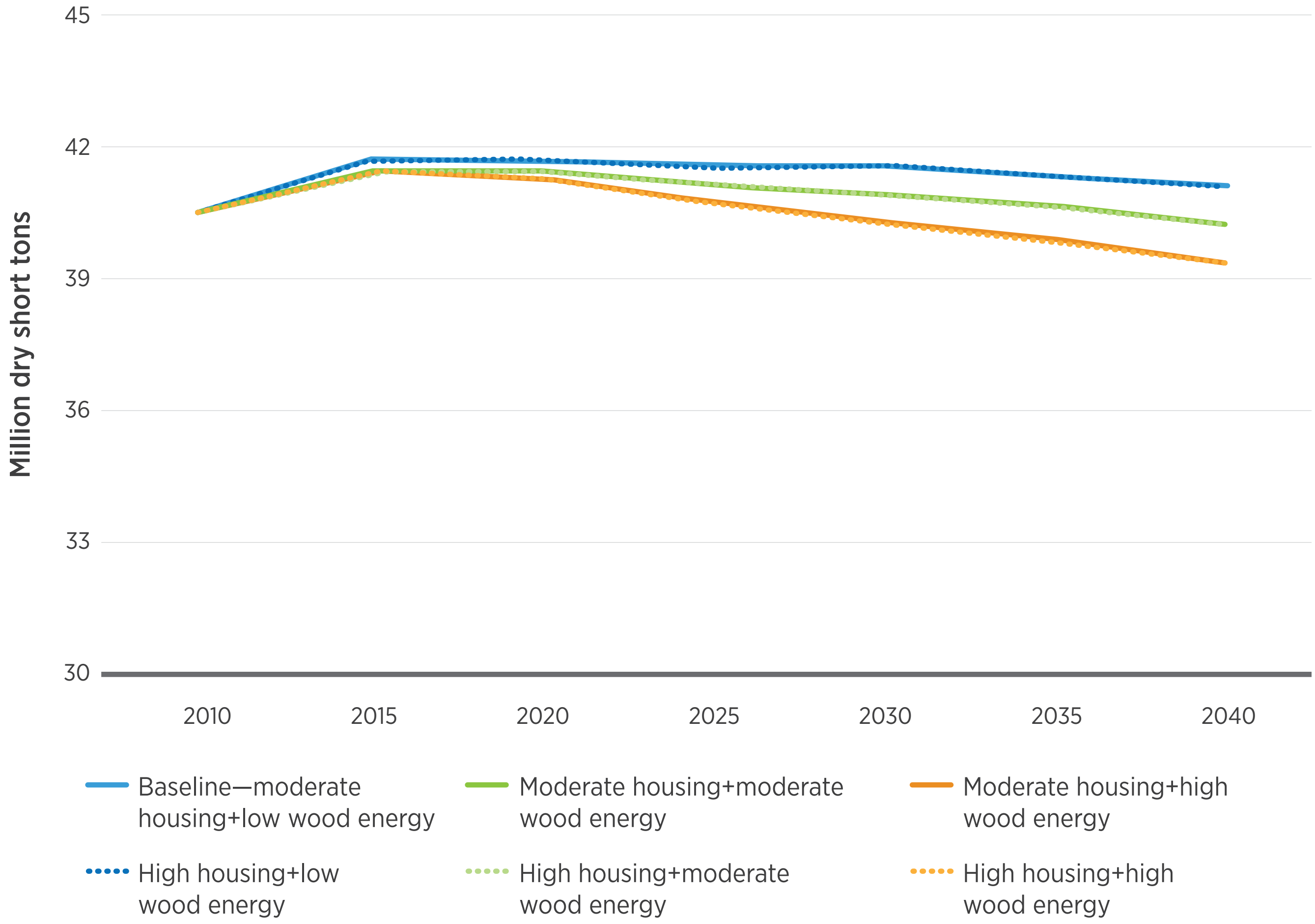


In addition to the shift of small roundwood to wood energy, the higher wood energy demand scenarios use higher amounts of logging residues as feedstocks. As the demand for wood energy and the supply of fuel feedstock increase, the proportion of feedstock from logging residues increases. This increase is due to relatively lower costs for logging residue versus other feedstocks at higher levels of demand (fig. 3.13). In 2015, few logging residues are used for wood energy because of the (relatively) high cost of procurement. As demand increases, however, logging residues begin to fulfill more of the demand for wood biomass feedstocks. By 2040, logging residue inputs to wood energy are greater than the small roundwood inputs in both the moderate and high wood energy demand scenarios.

3.3.5 Summary

This study investigates the impacts on the U.S. forest sector of scenarios projecting moderate and high growth in U.S. single family housing starts, and low

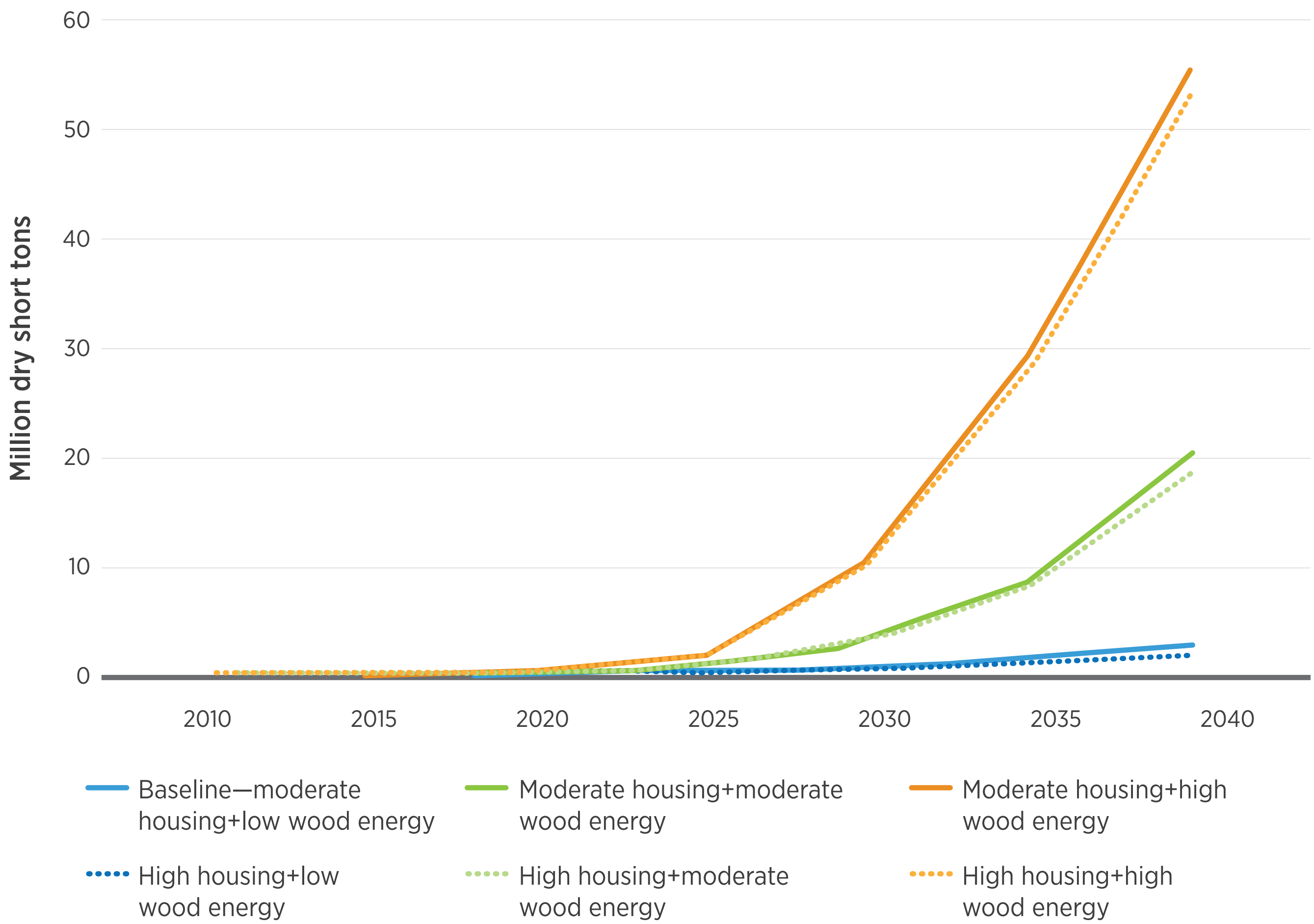
Figure 3.12 | Projected U.S. paper and paperboard production by scenario, 2015–2040



Note: Vertical axis does not extend to 0 to highlight scenario differences.

and moderate growth in wood energy demands. In addition, we model a high wood energy demand scenario, coupled with a timber supply response that involves increased growth rates on pine plantations in the South, presumably spurred by the increased wood energy demands. The low wood energy demand scenario reflects an assumed increase in wood energy, linked historically to increases in GDP, and results in an increase in demand of 53 million dry short tons by 2040. Moderate and high wood energy demand scenarios (an additional 125 and 250 million dry short tons, respectively, over the baseline in 2040) represents potential demand that could occur because of increases in either domestic or international use of wood for energy.

Figure 3.13 | Projected U.S. logging residue use for wood energy by scenario, 2015–2040



The USFPM/GFPM+SRTS modeling framework was designed to allow for competition in wood product markets. The results of the projections show tradeoffs among fuel feedstock sources (logging residues, fuelwood, mill residues, and small roundwood) and between end uses (wood energy and conventional wood products). The analysis focuses on understanding the impacts of a combination of housing starts, wood energy demands, and plantation growth on timber harvest, timber growth and inventory, timber prices, and competition for wood biomass between conventional uses (e.g., production of lumber, panels, papers) and wood energy use.

The results show that the U.S. timber harvest increases in response to increased housing starts and increased wood energy demand, affecting product prices, biological forest growth, and increased pine plantation area in the South. Because of assumed relationships between increasing softwood sawtimber prices and timberland area in the South, all scenarios show timberland area changing as sawtimber prices change, offsetting some of the inventory loss due to increased harvests over the baseline. The demand for wood energy competes with the demand for wood for conventional products such as lumber, panels, and paper. Increased wood energy demand coupled with increased housing demand raises both fuel feedstock prices and small roundwood prices, making both recovery of logging residues and the diversion of mill fiber residues and roundwood pulpwood to wood energy use economically feasible. Most of the logging residues and small roundwood needed to meet the increased wood energy demand come from the South. Because of increased competition for small roundwood, the projected production of paper and paperboard declines more under the moderate and higher wood energy demand scenarios than under the low wood energy demand scenario (baseline).

The USFPM/GFPM+SRTS modeling framework uses the latest available information on timber productivity and costs of production for each of the wood inputs and assumes that current market structures will continue through 2040. Most of the structural relationships are based on historical relationships as derived through statistical modeling. Thus, the outcomes of the projections provide consistent and reproducible results that can be used to compare policy alternatives or "what if" scenarios, but we do not assess the probability that any of these scenarios would occur.

3.4 Biomass from U.S. Timberland Using the Forest Sustainable and Economic Analysis Model

3.4.1 Introduction

The United States has extensive forest resources. These resources provide a number of benefits, one of which is wood fiber. This chapter provides estimates of forest biomass available at different prices from timberland in the contiguous United States. The biomass cost estimates incorporate the costs of stumpage, harvest, collection, and chipping. They represent biomass available at the roadside and its corresponding breakeven price.[3] Supply curves are developed for each county in the contiguous United States. In this analysis, biomass from forests includes forest residues from integrated forest operations and whole-tree biomass, in which both commercial and noncommercial trees are harvested for biomass. In both cases, harvests are only on forestland classified as timberland.

There are about 750 million acres of forested land in the United States. About 2/3 of these lands are classified as timberlands[4] (Oswalt et al. 2014; USDA Forest Service 2007; Smith 2014; Miles 2015; Perry 2014; Pugh 2014). According to Smith et al. (2009), the timber volume on timberland has increased by 50% since the 1950s. Most U.S. forestland is owned privately (58%) with private ownership dominating the North (74%) and South (87%). Private forests provide most (90%) of the wood and paper products. After harvest, most forestland regenerates naturally. However, 13% of the timberland is planted, mostly in the South (72%); 25% of the planted acres are located in the Pacific Northwest (Oswalt et al. 2014). These forestlands, in all likelihood, will contribute cellulosic feedstocks in the future. Timber resources are projected to be abundant enough to meet demands, especially if efficiency gains in harvesting and conversion technology continue. In a recent analysis conducted by the Forest Service (USDA Forest Service 2012), increased competition for land resources occurs in the RPA scenario; and the highest increase is in wood biomass use for energy (Bentley and Steppleton 2012).

Forest biomass is a potential biomass feedstock consisting of a combination of sources:

- Removal of a portion of logging residue that is currently generated during the harvesting of timberlands for conventional forest products

[3] Roadside price is the price a buyer pays for wood chips at a roadside in the forest before any transport and preprocessing to the end-use location.

[4] Timberland is defined as lands capable of producing 20 ft^3 per year per acre and not legally reserved from timber harvest.

- Removal of excess biomass from fuel treatment operations (reducing biomass to help forests increase fire resistance) and thinning operations designed to reduce risks and losses from catastrophic fires and improve forest health
- Whole tree removal from primarily smaller-diameter merchantable stands (i.e., pulpwood and/or small-diameter stands).

It is projected that access to biomass will come from integrated harvesting operations that provide sawlogs and pulpwood to meet existing market demand and provide biomass for energy and bioproducts. Three potential resources are not considered in this chapter (and are instead considered in chapter 5):

- Other removal residue that occurs when wood is cut during the conversion of timberland to nonforest uses and during thinning of "other forestland"[5] (non-timberland) that is conducted to improve forest health by removing excess biomass on low-productivity land
- Forest residues, mill wastes, and so forth created once the trees leave the landing
- Urban wood waste.

The processing of sawlogs, pulpwood, and veneer logs into conventional forest products generates significant quantities of bark, mill residues (coarse and fine wood), and pulping liquors, along with fuelwood used primarily in the residential and commercial sectors for space heating and by some electric utilities for power generation. These resources are not considered in this chapter.

3.4.2 Methods

The linear programming model ForSEAM was constructed to estimate forestland production over time, and its capacity to produce not only traditional forest products but also products to meet biomass feedstock demands. The model, based on earlier work (He et al. 2014), can be used to assess the quantity of biomass that might be available as biomass feedstocks and at what marginal cost. It assumes that projected traditional timber demands will be met and estimates costs, land use, and competition between lands. A cost minimization model requires both price and cost information to produce end products. It has an objective function of minimizing the total costs (harvest costs and other costs) under a production target goal in addition to land, growth, and other constraints. The cost minimization model requires harvesting and stumpage costs for removing timber products. No product price information is needed for the model; however, a production volume is required.

For each of the six scenarios, ForSEAM was run at demand levels ranging from 1 million dry tons to approximately 185 million dry tons in 1-million-dry-ton increments. The large volume of data precludes us from summarizing the results of every demand level. Instead, we selected the highest demand run that had a solution in all years of the simulation to provide a representative summary of production and harvested acreage. These were used to develop the supply curves of available biomass. Table 3.7 summarizes the demand level chosen for each scenario.

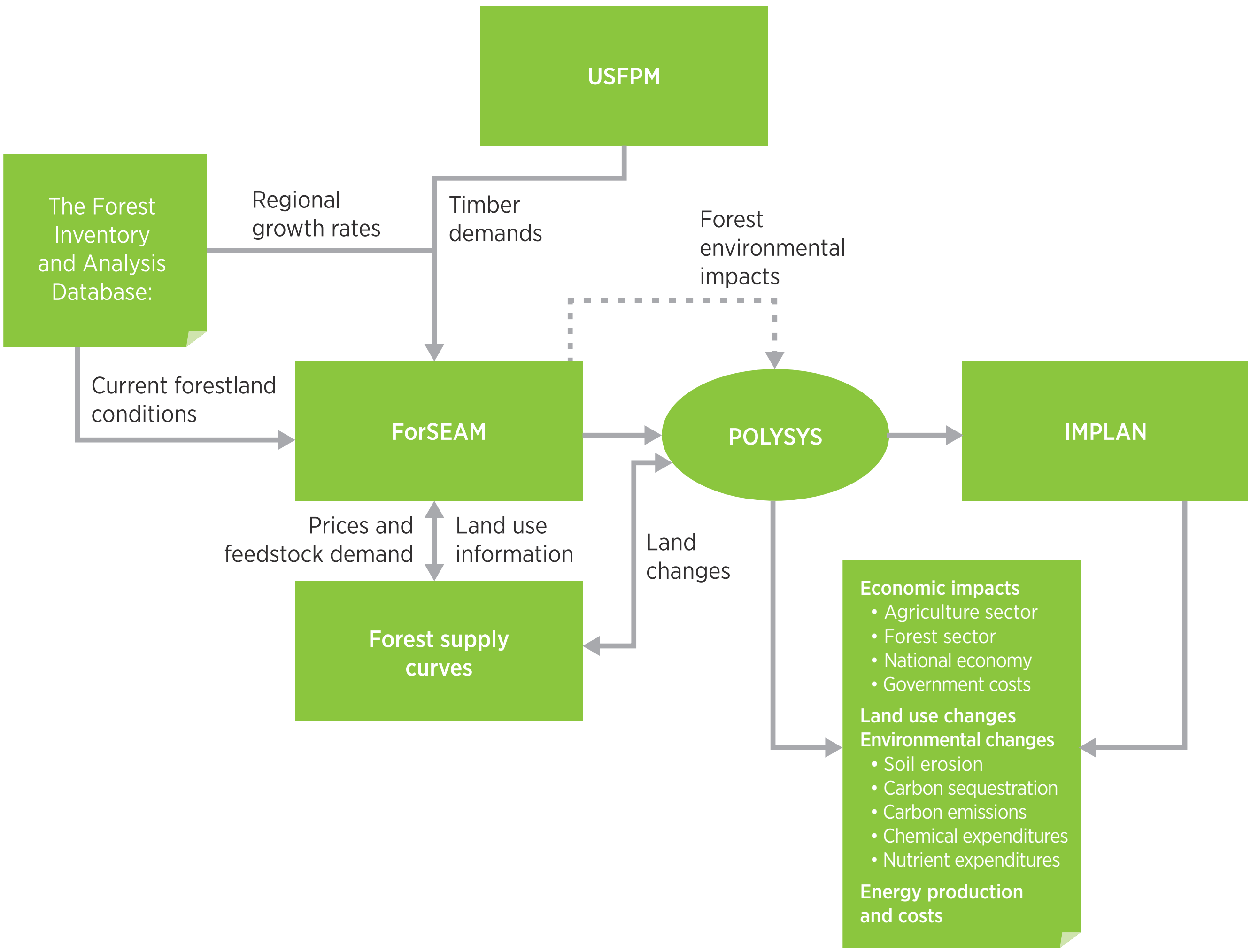
Table 3.7 | Supply Curve Demands

Scenario	Demand levels simulated	Selected demand level
	Million dry tons	
ML (baseline)	1 to 187	116
MM	1 to 184	93
MH	1 to 184	82
HL	1 to 187	117
HM	1 to 184	94
HH	1 to 184	83
HM	1 to 184	94

[5] See text box 3.1 to understand forestlands vs. timberland in the USDA Forest Service FIA database.

The remainder of this section describes the cost minimization model ForSEAM. The system of models incorporates the USFPM, ForSEAM, POLYSYS, and IMPLAN (IMpact analysis for PLANning). USFPM is used to determine what traditional forest product supplies will be required for the scenario. ForSEAM provides biomass demand and supply components from conterminous U.S. timberland (excluding Alaska and Hawaii). These supply curves can be used either in a stand-alone manner or within POLYSYS (De La Torre Ugarte and Ray 2000). POLYSYS output can then be used to determine the impacts on land use, farm sector income, and environmental indicators for soil erosion, carbon, fertilization application, and chemical application. In addition, it can be used in IMPLAN, an input-output model that estimates the impacts to the economy (fig. 3.14).

Figure 3.14 | ForSEAM modeling system



3.4.3 Mathematical Model

ForSEAM minimizes costs, subject to numerous constraints. As constructed, ForSEAM has about 30,000 decision variables and 17 constraints with a density of more than 189,000 single equations. The model minimizes the costs of traditional harvest (*X,X CT L*), harvest of whole trees for biomass (*Z*), and logging residue collection (*U*) (Eq. [1]). The choice variables (*X,X CT L, Z, U*) defined in table 3.8, along with the indexes defined in table 3.9, reflect location (*i*), stand type (*j*), average stand tree diameter (*k*), slope of the land the stand is on (*m*), method used for harvest (*c*), type of product that will be produced (*p*), and time of harvest (*t*). Every time the choice variable enters the solution, an acre of land is used.

$$COST_{X,XCT\,L,Z,U\,(t)} = \Sigma_{i=1}^{305}\Sigma_{j=1}^{5}\Sigma_{k=1}^{2}\Sigma_{m=1}^{2}\Sigma_{c=1}^{2}\left[\Sigma_{o=1}^{2} X_{i,j,k,o,m,c,p,t}\,\alpha_{i,j,k,c,t}\left(\mathrm{CL}_{i,j,o,m,c} + SC_{i,j,k}\right) + XCTL_{i,j,k,o=1,m,c,p,t}\,\alpha_{i,j,k,c,t}\left(\mathrm{CTL}_{i,j,m,c} + SC_{i,j,k}\right)\right] + \Sigma_{i=1}^{305}\Sigma_{j=1}^{5}\Sigma_{k=2}^{3}\Sigma_{m=1}^{2}\Sigma_{c=1}^{2}\Sigma_{o=1}^{2}\left[\mathrm{Z}_{i,j,k,o,m,c,t}\,\beta_{i,j,k,c,t}\left(\mathrm{CW}_{i,j,o,m,c} + SC_{i,j,k}\right)\right] + \Sigma_{i=1}^{305}\Sigma_{j=1}^{5}\Sigma_{k=1}^{2}\Sigma_{m=1}^{2}\Sigma_{c=1}^{2}\Sigma_{o=1}^{2}\left[\mathrm{U}_{i,j,k,o,m,c,t}\,\theta_{i,j,k,c,t}\left(\mathrm{CR}_{i,j,m,c} + SCR_{i,j,k}\right)\right]$$

Table 3.8 | Descriptions of the ForSEAM Decision Variables and Coefficients

Variables and coefficients	Description
Decision variables	
$XCTL_{i,j,k,o,m,c,p,t}$	Acres of timber land harvested using cut-to-length logging option in POLYSYS region i for tree species j, stand diameter class k = 2, land slope m, and cutting option c and conventional wood product *p* at time period *t*; only on private land o = 1; there is no cut-to-length on federal timber land
$X_{i,j,k,o,m,c,p,t}$	Acres of timber land harvested to meet conventional demand for all *i, j, t, o, m, c, k* = 1, 2
$Z_{i,j,k,o,m,c,p,t}$	Acres of class 2 and class 3 whole trees harvested to meet woody biomass demand, for all *i, j, t, o, m, c, k* = 2, 3
$U_{i,j,k,o,m,c,t}$	Acres of logging residue harvested to meet woody biomass demand for all *i, j, t, o, m, c, k* = 1, 2
Right-handed sides	
$A_{i,j,k,o,m,t}$	Available acreage at time *t* for all *i, j, k, o, m*, and *t* (*acres*)
$\bar{G}_{i,j,k,o,m}$	Growth (*cubic feet*) for all *i, j, k, o*, and *m*
B_t	Woody biomass targets (*dry tons*) in period *t*
$D_{s,k,p,t}$	State conventional demand for sawlogs and pulpwood for all *p, t, k* = 1, 2 (*cubic feet*)
$A_{t,j,k,o,m}$	Initial available timber acres in POLYSYS region *i* for tree species *j* and stand diameter class *k* on timber land *o* with slope *m*
Coefficients	
$CR_{i,j,o,m,c}$	Logging residue harvesting costs for thinned (*partial cut*) trees and clear-cut trees in POLYSYS region *i* for tree species *j*, ownership *o*, land slope *m*, and cutting option *c* (*$ per acre)*
$CL_{i,j,o,m,c}$	Log harvesting costs for thinned (*partial cut*) and clear-cut trees (*$ per dry ton*) in POLYSYS region *i* for tree species *j*, ownership *o*, land slope *m*, and cutting option *c* (*$ per acre*)
$CTL_{i,j,o,m,c}$	Logging harvest costs for cut-to-length (*$ per dry ton*) at POLYSYS region *i* for tree species *j*, ownership *o*, land slope *m*, and cutting option *c* (*$ per acre*)
$CW_{i,j,o,m,c}$	Whole tree harvesting costs for thinned (*partial cut*) and clear-cut trees (*$ per dry ton*) as developed and explained in preceding section in POLYSYS region *i* for tree species *j*, ownership *o*, land slope *m*, and cutting option *c* (*$ per acre*)
$SC_{i,j,k}$	Stumpage costs (*$ per dry ton*) of logs in POLYSYS region *i* for tree species *j*, and stand diameter class *k* (*$ per acre*)

Variables and coefficients	Description
Decision variables	
$SCR_{i,j,k}$	Stumpage costs (*$ per dry ton*) of logging residues in POLYSYS region *i* for tree species *j*, and stand diameter class *k* (*$ per acre*)
$\omega_{i,j,k}$	Percentage of timberland that can be harvested at each period in region *i* of stand species *j* and stand diameter class *k*
$\alpha_{i,j,k,c,t}$	Log yield 2015 in POLYSYS region *i* for tree species *j*, stand diameter class *k*, cutting option *c*, and time *t* (*dry tons per acre*)
$\beta_{i,j,k,c,t}$	Whole tree yield in POLYSYS region *i* for tree species *j*, stand diameter class *k*, cutting option *c*, and time *t* (*dry tons per acre*)
$\theta_{i,j,k,c,t}$	Logging residue yield in POLYSYS region *i* for tree species *j*, stand diameter class *k*, cutting option *c*, and time *t* (*dry tons per acre*)
$\Upsilon_{i,j}$	Ratio of clear cut to thinning
$\vartheta_{i,j,k,o,m}$	Annual growth in POLYSYS region *i* for tree species *j*, stand diameter class *k*, ownership *o*, land slope *m* (*dry tons per acre*)
$\upsilon_{i,j,kk,k,t}$	The inter-period stand class determination matrix from class 2 to class 1 or class 3 to class 2 at time *t*
$u_{i,j,n}$	The inter-period stand class determination matrix from class 0 (*replantation or regeneration of tree*) to class 3 at age *n* for each region *i* and tree species *j*

Table 3.9 | Indexes Used in the Model

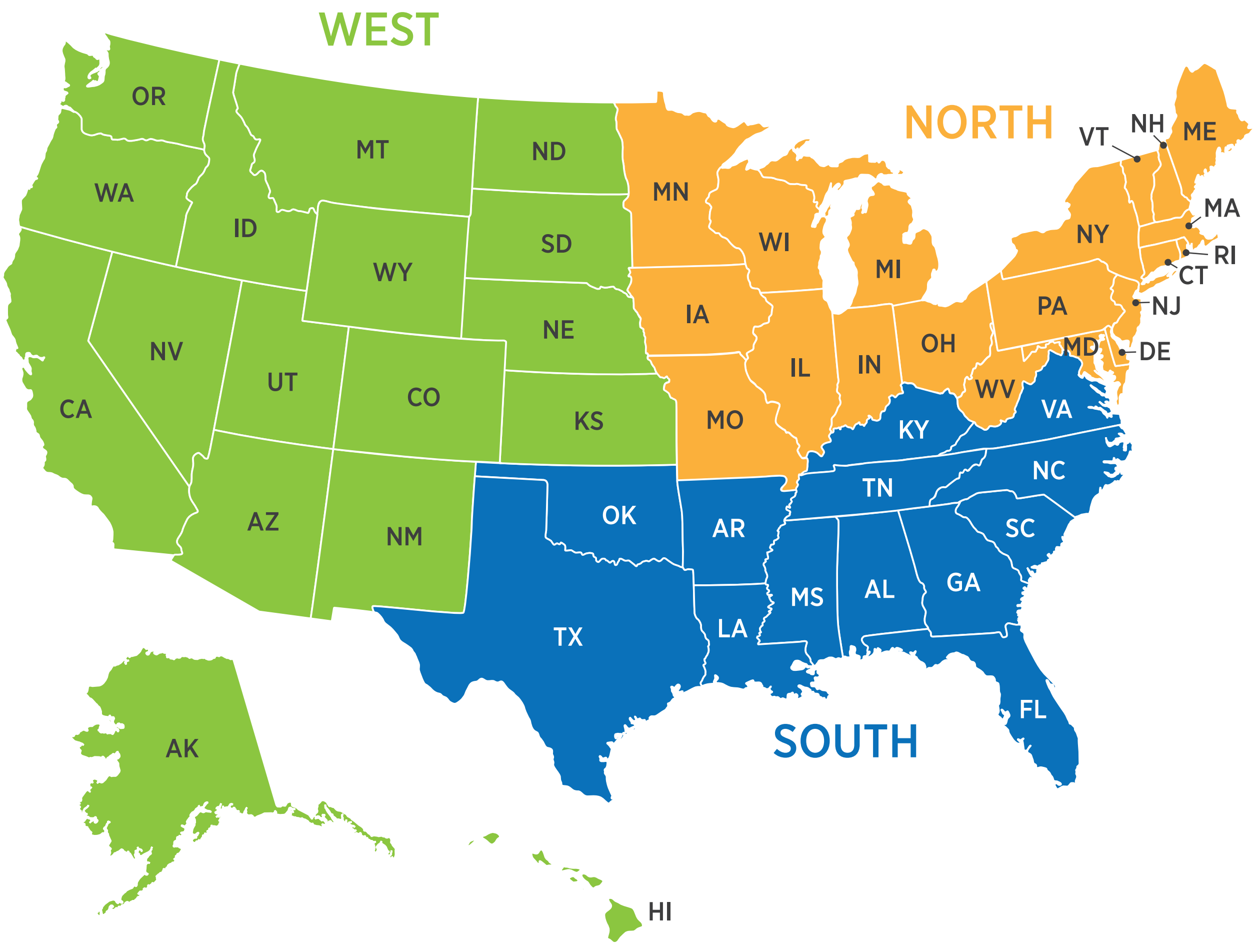
Index	Description	Magnitude
c	Cut options	*c* = 1, 2; where 1 = thinning (partial cut) and 2 = clear cut
f	Wood type	*f* = 1, 2; where 1 = hardwood and 2 = softwood
i	POLYSYS regions	*i* = 1, ... , 305
s	States	*i* = 1, ... , 48; 48 states
si	POLYSYS regions in each state	
j	Stand type	*j* = 1, ... , 5; where 1 = upper land hardwood, 2 = lowland hardwood, 3 = natural softwood, 4 = planted softwood, 5 = mixed wood
k	Stand class	*k* = 1, 2, 3; class 1 has a diameter >11 in. for hardwood and >9 in. cor softwood, class 2 has a diameter between 5 and 11 in. for hardwood and 5 and 9 in. for softwood, and class 3 has a diameter of <5 in.
o	Timberland ownership	*O* = 1, 2; where 1 = private, 2 = federal
m	Slope of land	*m* = 1, 2; where 1 = private, 2 = federal
n	The stand age calculated only for replanted or regenerated trees	*n* = 1, ... , 26
p	Conventional wood products	*p* = 1, 2; where 1 = slope $\leq$40% (LE40); 2 = slope $\geq$40% (GT40)
t	Model period	*t* = 2014, ... , 2040

The objective function is subject to a set of constraints (see equations in appendix B). The timberland constraints limit harvested timberland for conventional wood to the maximum percentage of the existing volume of class 1 land that can be harvested in any one period (Eq. [A.1]). Equations (A.2) and (A.3) constrain the harvest intensity to the existing volume of classes 2 and 3. The third timberland constraint (Eq. [A.4]) requires cut-to-length harvest acres to equal full-tree harvesting acres in the North Central region and Inland West region. The final timberland constraint (Eq. [A.5]) restricts logging residue removal (*U*) to those lands that provided traditional products (*X*). Regional constraints on thinning and clear-cut ratios are specified in Eq. (A.6).

Growth is also restricted (Eq. [A.7]). The volume of trees removed must be less than the 2014 base year harvest plus the annual growth that occurs within the state on the remaining stands. Over time, stands change. Movement of timber from small-diameter wood to pulp and sawtimber material is tracked by determining movement from one stand diameter class to another (Inter-Period Movement) through six equations ([A.8]–[A.13]).

Cost minimization models are normally driven by demand, and ForSEAM is no exception. Equations (A.14)–(A.17) require production to meet the projected demands for sawlogs and pulpwood. These demand levels are projected by USFPM for the northern, southern, and western parts of the United States (fig. 3.15). Weights are developed based on inventory to develop state estimates of demand for these traditional wood products. Equation (A.18) represents the woody biomass target for biomass feedstocks. The right hand side B_t is a national quantity for time t, and the model can iterate this variable, moving up to larger and larger supplies; or it can use a pre-specified value as projected by USFPM and the scenario being analyzed.

Table 3.15 | Three USFPM supply and production regions: North, South, and West



Source: Data from Ince et al. (2011a).

Model Solution

The model is solved in two steps:

Step 1: The model is solved for the first time period *t* (*t* = 1). In this model, neither the growth constraints (Eq. [A.7]) nor the woody biomass supply target (Eq. [A.18]) is incorporated into the model structure. The solution of *X* and *XCTL* is then used to determine the RHS of growth constraints.

$$\bar{G}_{i,j,k,o,m} = \sum_{c=1}^{2} (X^*_{i,j,k,o,m,c,p,t} + X\,CT\,L^*_{i,j,k,o=1,m,c,p,t})(\alpha_{i,j,k,o,m,c,t} + \beta_{i,j,k,o,m,c,t})$$

$\forall$ all $i,j,m,k = 1,2, t = 1$

Step 2: Then the model is solved with objective function and all the constraints. The right-hand side of Eq. (A.18) will be changed from 0 to 185 million dry tons with a 1 million ton increment to simulate the shadow values (λ_t). These shadow values hence will be used to plot the supply curve of woody biomass.

Assumptions and Input Data

This section provides in more detail all the assumptions made to use ForSEAM and the sources and levels of input data and parameters.

Geographic Definition (i)

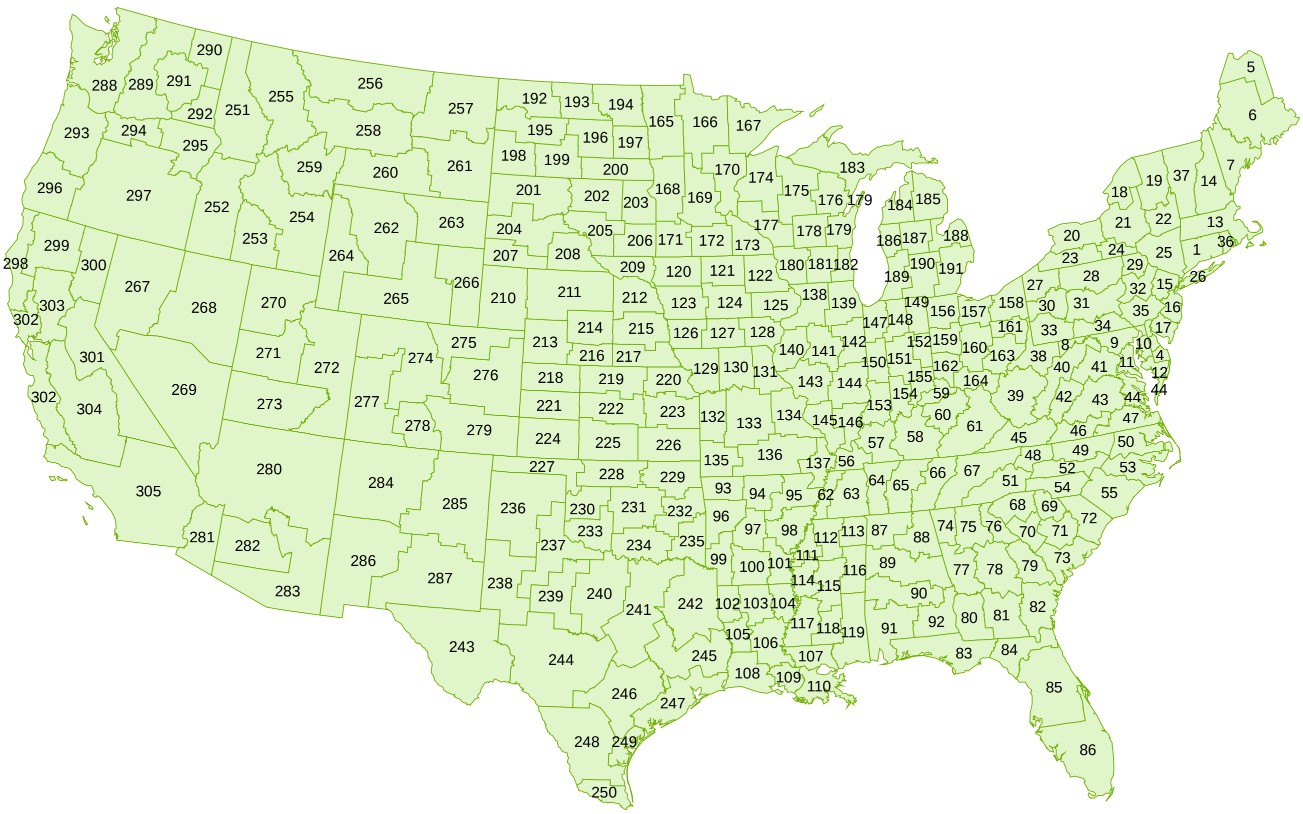
The USFPM projections are reported for three macro-regions of the United States: West, North, and South (fig. 3.15). Other data and parameters are collected and calculated for five forest regions: Northeast, South, North Central, Inland West, and Pacific Northwest (see table 3.5 for a list of states in forest regions and table 3.10 for species listings for those regions). ForSEAM is modeled and solved for 305 POLYSYS regions (fig. 3.16), which are also crop reporting districts.

Table 3.10 | Forest Regions and Forest Types

Region	Forest types
Northeast	White-Red-Jack Pine; Spruce-Fir; Maple-Beech-Birch; Oak-Hickory; Oak-Pine
South	Longleaf-Slash Pine; Loblolly-Shortleaf Pine; Oak-Pine; Oak-Hickory; Oak-Gum-Cypress
North Central	Aspen-Birch; Maple-Beech-Birch; Elm-Ash-Cottonwood; Oak-Hickory; Spruce-Fir; White-Red-Jack Pine
Inland West	Lodgepole Pine; Ponderosa Pine; Fir-Spruce; Western Hardwoods (Aspen); Chaparral; Pinyon-Juniper; Larch; Western White Pine
Pacific Northwest	Douglas Fir; Hemlock-Sitka spruce; Ponderosa Pine; Fir-Spruce; Redwood; Western Hardwoods (Scrub Oak, Alder)

Note: Forest types were identified from a map available at USDA Forest Service, Forest Inventory and Analysis National Program, http://www.fia.fs.fed.us/library/maps/.

Figure 3.16 | The 305 POLYSYS regions



Stand Species (j)

There are five stand species in ForSEAM: upland hardwood (UHW), lowland hardwood (LHW), natural softwood (NS), planted softwood (PS), and mixed wood (MIXED).

Stand Size (k)

There are three stand diameter sizes in the model:

- **Class 1:** Stands with dbh >11 inches for hardwood and >9 inches for softwood
- **Class 2:** Stands with dbh between 5 inches and 11 inches for hardwood and dbh between 5 inches and 9 inches for softwood
- **Class 3:** Stands with dbh <5 inches.

Timber Products (p)

There are five timber products from the USFPM projection (Ince and Nepal 2012; Skog 2015). The USFPM products, the corresponding ForSEAM products, and the stand sizes are presented in figure 3.17. USFPM projects demand for products including softwood sawlogs, softwood pulpwood, hardwood sawlogs, hardwood pulpwood, and other industrial roundwood. Among these products, the demands for hardwood sawlogs and other industrial roundwood are aggregated to hardwood sawlogs in ForSEAM. The fuelwood roundwood harvest is disaggregated to softwood fuelwood and hardwood fuelwood, using a ratio calculated with data from Howard, Quevedo, and Kramp (2009). In ForSEAM, sawlogs originate from class 1 stand size trees. Pulpwood originates-from trees in both class 1 and class 2 stand sizes. Biomass feedstocks are from trees in class 2 and class 3 stand sizes. The volume of UHW, LHW, and 37.5% of MIXED stand species is used in the model for hardwood timber products. The volume of NS, PS, and 62.5% of MIXED stand species is used for softwood timber products. The USFPM regional and national demand scenarios for 5-year intervals are displayed in appendix B.

Logging Methods and Options

There are four types of logging methods: (1) full-tree clear cut, (2) full-tree thinning, (3) cut-to-length clear cut, and (4) cut-to-length thinning. Descriptions of these harvest options are presented in table 3.11. The full-tree method can use the entire tree, including branches and tops. The cut-to-length method harvests logs only, leaving logging residue on the field. For both logging methods, the harvest can be clear cut or thinning. Clear cutting removes all the standing trees in a selected area. Thinning removes part of the standing trees in a selected area.

All stand classes can be harvested using full-tree clear cutting. Only class 2 stands may be harvested by clear cutting or thinning. Cut-to-length logging is used only for softwood timber in the POLYSYS North Central and Inland West regions of the country for class 1 and class 2 stands.

A proportion for clear-cut and thinning areas was applied in the West, South, and North so that a certain amount of production was guaranteed from thinning. This is because the benefits of thinning, such as increased yields and revenue, are hard to measure and capture at such a scale in the current model. With only stumpage costs and harvesting costs, the thinning option has fewer disadvantages than clear cutting because of the lower yield level per acre of timberland. Figure 3.18 shows the proportion of timberland harvested using clear cutting and thinnings (partial cutting). In the current model, we use the proportion that was used in 2006–2011. The clear-cut portion is 42%, 28%, and 10% for the West, South, and North, respectively.

Figure 3.17 | Conventional timber products in USFPM and ForSEAM

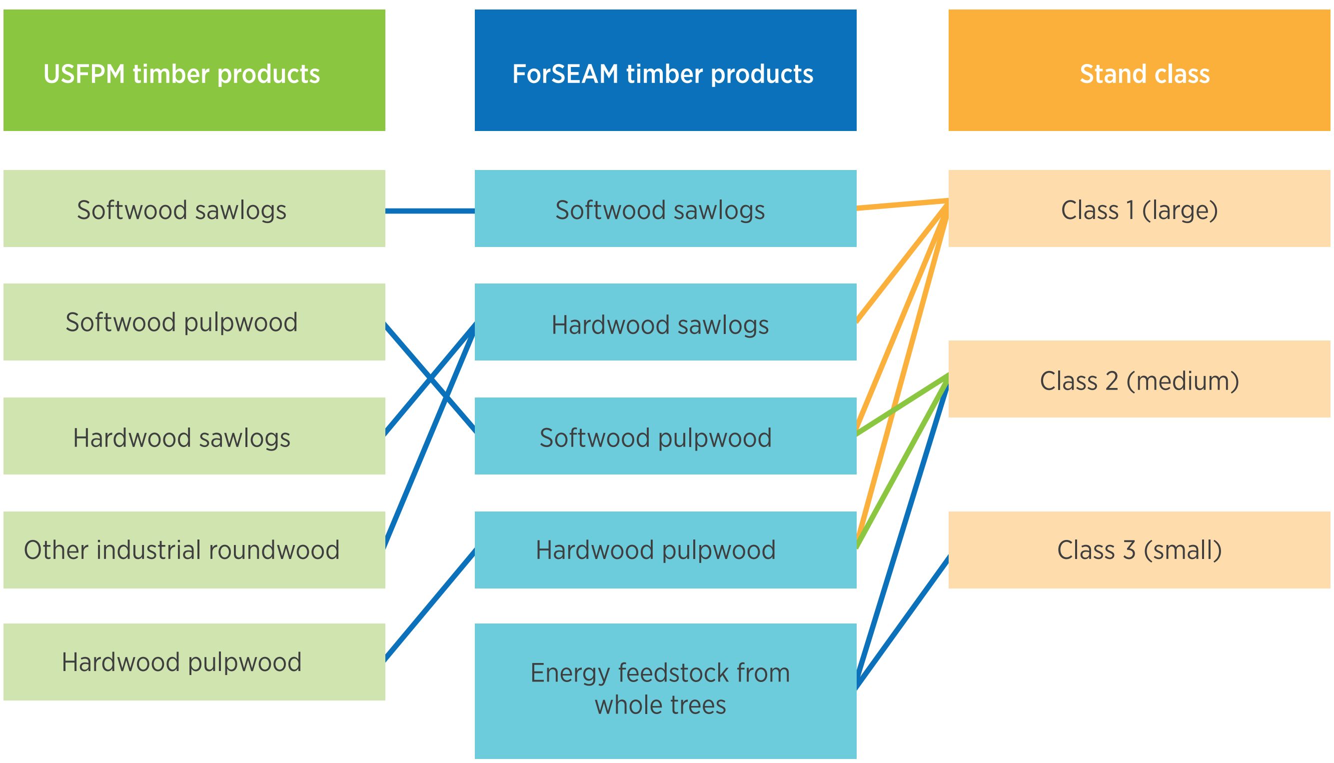
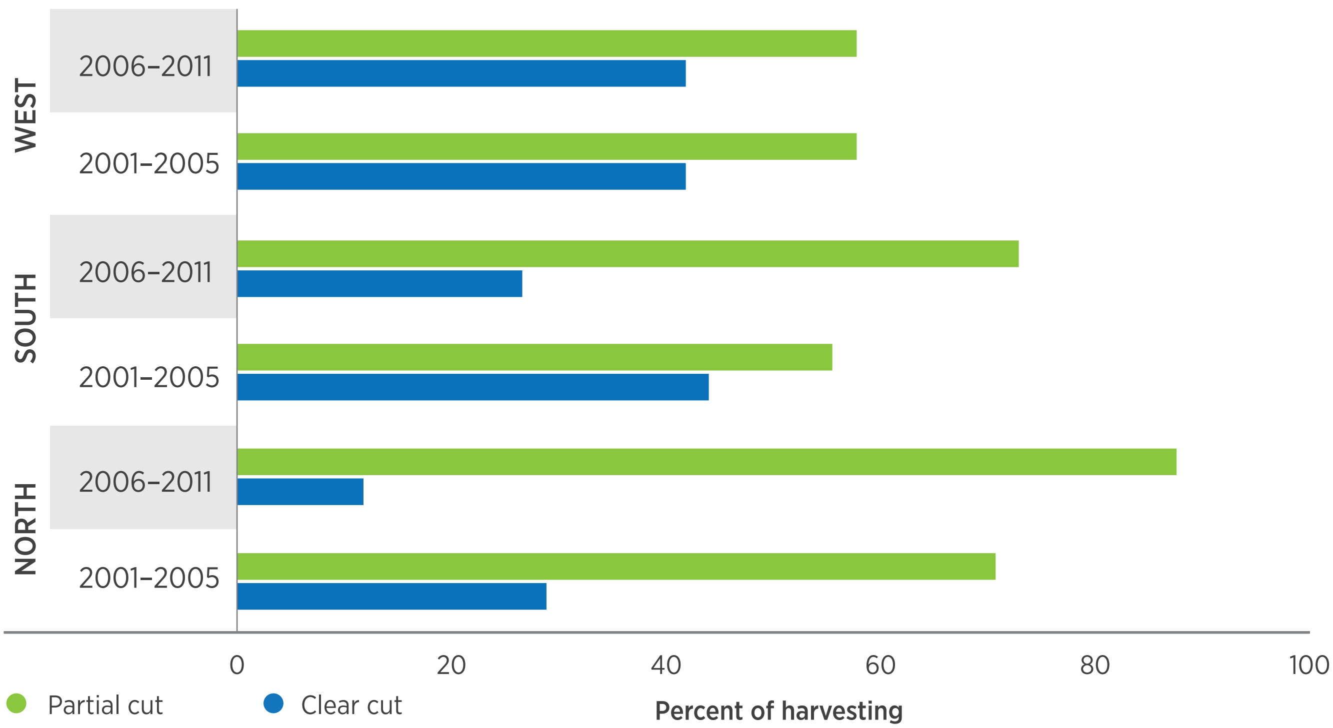


Table 3.11 | Logging Methods and Options

	Clear cut	Thinning
Full tree	1. Full-tree clear cut • Removes all the standing trees in a selected area • The entire tree can be used, including branches and tops • Class 1, class 2, and class 3 stands • All regions.	2. Full-tree thinning • Partially removes standing trees in a selected area • The entire tree can be used, including branches and tops • Class 2 stands only • All regions.
Cut-to-length	3. Cut-to-length clear cut (softwoods only) • Removes all the standing trees in a selected area • Only logs can be used, and branches and tops are left on the field • Class 1 stands only • North Central and Inland West regions only.	4. Cut-to-length thinning (softwoods only) • Partially removes standing trees in a selected area • Only logs can be used, and branches and tops are left on the field • Class 2 stands only • North Central and Inland West regions only.

Figure 3.18 | Proportion of timberland harvested in the United States by method of harvest for 2001–2005 and 2006–2011



Source: USDA Forest Service (2015b).

Timberland Area (A) and Slope (m)

There are 514 million acres of timberland in the United States (FAZ 2015), including Alaska and Hawaii. Timberland is defined as available forestland that is producing or is capable of producing crops of industrial wood. Areas qualifying as timberland have the capability to produce more than 20 ft^3 per acre annually of industrial wood in natural stands on which harvesting is not prohibited. Currently inaccessible and inoperable areas are included. ForSEAM takes into account timberland in the 48 conterminous states that is privately or federally owned and no more than a half mile from the existing road system. Data from the FIA database (2015) indicate that there are about 300 million acres of privately owned timberland and another approximately 87 million acres of federal lands (see table 3.12 and table 3.13). A total of 386 million acres of federal and private timberlands are within 0.5 miles of a road and are the available acres in the ForSEAM model under the stated assumptions; but of course, only a few million acres are harvested annually. The assumption is that timber and biomass could be harvested within that distance to a road without any road-building. No road building is a sustainability criterion built into the model that was also used in the 2011 *BT2*. Therefore, the available biomass is severely limited by several assumptions of timberland area and access, such as distance to road and land slope.

Land slope is categorized into two groups (table 3.14): (1) slope ≤40% (LE40) and (2) slope >40% (GT40). Not all stand species on timberland in slope category GT40 are available for harvesting in the model. As table 3.14 indicates, no trees in the Northeast, South, North Central, and Inland West regions in category GT40 are harvested, as the assumption is the lack of cable systems in these regions. The model assumes that only in the Pacific Northwest can trees be harvested on both LE40 and GT40 timberland; again, the assumption is for conventional timber products only, as the biomass is not extracted with cable systems on slopes in category GT40.

Table 3.12 | Acres Included in the Model by Stand Class, Slope, Ownership, and Species Type

Class	Slope	Ownership	LHW	UHW	NP	PP	MIXED	Total
			Million acres					
1	LE40	Private	35.57	59.54	29.76	14.47	9.82	149.16
		Federal	6.41	9.98	25.56	2.84	1.96	46.75
	GT40	Private	2.77	10.24	3.61	0.70	0.48	17.80
		Federal	0.66	2.19	8.41	0.72	0.10	12.07
2	LE40	Private	17.08	25.39	10.09	15.24	4.86	72.67
		Federal	2.63	5.07	4.27	1.46	0.71	14.14
	GT40	Private	0.46	2.15	0.54	0.43	0.21	3.80
		Federal	0.13	0.62	0.70	0.21	0.04	1.71
3	LE40	Private	10.75	19.52	8.60	9.32	5.28	53.48
		Federal	1.57	3.60	4.37	0.82	0.55	10.91
	GT40	Private	0.34	0.76	0.64	0.47	0.03	2.25
		Federal	0.08	0.34	0.80	0.18		1.40
Total			**78.45**	**139.40**	**97.37**	**46.87**	**24.05**	**386.14**

Note: LE40 is slope ≤40%; GT40 is slope > 40%.

Table 3.13 | Acres in the Three USFPM Regions (see regions in fig. 3.15)

Region	Diameter Class	Ownership	Slope	Stand types (million acres)					
				LHW	UHW	NP	PP	MIXED	Total
North	1	Private	LE40	21.06	29.89	5.59	0.72	2.32	59.59
			GT40	1.69	4.09	0.12	0.02	0.15	6.06
		Federal	LE40	4.15	5.78	1.73	0.85	0.63	13.14
			GT40	0.37	0.54	0.02	0.02	0.01	0.96
	2	Private	LE40	11.48	12.77	3.27	0.50	0.99	29.01
			GT40	0.25	0.69	0.03	0.00	0.05	1.02
		Federal	LE40	1.95	3.24	1.09	0.29	0.26	6.83
			GT40	0.07	0.12	0.00		0.00	0.20
	3	Private	LE40	5.10	6.72	2.95	0.19	0.40	15.36
			GT40	0.13	0.18	0.02		0.01	0.34
		Federal	LE40	0.93	2.22	0.90	0.17	0.17	4.39
			GT40	0.01	0.03	0.00			0.03
		Total		**47.18**	**66.26**	**15.72**	**2.76**	**4.99**	**136.92**
South	1	Private	LE40	12.61	28.09	13.43	12.04	7.48	73.65
			GT40	0.68	5.43	0.16	0.04	0.32	6.63
		Federal	LE40	1.85	3.56	4.17	0.78	1.33	11.70
			GT40	0.04	1.23	0.13		0.09	1.50
	2	Private	LE40	4.84	11.46	5.36	13.87	3.82	39.35
			GT40	0.07	1.11	0.09	0.06	0.15	1.47
		Federal	LE40	0.50	1.08	0.69	0.82	0.44	3.53
			GT40	0.01	0.19	0.01		0.04	0.25
	3	Private	LE40	5.02	12.17	3.17	7.80	4.84	33.01
			GT40	0.04	0.40	0.06	0.02	0.03	0.55
		Federal	LE40	0.48	0.85	0.44	0.32	0.38	2.47
			GT40	0.00	0.06	0.01			0.07
		Total		**26.15**	**65.65**	**27.71**	**35.75**	**18.91**	**174.17**
West	1	Private	LE40	1.90	1.56	10.73	1.71	0.02	15.92
			GT40	0.40	0.73	3.34	0.64	0.01	5.12
		Federal	LE40	0.40	0.64	19.66	1.22		21.92
			GT40	0.24	0.42	8.26	0.70		9.62
	2	Private	LE40	0.76	1.15	1.47	0.87	0.05	4.30
			GT40	0.14	0.35	0.43	0.37	0.02	1.32
		Federal	LE40	0.18	0.74	2.50	0.36	0.01	3.78
			GT40	0.06	0.31	0.69	0.21		1.27
	3	Private	LE40	0.63	0.63	2.48	1.32	0.04	5.10
			GT40	0.16	0.18	0.56	0.45		1.35
		Federal	LE40	0.16	0.53	3.03	0.33		4.06
			GT40	0.07	0.25	0.79	0.18		1.29
		Total		**5.12**	**7.49**	**53.94**	**8.35**	**0.15**	**75.05**

Table 3.14 | Timberland and Stand Species That Are Available for Harvesting in Different Regions

Region	Slope	UHW	LHW	NS	PS	MIXED
Northeast	LE40	Yes	Yes	Yes	Yes	Yes
	GT40	—	—	—	—	—
South	LE40	Yes	Yes	Yes	Yes	Yes
	GT40	—	—	—	—	—
North Central	LE40	Yes	Yes	Yes	Yes	Yes
	GT40	—	—	—	—	—
Inland West	LE40	Yes	Yes	Yes	Yes	Yes
	GT40	—	—	—	—	—
Pacific Northwest	LE40	Yes	Yes	Yes	Yes	Yes
	GT40	Yes	Yes	Yes	Yes	Yes

Note: Land in the Pacific Northwest is available for harvesting for timber products because of available cable systems in use, whereas the other regions are assumed to have limited or no cable systems available.

Yield Levels for Clear Cut, Thinning, and Annual Growth (α, β, θ, g)

In the first simulation year, yield levels (cubic feet/acre or dry ton/acre) for logging and harvesting of woody biomass using the clear-cut option are calculated using existing information on standing tree volume and corresponding timber area from the FIA database aggregated at the POLYSYS county level. The thinning yield is 70% of the clear-cut yield, assuming thinning treatment would be a thinning-from-above (Coops et al. 2009; Penn State 2016) when harvesting conventional products and only the smaller diameter trees when harvesting whole-tree biomass.

Annual growth yield (cubic feet/acre or dry ton/acre) is based on the net annual growth and the corresponding timber area. It is assumed that for each acre of a certain stand, the current yield of the simulation year is the yield level from the beginning of the simulation period, plus the total growth yield, multiplied by the total numbers of years from the beginning to the present.

Wood Harvesting Intensity (ω)

Wood harvesting intensity is an indicator of the annual felling as a percentage of the allowable cut. We first tried to obtain wood harvesting intensity from Timber Product Output (TPO) removal data divided by the standing volume of live trees in the corresponding counties. The results varied by county, by timber product (sawlogs, pulpwood, and fuelwood), and by hardwood and softwood. That method proved not to be a preferable way to obtain the ratios, because TPO has significant gaps in information for counties that have a timber acreage inventory. We decided to take the potential production quantities and compare them with the 2010 projected demand from USFPM. We found that 5% of the existing standing volume, at most, is sufficient to meet the future demand for conventional wood.

Wood harvesting intensity limits to 5% the amount of forest within a POLYSYS region that can be harvested in any one year. It limits how much acreage is actually available for harvest. The growth rate limits the volume to growth at the state level. Therefore, the model does not allow the wood harvest to exceed state growth levels within a state. The 5% figure is estimated by taking the potential production compared with the 2010 projected demand estimated by USFPM.

Logging Residue Retention

Not all available logging residues are harvested for biomass feedstock use. A retention rate of 30% is applied to residues from clear-cut full-tree harvesting on timberland with a slope of LE40. If the available logging residues are from stands located on timberland with a slope of GT40, all of the logging residues are left on the site. If the timberland is thinned (partially cut), 30% of the residues are retained on-site (i.e., a 30% retention rate) rate) if slope is GT40. If the available logging residues are from thinnings (partial-cut) stands, all residues are harvested as biomass feedstocks in the model if slope is LE30. The underlying assumption is that there will still be residues left on-site because of tree breakage and losses from harvesting trees, and that the remaining trees will provide sufficient site protection.

In the 2005 *BTS* and 2011 *BT2*, a technical recovery efficiency of 65% for residues is used in addition to the retention coefficient. Mechanical systems cannot feasibly recover more than 65% of the broken limbs, broken tops, and foliage spread across sites (Dykstra, Hartsough, and Stokes 2009). So with a 30% retention rate, in actuality 35% is retained. For this study, the technical recovery coefficient is assumed to be 70% because of system and equipment improvements. Therefore, a retention level of 30% results in a 70% technical recovery of forest residues.

Inter-Period Class Determination Matrix (v, u)

After timberland is clear cut, we assume replanting and regeneration of the land follows. We also assume that if class 2 and class 3 standing trees are not harvested, they continue to grow and became class 1 and class 2 stands, depending on the annual increment of quadratic mean diameters. We form an inter-period class determination matrix to model the change from replanting to class 3 stands, class 3 to class 2 stands, and class 2 to class 1 stands over the simulation periods. If class 2 stands are harvested with the thinning option, they are not available until they become class 1 stands. Replanting or regeneration acres are available for harvesting when the stands become class 2.

Stumpage Costs (SC, SCR)

Stumpage prices are derived using the following steps. We first obtain a pulpwood price update for 2014 based on RISI, International Wood[6] fiber report data, and calculations of stumpages.

As seen in table 3.15, data for hardwood pulpwood roundwood prices in the West region are missing. Instead, we use the 2007 data of $23.48 per dry ton for hardwood in the West, as reported in *BT2*. We used the RISI (2008) pulpwood price as the stumpage price for class 2 stands of the corresponding hardwood and softwood (table 3.16). For mixed wood, the price is calculated as 37.5% of the hardwood stumpage price plus 62.5% of the softwood stumpage price (table 3.16). For each stand species, the stumpage price of a class 1 stand is twice that of a class 2 stand. The class 3 stand stumpage price is 50% of the class 2 stand price. If logging residues are collected from the harvested site, their stumpage price is the fraction of the whole-tree stumpage price from table 3.15; it is based on the ratio of the yield from residues to the yield from a whole tree, using the FIA database to calculate that fraction.

[6] Accessed by Ken Skog, who provide updated calculations of estimated 2007 delivery cost fractions. See table 3.2 of the 2011 *BT2* (DOE 2011, 27) for more information on these calculations. Table 3.14 stumpage prices are derived from these calculations.

Table 3.15 | RISI Pulpwood Prices, Roundwood ($ per dry ton stumpage)

Region	2014			2013	
	3Q	2Q	1Q	4Q	3Q
Hardwood					
North	22	22	20	19	19
South	17	17	17	17	16
West	N/A	N/A	N/A	N/A	N/A
Softwood					
North	21	21	20	19	19
South	16	16	16	16	16
West	17	17	17	16	15

Source: Data from Skog (2015).

Table 3.16 | Stumpage Price of Conventional Wood ($ per dry ton)

Stand species	North			South			West		
	Class 1	Class 2	Class 3	Class 1	Class 2	Class 3	Class 1	Class 2	Class 3
UHW	44.00	22.00	11.00	34.00	17.00	8.50	46.96	23.48	11.74
LHW	44.00	22.00	11.00	34.00	17.00	8.5	46.96	23.48	11.74
PS	42.00	21.00	10.50	32.00	16.00	8.00	24.00	17.00	8.50
NS	42.00	21.00	10.50	32.00	16.00	8.00	24.00	17.00	8.50
MIXED	42.75	21.38	10.69	32.75	16.38	8.19	38.86	19.43	9.72

Harvesting Costs (CL, CTL, CW)

Harvesting costs are different depending on whether logging residues are retrieved when merchantable timber is harvested, or stands are harvested as whole-tree woody biomass. If only merchantable timber is harvested, the harvesting costs include felling, skidder, delimbing, and loader costs. This type of harvest occurs only on sites that are steep or when a cut-to-length harvesting option is used. If logging residues are collected as woody biomass in the integrated system with merchantable timber, extra costs are added to the timber harvest costs. A chipper and extra loader are added to the timber harvest system to make it an "integrated timber and biomass harvest system." However, the logging residue cost is only for the added chipper and loader and, as explained in section 3.2, an apportioned 10% of the timber harvest costs.

The harvesting costs for the timber, conventional sawtimber, and pulpwood components only are shown in table 3.17. These timber costs include the 10% reductions charged to biomass (logging residues) because all harvesting, unless explicitly categorized as either cable or cut-to-length, is assumed to be integrated timber harvesting. The costs are by stand type, harvest option, cutting option, slope, and forest region. Under full-tree logging options, logging residues can be collected as woody biomass. Cut-to-length systems process the trees at the stump, which disperses the biomass across the site, whereas full-tree systems bring the limbs and tops to the roadside for processing. Although residues can be recovered after cut-to-length harvests, the option is considered to be too costly in this model. On sites in slope category GT40, only merchantable trees and logs are extracted to the roadside—biomass is not integrated into this system, and no logging residues are removed from GT40 sites. There are two reasons behind this assumption: (1) the residues are needed to protect the steep slopes, and (2) cable logging is not efficient or economical for extracting trees with limbs and tops attached. The costs of harvesting the logging residues with the timber are shown in table 3.18 as the additional cost for the added chipper and loader. As stated, these costs also include 10% of the timber harvest costs.

Costs for harvesting logging residues are presented in table 3.18, and whole-tree costs for both clear-cut and thinning harvesting are in table 3.19. The logging residues costs are region specific, whereas the whole-tree costs are applied across all regions.

Table 3.17 | Harvesting Costs for Timber Products ($ per dry ton)

Stand type	Harvest option	Cut option	North-east	South	North Central	Inland West	Pacific Northwest	
			LE40	LE40	LE40	LE40	LE40	GT40
UHW	Full tree	Thinning	31.46	29.49	31.46	31.46	31.46	41.72
		Clear cut	29.22	25.45	29.22	29.22	29.22	27.77
LHW	Full tree	Thinning	31.46	29.49	31.46	31.46	31.46	41.72
		Clear cut	25.45	25.45	25.45	25.45	25.45	27.77
NS	Full tree	Thinning	29.62	29.49	29.49	29.62	29.62	41.72
		Clear cut	24.68	24.25	24.25	24.68	24.68	27.77
	Cut-to-length	Thinning	–	–	57.03	57.03	–	–
		Clear cut	–	–	49.63	49.63	–	–
PS	Full tree	Thinning	29.22	29.22	17.05	29.62	29.62	41.72
		Clear cut	24.25	24.25	24.25	25.45	25.45	27.77
	Cut-to-length	Thinning	–	–	65.58	65.58	–	–
		Clear cut	–	–	49.63	49.63	–	–
MIXED	Full tree	Thinning	29.62	29.62	28.29	29.62	29.62	41.72
		Clear cut	24.68	24.68	23.48	25.45	25.45	27.77
	Cut-to-length	Thinning	–	–	65.58	65.58	–	–
		Clear cut	–	–	49.63	49.63	–	–

Note: All harvests on slope category GT40 are actually "tree-length" or logs, as cable yarding is used. Limbs and tops are left at the stump and only merchantable timber is extracted.

Table 3.18 | Logging Residue Harvest Costs for Integrated Harvesting ($ per dry ton)

Stand type	Cut option	North-east	South	North Central	Inland West	Pacific Northwest	
		LE40	LE40	LE40	LE40	LE40	GT40
UHW	Clear cut	14.62	14.20	14.62	14.62	14.62	14.45
	Thinning	17.30	17.08	17.30	17.30	17.30	18.44
LHW	Clear cut	14.20	14.20	14.20	14.20	14.20	14.45
	Thinning	17.30	17.08	17.30	17.30	17.30	18.44
NS	Clear cut	14.11	14.06	14.06	14.11	14.11	14.45
	Thinning	17.09	17.08	14.11	17.08	17.09	18.44
PS	Clear cut	14.06	14.06	14.06	14.20	14.20	14.45
	Thinning	17.05	17.05	17.05	17.09	17.09	18.44
MIXED	Clear cut	14.11	14.11	13.98	14.20	14.20	14.45
	Thinning	17.09	17.09	16.94	17.09	17.09	18.44

Table 3.19 | Harvesting Costs for Whole Trees as Woody Biomass ($ per dry ton)

	Clear cut	Thinning
UHW	19.85	35.92
LHW	25.21	35.92
NS	29.85	30.34
PS	29.85	35.92
MIXED	29.85	35.92

3.4.4 Results

Although six scenarios are analyzed in the model, only two scenario analyses are consistently presented in this chapter. All of the results of these scenarios and the other scenarios are available online within the Bioenergy KDF. These scenarios are developed and projected using USFPM as explained in section 3.3, with the characteristics described in table 3.20. The baseline scenario (Baseline_ML) assumes low growth in woody biomass demand for energy; moderate new plantation management intensity in the South; and moderate demand for conventional wood for housing, paper and paperboard, and exports. The high, high (HH) scenario assumes a high increase in demand both for conventional wood for housing, paper and paperboard, and exports and for woody biomass for energy.

Table 3.20 | USFPM Scenarios (see table 3.6)

Scenario name	Characteristics				
	Growth in wood biomass demand for energy	Growth in housing starts	New plantation management intensity in the South	Growth in demand for paper and paperboard	Growth in demand for biomass for energy, and wood and paper products (foreign countries)
Baseline_ML	Low	Moderate	Moderate	Moderate	Moderate
MM	Moderate	Moderate	Moderate	Moderate	Moderate
MH	High	Moderate	High	Moderate	Moderate
HL	Low	High	Moderate	Moderate	Moderate
HM	Moderate	High	Moderate	Moderate	Moderate
HH	High	High	High	Moderate	Moderate

Note: The first letter of the code for the scenarios indicates the level of housing starts (high and medium), and the second letter indicates the level of biomass harvested for fuel (high, medium, and low).

Table 3.21 | USFPM Projection of Feedstocks from Woody Biomass (million dry tons)

Scenario	2015–2019	2020–2024	2025–2029	2030–2034	2035–2039	2040
Baseline_ML	14	14	14	14	14	15
MM	21	25	29	33	34	34
MH	22	29	39	51	55	55
HL	14	14	14	14	14	15
HM	21	25	29	33	34	34
HH	22	29	38	51	54	55

The USFPM projections (from section 3.3) for woody biomass as a biomass feedstock (in million dry tons) under all six scenarios are presented in table 3.21. From 2015 to 2040, the woody biomass projection is relatively low, ranging from 14 million to 15 million dry tons in Baseline_ML, while woody biomass demand ranges from 22 million to 55 million dry tons in scenario HH. ForSEAM uses the projection as the exogenous demand level for woody biomass and solves the model at the POLYSYS level.

Table 3.22 | Acres Harvested by Feedstock Type, Stand Diameter Class, Cut Option, Ownership, Scenario, and Year at $60 per Dry Ton (P = private; F = federal)

Scenario	Year	Conventional wood (logging residues) (million acres)						Whole-tree biomass (million acres)						Total (million acres)			
		Class 1 stand		Class 2 stand				Class 2 stand				Class 3 stand					
		Clear cut		Clear cut		Thinning		Clear cut		Thinning		Clear cut		Clear cut		Thinning	
		P	F	P	F	P	F	P	F	P	F	P	F	P	F	P	F
Baseline_ML	2015	1.3	0.3	0.0	0.0	2.2	0.3	1.0	0.2	0.3	0.2	2.5	0.5	4.9	1.0	2.5	0.5
	2017	1.2	0.3	0.1	0.0	2.5	0.3	1.1	0.3	0.3	0.3	1.8	0.3	4.1	0.9	2.9	0.6
	2020	1.3	0.3	0.1	0.0	2.4	0.3	1.1	0.3	0.5	0.3	1.3	0.3	3.7	0.9	2.8	0.6
	2022	1.3	0.3	0.0	0.0	2.2	0.3	1.0	0.3	0.5	0.3	1.1	0.3	3.5	0.8	2.6	0.6
	2025	1.4	0.3	0.1	0.0	1.9	0.2	0.9	0.3	0.4	0.3	0.8	0.2	3.2	0.8	2.2	0.5
	2030	1.6	0.3	0.0	0.0	1.4	0.2	0.7	0.3	0.4	0.3	0.4	0.2	2.8	0.7	1.8	0.5
	2035	1.9	0.3	0.0	0.0	0.8	0.2	0.6	0.2	0.6	0.3	0.2	0.1	2.6	0.6	1.4	0.4
	2040	2.1	0.4	0.0	0.0	0.0	0.0	0.4	0.2	0.7	0.2	0.1	0.0	2.6	0.6	0.7	0.3

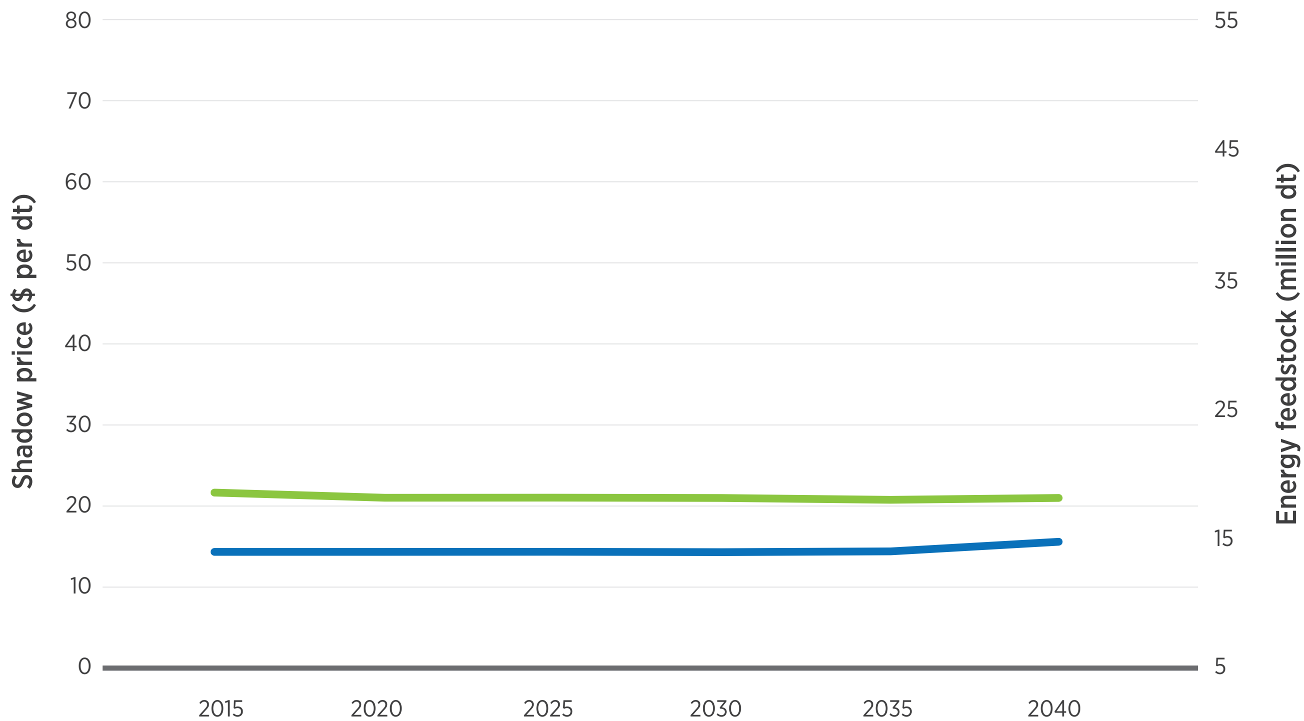
Table 3.22 ***(continued)***

Scenario	Year	Conventional wood (logging residues) (million acres)						Whole-tree biomass (million acres)						Total (million acres)			
		Class 1 stand		Class 2 stand				Class 2 stand				Class 3 stand					
		Clear cut		Clear cut		Thinning		Clear cut		Thinning		Clear cut		Clear cut		Thinning	
		P	F	P	F	P	F	P	F	P	F	P	F	P	F	P	F
MM	2015	1.2	0.2	0.3	0.0	2.3	0.3	0.7	0.2	0.2	0.2	2.5	0.5	4.7	1.0	2.5	0.5
	2017	1.2	0.3	0.1	0.0	2.5	0.3	1.0	0.3	0.4	0.3	1.7	0.3	4.0	0.8	2.9	0.6
	2020	1.3	0.3	0.1	0.0	2.3	0.2	1.0	0.3	0.5	0.3	1.2	0.3	3.5	0.8	2.8	0.6
	2022	1.3	0.3	0.1	0.0	2.1	0.2	0.9	0.3	0.5	0.3	1.0	0.2	3.3	0.7	2.6	0.6
	2025	1.4	0.3	0.1	0.0	1.8	0.2	0.7	0.3	0.4	0.3	0.7	0.2	2.9	0.7	2.1	0.5
	2030	1.6	0.3	0.1	0.0	1.4	0.2	0.6	0.2	0.3	0.3	0.2	0.1	2.5	0.6	1.7	0.5
	2035	1.7	0.3	0.0	0.0	0.9	0.2	0.5	0.2	0.4	0.2	0.1	0.0	2.3	0.5	1.3	0.4
	2040	2.0	0.3	0.0	0.0	0.0	0.0	0.3	0.1	0.5	0.2	0.0	0.0	2.4	0.4	0.6	0.2
MH	2015	1.2	0.2	0.3	0.0	2.3	0.3	0.7	0.2	0.2	0.2	2.5	0.5	4.7	1.0	2.6	0.5
	2017	1.2	0.3	0.1	0.0	2.5	0.2	0.9	0.2	0.4	0.3	1.7	0.3	3.9	0.8	2.8	0.6
	2020	1.3	0.3	0.1	0.0	2.2	0.2	0.9	0.2	0.5	0.3	1.2	0.3	3.4	0.8	2.7	0.6
	2022	1.3	0.3	0.1	0.0	1.9	0.2	0.8	0.2	0.6	0.3	0.9	0.2	3.1	0.7	2.5	0.5
	2025	1.4	0.3	0.1	0.0	1.6	0.2	0.7	0.2	0.5	0.3	0.6	0.1	2.8	0.7	2.1	0.5
	2030	1.5	0.3	0.1	0.0	1.2	0.2	0.6	0.2	0.5	0.2	0.2	0.1	2.4	0.6	1.8	0.4
	2035	1.7	0.3	0.0	0.0	0.9	0.2	0.4	0.2	0.3	0.2	0.1	0.0	2.2	0.4	1.2	0.3
	2040	2.0	0.3	0.0	0.0	0.0	0.0	0.3	0.1	0.5	0.1	0.0	0.0	2.3	0.4	0.5	0.1
HL	2015	1.4	0.3	0.0	0.0	2.1	0.3	1.0	0.2	0.4	0.2	2.5	0.5	4.9	1.0	2.5	0.5
	2017	1.2	0.3	0.1	0.0	2.5	0.3	1.1	0.3	0.3	0.3	1.8	0.3	4.1	0.9	2.9	0.6
	2020	1.3	0.3	0.1	0.0	2.4	0.3	1.1	0.3	0.5	0.3	1.3	0.3	3.7	0.9	2.8	0.6
	2022	1.3	0.3	0.0	0.0	2.2	0.3	1.0	0.3	0.5	0.3	1.1	0.3	3.5	0.8	2.6	0.6
	2025	1.4	0.3	0.1	0.0	1.8	0.2	0.9	0.3	0.4	0.3	0.8	0.2	3.2	0.8	2.2	0.5
	2030	1.7	0.3	0.0	0.0	1.4	0.2	0.7	0.3	0.4	0.3	0.4	0.2	2.8	0.7	1.8	0.5
	2035	1.9	0.3	0.0	0.0	0.8	0.2	0.6	0.2	0.6	0.3	0.2	0.1	2.6	0.6	1.4	0.4
	2040	2.2	0.4	0.0	0.0	0.0	0.0	0.4	0.2	0.7	0.2	0.1	0.0	2.6	0.6	0.7	0.2
HM	2015	1.2	0.2	0.3	0.0	2.3	0.3	0.7	0.2	0.2	0.2	2.5	0.5	4.7	1.0	2.5	0.5
	2017	1.2	0.3	0.1	0.0	2.5	0.3	1.0	0.3	0.4	0.3	1.7	0.3	4.0	0.8	2.9	0.6
	2020	1.3	0.3	0.1	0.0	2.3	0.3	1.0	0.3	0.5	0.3	1.2	0.3	3.6	0.8	2.8	0.6
	2022	1.3	0.3	0.1	0.0	2.1	0.3	0.9	0.3	0.5	0.3	1.0	0.2	3.3	0.7	2.6	0.6
	2025	1.4	0.3	0.1	0.0	1.8	0.2	0.7	0.3	0.4	0.3	0.7	0.2	2.9	0.7	2.1	0.5
	2030	1.6	0.3	0.1	0.0	1.4	0.2	0.6	0.2	0.3	0.3	0.3	0.1	2.5	0.6	1.7	0.5
	2035	1.8	0.3	0.0	0.0	0.9	0.2	0.5	0.2	0.4	0.2	0.1	0.0	2.3	0.5	1.3	0.4
	2040	2.1	0.3	0.0	0.0	0.0	0.0	0.3	0.1	0.5	0.2	0.0	0.0	2.4	0.5	0.5	0.2
HH	2015	1.2	0.2	0.3	0.0	2.3	0.3	0.7	0.2	0.2	0.2	2.5	0.5	4.7	1.0	2.6	0.5
	2017	1.2	0.3	0.1	0.0	2.5	0.2	0.9	0.2	0.4	0.3	1.7	0.3	3.9	0.8	2.8	0.6
	2020	1.3	0.3	0.1	0.0	2.2	0.2	0.9	0.2	0.5	0.3	1.2	0.3	3.5	0.8	2.7	0.6
	2022	1.4	0.3	0.1	0.0	1.9	0.2	0.8	0.2	0.6	0.3	0.9	0.2	3.2	0.7	2.5	0.5
	2025	1.4	0.3	0.1	0.0	1.6	0.2	0.7	0.2	0.5	0.3	0.6	0.1	2.8	0.7	2.1	0.5
	2030	1.6	0.3	0.1	0.0	1.2	0.2	0.6	0.2	0.5	0.2	0.2	0.1	2.4	0.6	1.8	0.4
	2035	1.7	0.3	0.0	0.0	0.9	0.2	0.4	0.2	0.3	0.2	0.1	0.0	2.2	0.4	1.2	0.3
	2040	2.0	0.3	0.0	0.0	0.0	0.0	0.3	0.1	0.5	0.1	0.0	0.0	2.3	0.4	0.5	0.1

Table 3.22 presents the harvested acres by scenario to meet the USFPM projection for conventional wood and biomass feedstocks demand. Annually, the number of acres harvested varies from a maximum of about 5.4 million acres to a low of 2.8 million acres, with variations among both scenario and year. This is about 1% of the total 386 million acres available. Under scenarios Baseline_ML and HL, logging residues alone are sufficient to meet the woody biomass demand for biomass feedstock; therefore, class 2 and class 3 stands for biomass feedstocks are not harvested as biomass feedstocks. Whole trees in class 2 and class 3 stands are harvested to meet the woody biomass demand under scenarios MM, MH, HM, and HH. Among them, most of the acres harvested are from class 3 stands. Overall, a significant portion of the harvest is from thinning class 2 timberland stands. Overall, thinning accounts for 33%–52% of the acres harvested. This occurs because the fixed ratio of clear-cut to thinning acres is pre-specified in the model. Finally, most of the acres are private land—more than 80% or 90% in every scenario and every year.

Following the USFPM projected demand pathways (fig. 3.19), the model can also be used to simulate supply curves for a particular year of interest for each scenario. Section 3.4.2 provides an explanation of the methodology. For example, in the HH scenario, the supply target for 2014 is 17 million dry tons, for 2015–2019 is 22 million dry tons, and for 2020 is 29 million dry tons. To simulate the supply curve for 2025, the model will solve from 2014 to 2024 first to meet each year's demand, then simulate supply targets from low to high with a 1 million dry ton increment to obtain shadow prices at the different supply targets, up to 184 million dry tons for 2025. The same is true for the supply curve for 2040: the model will solve for the projected supply for previous years before starting to simulate the supply curve for 2040. Figure 3.20 presents the derived supply curve for the Baseline_ML and HH scenarios for 2015, 2020, 2025, 2030, 2035, and 2040.

Figure 3.19 | USFPM projected biomass feedstock demand pathways for the Baseline_ML (top) and HH (bottom) scenarios along with the corresponding shadow prices



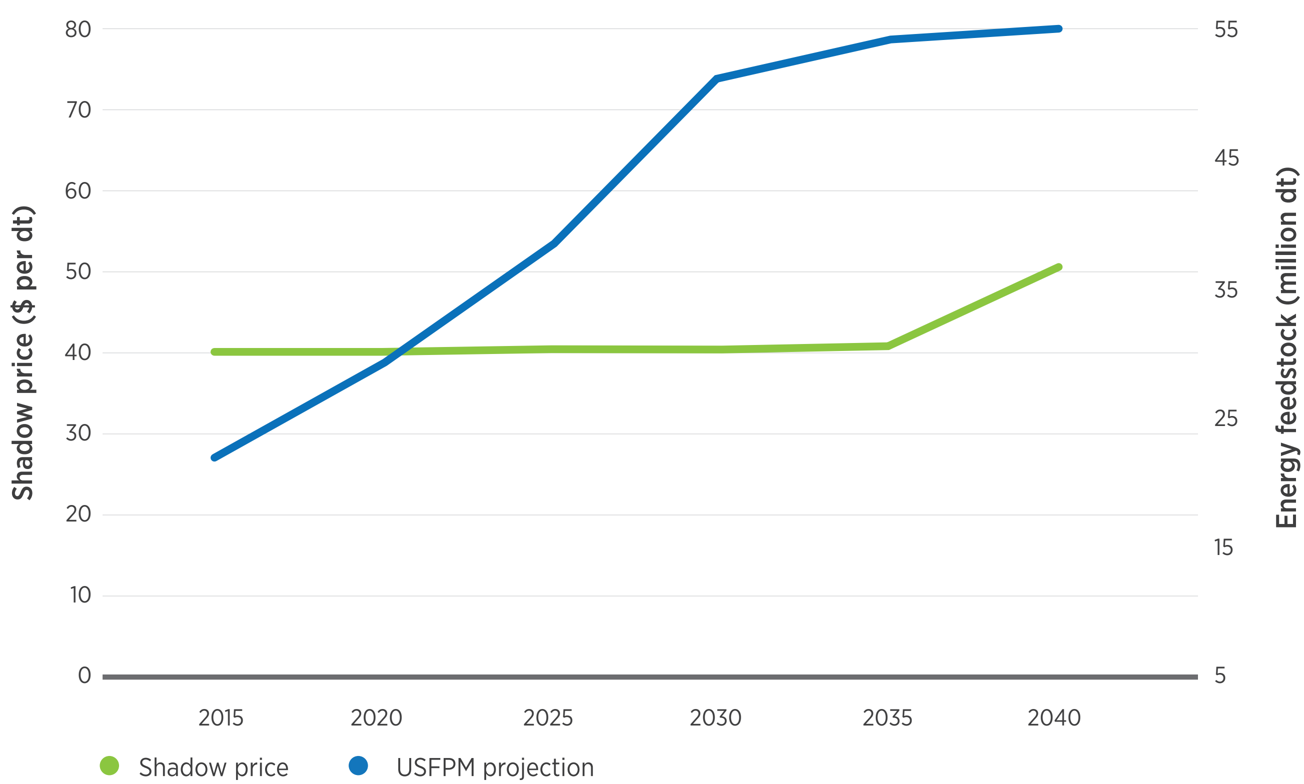
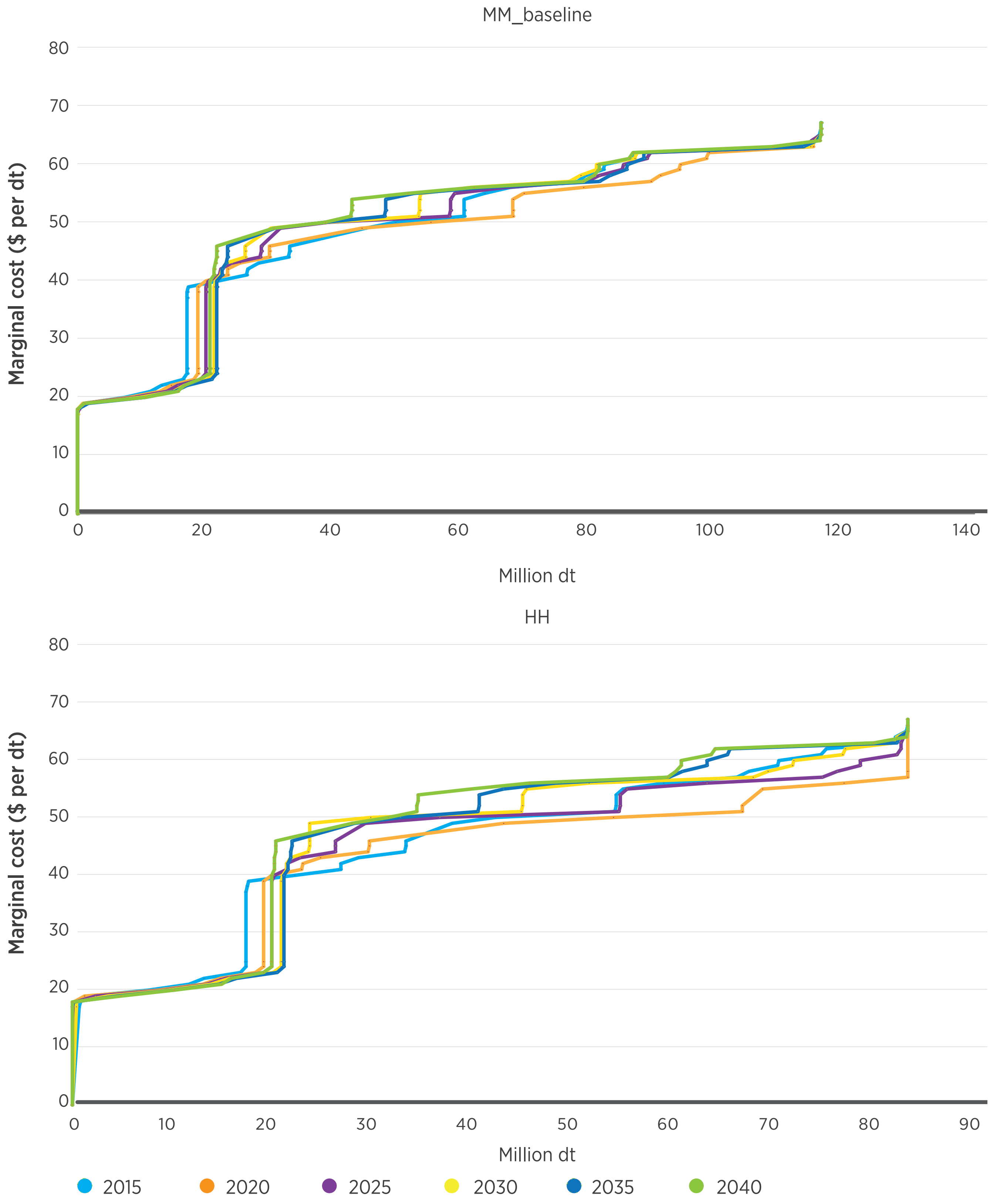


Figure 3.20 | Supply curves for the Baseline_ML and HH scenarios for 2015, 2020, 2025, 2030, 2035, and 2040



Note: Marginal costs are the production costs derived from stumpage prices and harvest costs.

Table 3.23 | Acres Harvested by Scenario, Ownership, Year, and Cost per Dry Ton (P = private; F = federal)

Year	Marginal cost ($/dry ton)	Scenario (million acres)																	
		Baseline_ML			MM			MH			HL			HM			HH		
		P	F	Total	P	F	Total	P	F	Total	P	F	Total	P	F	Total	P	F	Total
2015	40	4.5	0.7	5.2	4.7	0.7	5.4	4.7	0.7	5.4	4.4	0.7	5.1	4.7	0.7	5.4	4.7	0.7	5.4
2015	60	7.4	1.5	8.9	7.2	1.4	8.7	7.2	1.4	8.7	7.4	1.5	8.9	7.3	1.4	8.7	7.2	1.4	8.7
2015	80	8.6	1.7	10.3	8.1	1.6	9.7	7.7	1.6	9.2	8.6	1.7	10.4	8.1	1.6	9.7	7.7	1.6	9.3
2017	40	4.3	0.6	4.9	4.2	0.6	4.8	4.2	0.6	4.8	4.3	0.6	4.9	4.2	0.6	4.8	4.2	0.6	4.8
2017	60	7.0	1.5	8.5	6.9	1.4	8.3	6.7	1.4	8.1	7.0	1.5	8.5	6.9	1.4	8.3	6.7	1.4	8.1
2017	80	8.0	1.7	9.7	7.2	1.6	8.7	6.8	1.4	8.3	8.0	1.7	9.7	7.2	1.6	8.8	6.9	1.4	8.3
2020	40	3.9	0.6	4.4	3.7	0.5	4.3	3.7	0.5	4.2	3.9	0.6	4.4	3.8	0.5	4.3	3.7	0.5	4.2
2020	60	6.6	1.4	8.0	6.3	1.4	7.7	6.1	1.3	7.4	6.6	1.4	8.0	6.3	1.4	7.7	6.2	1.3	7.5
2020	80	7.3	1.6	8.9	6.5	1.5	8.0	6.1	1.3	7.4	7.3	1.6	8.9	6.5	1.5	8.0	6.2	1.3	7.5
2022	40	3.7	0.6	4.2	3.5	0.5	4.1	3.4	0.5	3.9	3.7	0.6	4.2	3.6	0.5	4.1	3.5	0.5	4.0
2022	60	6.2	1.4	7.6	5.8	1.3	7.2	5.6	1.2	6.9	6.2	1.4	7.6	5.9	1.3	7.2	5.7	1.2	6.9
2022	80	6.9	1.5	8.4	6.0	1.4	7.4	5.6	1.2	6.9	6.9	1.6	8.5	6.1	1.4	7.5	5.7	1.2	6.9
2025	40	3.4	0.5	3.9	3.3	0.5	3.8	3.1	0.5	3.6	3.4	0.5	4.0	3.3	0.5	3.8	3.2	0.5	3.7
2025	60	5.4	1.3	6.7	5.0	1.2	6.2	4.9	1.2	6.0	5.4	1.3	6.7	5.0	1.2	6.2	4.9	1.2	6.1
2025	80	6.3	1.5	7.8	5.4	1.3	6.8	5.0	1.2	6.3	6.3	1.5	7.8	5.5	1.3	6.8	5.1	1.2	6.3
2030	40	3.1	0.5	3.6	3.0	0.5	3.5	2.9	0.5	3.3	3.1	0.5	3.6	3.1	0.5	3.5	2.9	0.5	3.4
2030	60	4.6	1.2	5.8	4.2	1.1	5.3	4.1	1.0	5.1	4.6	1.2	5.8	4.2	1.1	5.3	4.2	1.0	5.2
2030	80	5.6	1.4	6.9	4.8	1.2	6.0	4.4	1.1	5.5	5.6	1.4	7.0	4.9	1.2	6.1	4.5	1.1	5.6
2035	40	2.7	0.5	3.2	2.7	0.4	3.1	2.6	0.4	3.0	2.7	0.5	3.2	2.7	0.4	3.1	2.6	0.4	3.0
2035	60	4.0	1.1	5.1	3.6	0.9	4.5	3.4	0.8	4.2	4.1	1.1	5.1	3.6	0.9	4.5	3.4	0.8	4.2
2035	80	4.7	1.3	5.9	4.1	1.0	5.1	3.8	0.9	4.7	4.7	1.3	6.0	4.1	1.0	5.2	3.8	0.9	4.8
2040	40	2.2	0.4	2.5	2.1	0.3	2.4	2.0	0.3	2.3	2.2	0.4	2.6	2.1	0.3	2.4	2.0	0.3	2.3
2040	60	3.3	0.9	4.2	2.9	0.6	3.5	2.8	0.5	3.3	3.3	0.8	4.2	2.9	0.6	3.6	2.8	0.5	3.4
2040	80	4.0	1.1	5.1	3.5	0.8	4.3	3.2	0.7	3.9	4.1	1.1	5.2	3.5	0.8	4.3	3.3	0.7	4.0

Table 3.23 shows the acres harvested for three selected costs from the developed supply curves. The associated tonnages are shown in table 3.24. Since these acres and tons are derived from the supply curves, the result is the amount of biomass available at a given price by year and scenario. The variables are also broken out by ownership—federal and private. As would be expected, the amount of available biomass and the associated acres increase with price (i.e., more biomass is available at a higher price on the market). As an example, for 2015 baseline and HH scenarios, the amount of biomass increases about eightfold, going from $40 per dry ton to $80 per dry ton. Similar supply curves produce the approximate same increases for the other scenarios. Available biomass ranges from about 20 million dry tons annually to about 185 million dry tons annually depending on the scenario, year, and selected cost. There is a general trend to increase the amount of available biomass over time because of the growing, dynamic forests.

However, there are noticeable decreases of available biomass in the 2040 time period compared with earlier years. The reason is that additional biomass is not grown on plantations, as reported in the RPA (U.S. Forest Service 2012). In higher biomass demand scenarios, in this model as well, additional plantations are established to provide the supply. However, in the ForSEAM model, natural forests are not reestablished as plantations for biomass. No additional plantations are established to meet the high demand scenario biomass requirements. (This issue is discussed in more detail in section 3.1.)

Density maps (fig. 3.21) illustrate where whole trees (by stand species: softwood, hardwood, mixed wood) could be harvested based on the model solution if the woody biomass supply target were 40 million dry tons in 2020. Most softwood is harvested in the southern regions, and most hardwood in the northeastern and southern regions.

Table 3.24 | Dry Tons of Biomass by Feedstock Type, Stand Diameter Class, Cut Option, Ownership, Scenario, and Year at $60 per Dry Ton (P = private; F = federal)

Scenario	Year	Conventional wood (logging residues) (million dry tons)						Whole-tree biomass (million dry tons)						Total (million dry tons)			
		Class 1 stand		Class 2 stand				Class 2 stand				Class 3 stand					
		Clear cut		Clear cut		Thinning		Clear cut		Thinning		Clear cut		Clear cut		Thinning	
		P	F	P	F	P	F	P	F	P	F	P	F	P	F	P	F
Baseline_ML	2015	8.7	1.3	0.1	0.0	6.3	0.8	32.0	7.4	6.0	3.8	13.5	2.5	54.3	11.2	12.2	4.6
	2017	8.0	1.3	0.2	0.0	7.5	0.9	35.7	9.6	5.8	5.9	10.8	2.0	54.8	13.0	13.3	6.8
	2020	8.7	1.4	0.2	0.0	7.7	0.9	38.3	9.9	9.4	6.5	9.3	1.9	56.5	13.1	17.1	7.4
	2022	9.3	1.4	0.2	0.0	7.6	0.9	37.2	9.9	9.8	6.6	8.4	1.8	55.1	13.1	17.4	7.5
	2025	10.4	1.5	0.2	0.0	7.2	0.9	32.3	9.7	7.9	6.5	6.9	1.7	49.8	12.9	15.1	7.5
	2030	12.6	1.6	0.1	0.0	6.1	0.9	29.6	9.2	9.6	6.4	3.5	1.4	45.8	12.3	15.8	7.3
	2035	15.1	1.8	0.1	0.0	4.0	0.8	26.1	9.2	19.7	7.3	1.3	0.4	42.6	11.4	23.8	8.1
	2040	18.3	2.4	0.0	0.0	0.1	0.0	19.8	7.6	25.5	6.7	0.8	0.3	38.9	10.2	25.6	6.8
MM	2015	7.7	1.3	0.9	0.0	6.5	0.9	23.6	7.0	3.9	3.4	13.5	2.5	45.7	10.8	10.4	4.3
	2017	8.1	1.3	0.3	0.0	7.4	0.9	32.5	9.3	6.3	5.9	10.5	1.9	51.4	12.5	13.7	6.8
	2020	8.8	1.4	0.3	0.1	7.5	0.8	33.6	8.8	9.8	6.5	8.9	1.8	51.7	12.0	17.3	7.4
	2022	9.4	1.4	0.2	0.0	7.4	0.9	32.9	9.3	10.3	6.5	7.7	1.6	50.3	12.4	17.6	7.4
	2025	10.5	1.5	0.2	0.0	6.8	0.9	28.1	9.4	8.0	6.4	5.8	1.4	44.6	12.3	14.9	7.4
	2030	12.2	1.6	0.4	0.0	6.1	0.9	23.6	8.5	7.7	6.1	2.3	1.0	38.5	11.1	13.7	7.0
	2035	14.1	1.7	0.1	0.0	4.7	0.8	22.7	7.8	10.8	5.7	0.6	0.2	37.5	9.7	15.5	6.5
	2040	17.7	2.3	0.0	0.0	0.1	0.0	15.7	5.2	19.8	4.5	0.3	0.1	33.7	7.6	19.9	4.5

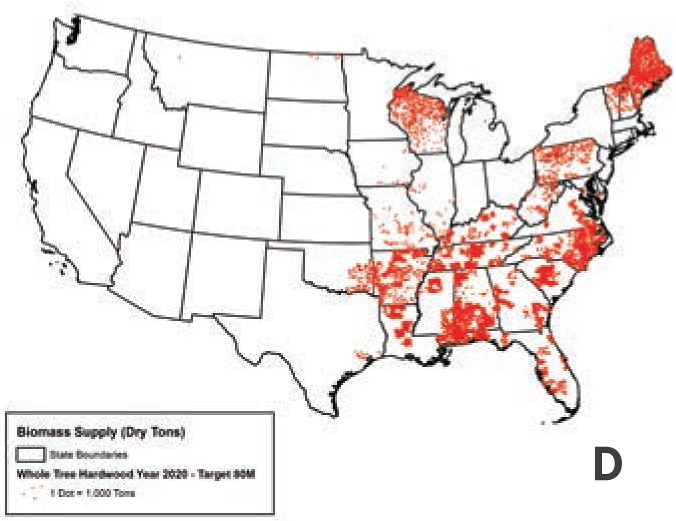
Table 3.24 ***(continued)***

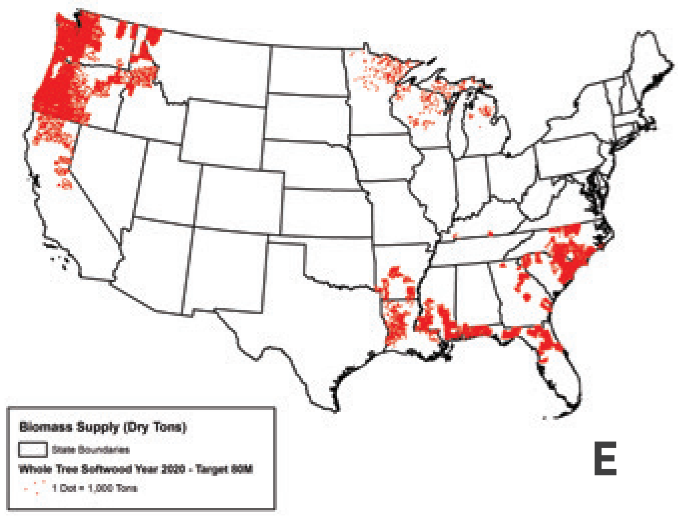
Scenario	Year	Conventional wood (logging residues) (million dry tons)						Whole-tree biomass (million dry tons)						Total (million dry tons)			
		Class 1 stand		Class 2 stand				Class 2 stand				Class 3 stand					
		Clear cut		Clear cut		Thinning		Clear cut		Thinning		Clear cut		Clear cut		Thinning	
		P	F	P	F	P	F	P	F	P	F	P	F	P	F	P	F
MH	2015	7.8	1.3	0.9	0.0	6.5	0.9	22.5	6.9	4.0	3.5	13.5	2.5	44.6	10.6	10.5	4.3
	2017	8.2	1.3	0.4	0.1	7.2	0.8	29.4	7.4	6.2	5.9	10.4	1.9	48.4	10.7	13.3	6.7
	2020	8.9	1.4	0.4	0.1	7.1	0.8	29.4	7.3	9.8	6.2	8.7	1.8	47.5	10.6	16.9	7.0
	2022	9.5	1.4	0.5	0.1	6.8	0.8	28.2	7.3	12.3	6.4	7.2	1.5	45.4	10.4	19.0	7.2
	2025	10.6	1.5	0.4	0.1	6.2	0.8	24.9	8.0	12.1	6.7	5.1	1.2	41.0	10.8	18.3	7.6
	2030	12.0	1.6	0.4	0.0	5.4	0.9	21.9	7.4	13.7	5.4	2.0	0.8	36.3	9.8	19.1	6.3
	2035	13.5	1.7	0.1	0.0	4.6	0.9	20.8	6.4	9.5	4.2	0.6	0.2	35.0	8.3	14.1	5.0
	2040	17.3	2.3	0.0	0.0	0.0	0.0	14.2	3.9	18.6	3.3	0.2	0.1	31.7	6.3	18.7	3.3
HL	2015	8.8	1.3	0.1	0.0	6.2	0.8	32.0	7.4	6.9	3.9	13.5	2.5	54.4	11.2	13.0	4.7
	2017	8.1	1.3	0.2	0.0	7.5	0.9	35.8	9.7	5.8	5.9	10.8	2.0	54.9	13.0	13.3	6.8
	2020	8.8	1.4	0.2	0.0	7.7	0.9	38.4	9.9	9.4	6.5	9.3	1.9	56.6	13.2	17.1	7.4
	2022	9.4	1.4	0.2	0.0	7.6	0.9	37.3	9.9	9.8	6.6	8.4	1.8	55.3	13.2	17.4	7.5
	2025	10.5	1.5	0.2	0.0	7.2	0.9	32.4	9.8	7.9	6.5	6.9	1.7	50.0	12.9	15.1	7.5
	2030	12.9	1.6	0.0	0.0	6.1	0.9	29.9	9.2	9.9	6.4	3.5	1.4	46.3	12.3	16.0	7.3
	2035	15.4	1.8	0.1	0.0	3.9	0.7	26.1	9.2	20.2	7.3	1.3	0.4	42.9	11.4	24.1	8.1
	2040	18.6	2.4	0.0	0.0	0.0	0.0	19.9	7.6	25.6	6.7	0.8	0.3	39.3	10.3	25.6	6.7
HM	2015	7.7	1.3	0.9	0.0	6.5	0.9	23.8	7.0	3.9	3.4	13.5	2.5	46.0	10.8	10.4	4.3
	2017	8.1	1.3	0.3	0.0	7.4	0.9	32.7	9.3	6.2	5.9	10.5	1.9	51.5	12.5	13.6	6.8
	2020	8.9	1.4	0.3	0.0	7.5	0.9	34.0	9.3	9.5	6.4	8.9	1.8	52.1	12.5	17.0	7.3
	2022	9.5	1.4	0.2	0.0	7.4	0.9	33.3	9.6	9.9	6.5	7.7	1.6	50.7	12.6	17.3	7.4
	2025	10.6	1.5	0.3	0.0	6.9	0.9	27.9	9.4	7.8	6.4	5.8	1.4	44.6	12.3	14.6	7.3
	2030	12.4	1.6	0.4	0.0	6.0	0.9	23.6	8.5	7.5	6.0	2.3	1.0	38.6	11.1	13.5	7.0
	2035	14.4	1.7	0.1	0.0	4.6	0.8	22.7	7.9	11.1	5.8	0.6	0.2	37.8	9.8	15.7	6.6
	2040	18.0	2.3	0.0	0.0	0.1	0.0	15.7	5.3	19.8	4.6	0.3	0.1	33.9	7.7	19.8	4.6
HH	2015	7.8	1.3	0.9	0.0	6.5	0.9	22.7	6.9	4.0	3.5	13.5	2.5	44.8	10.7	10.5	4.3
	2017	8.2	1.3	0.4	0.1	7.1	0.8	29.6	7.4	6.1	5.9	10.4	1.9	48.6	10.8	13.3	6.6
	2020	9.0	1.4	0.4	0.1	7.2	0.8	29.8	7.3	10.2	6.2	8.7	1.8	47.9	10.7	17.4	7.0
	2022	9.6	1.4	0.5	0.1	6.8	0.8	28.5	7.4	12.6	6.4	7.2	1.5	45.9	10.5	19.4	7.3
	2025	10.7	1.5	0.3	0.1	6.3	0.8	25.7	8.2	11.5	6.8	5.1	1.2	41.9	11.0	17.8	7.6
	2030	12.3	1.6	0.4	0.0	5.5	0.9	22.0	7.5	13.3	5.5	2.0	0.8	36.6	9.9	18.8	6.4
	2035	13.8	1.7	0.1	0.0	4.6	0.8	20.8	6.5	9.8	4.3	0.6	0.2	35.3	8.4	14.4	5.1
	2040	17.5	2.3	0.0	0.0	0.0	0.0	14.3	4.0	18.7	3.4	0.2	0.1	32.0	6.4	18.7	3.4

Table 3.24 is the companion table to table 3.22. Table 3.25 presents the biomass tons associated with the harvested acres in table 3.23. Tons are shown by selected years and cost for all scenarios. As expected, biomass availability increases with the higher marginal costs as represented graphically in figures 3.19 and 3.20. However, biomass availability does not always increase with years. As explained previously and shown in this tabular data summary, biomass tonnages do not necessarily increase with the higher biomass demand scenarios, MH and HH. This is a result of the restriction of the model not to replace natural stands with plantations for biomass. For the baseline (ML) scenario, there are about 20–115 million dry tons of biomass potential depending on selected cost and year. For the same factors in the HH scenario, the potential biomass is about 20–80 million dry tons.

Figure 3.21 | Density maps for whole trees harvested for 40 million dry tons of woody biomass in the baseline scenario, 2020, for (A) hardwood, (B) softwood, and (C) mixed, and for hardwood, softwood, and mixed for 80 million dry tons (D, E, F), and 120 million dry tons (G, H, I)

Figure 3.21 *(continued)* | 80 million dry tons, (D) hardwood, (E) softwood, and (F) mixed





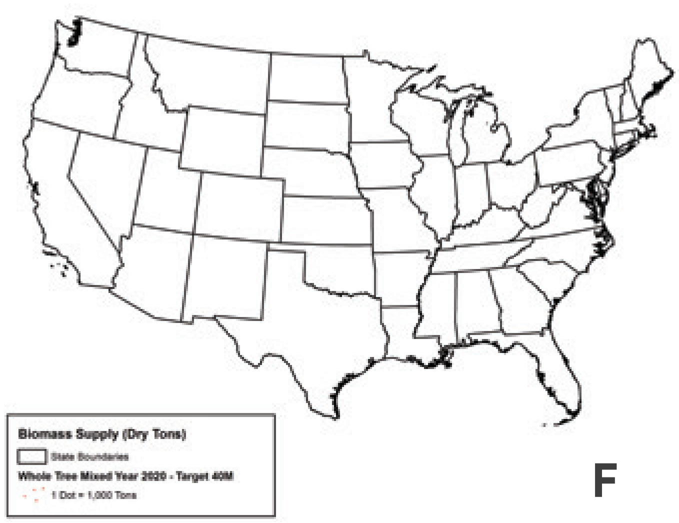


Figure 3.21 *(continued)* | 120 million dry tons, (G) hardwood, (H) softwood, and (I) mixed

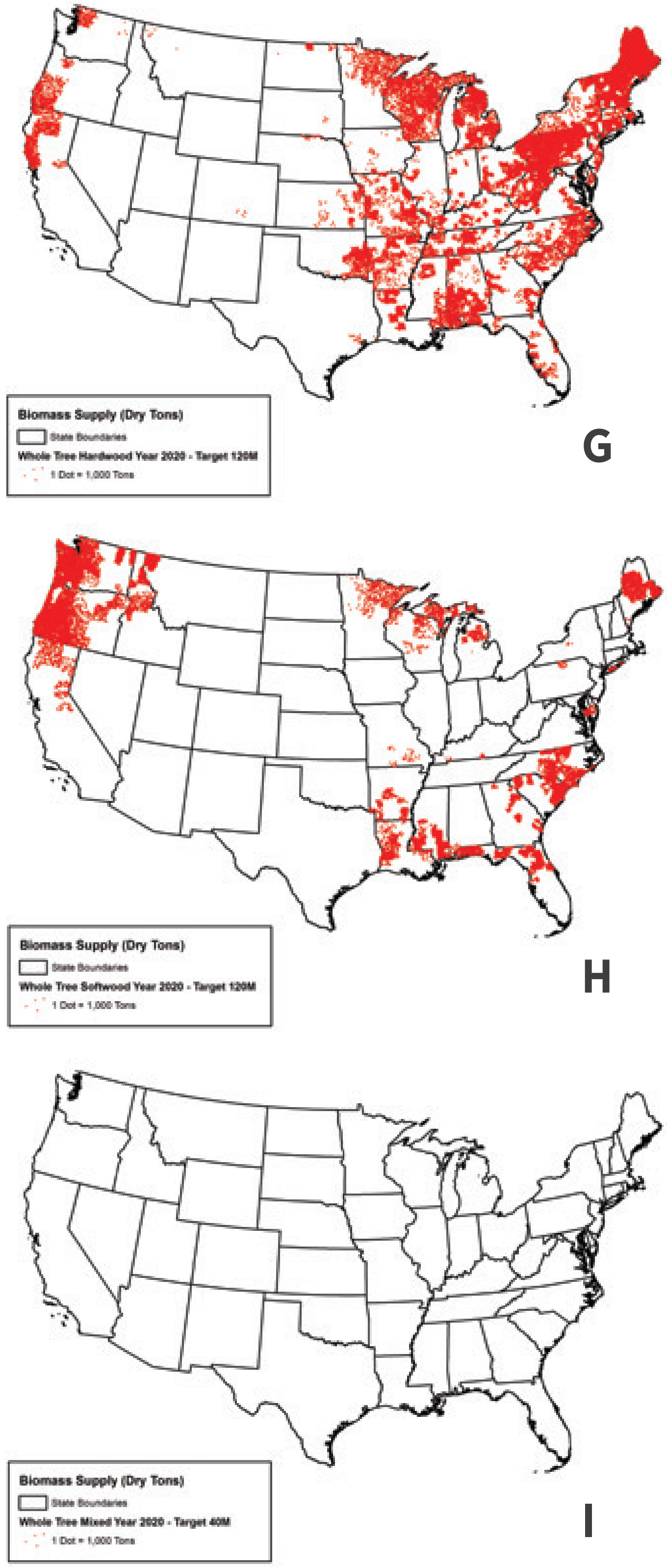


Table 3.25 | Dry Tons of Biomass Supplied by Price per Ton and Scenario, 2015–2040

Year	Marginal cost ($/dry ton)	Scenario (million dry tons)					
		ML	HL	MM	MH	HM	HH
2015	40	22.0	22.0	22.1	22.1	22.1	22.1
2015	60	82.3	83.3	71.1	70.0	71.4	70.2
2015	80	116.0	117.0	93.0	82.0	94.0	83.0
2017	40	21.0	21.1	20.6	20.6	20.7	20.6
2017	60	87.8	88.0	84.4	79.1	84.4	79.3
2017	80	116.0	117.0	93.0	82.0	94.0	83.0
2020	40	20.1	20.2	19.8	19.7	19.9	19.9
2020	60	94.1	94.3	88.4	82.0	89.0	83.0
2020	80	116.0	117.0	93.0	82.0	94.0	83.0
2022	40	20.5	20.6	20.1	19.8	20.2	20.0
2022	60	93.1	93.4	87.7	82.0	88.0	83.0
2022	80	116.0	117.0	93.0	82.0	94.0	83.0
2025	40	20.6	20.7	20.3	19.9	20.5	20.1
2025	60	85.2	85.4	79.1	77.7	78.8	78.3
2025	80	116.0	117.0	93.0	82.0	94.0	83.0
2030	40	21.7	21.8	21.2	20.6	21.5	20.8
2030	60	81.1	81.9	70.3	71.5	70.2	71.7
2030	80	116.0	117.0	93.0	82.0	94.0	83.0
2035	40	21.8	22.0	21.4	20.8	21.6	21.0
2035	60	85.8	86.5	69.3	62.4	69.9	63.2
2035	80	116.0	117.0	93.0	82.0	94.0	83.0
2040	40	20.8	21.1	20.2	19.6	20.4	19.9
2040	60	81.5	81.9	65.7	60.0	66.1	60.6
2040	80	116.0	117.0	93.0	82.0	94.0	83.0

3.4.5 Conclusions

ForSEAM is a dynamic linear optimization model that solves for a least-cost mix of both conventional wood and biomass feedstock from private timberland, subject to timberland area, harvest intensity, and forest management (e.g., thinning, cut-to-length, replanting). Because of regional differences in forest management and data limitations in certain regions, assumptions are made and parameters estimated to reflect reality. The dynamic feature of the model allows users to examine future supplies of wood products based on past activities.

Given USFPM projections of conventional wood and biomass feedstock supply targets, ForSEAM can derive the shadow price for each year as annual demand changes over time. The future shadow price tends to spike if the previous-year demand is high, leaving less available timber for biomass feedstocks. If annual demands are the same from 2014 to 2040, the HH supply curve tends to shift to the left because increasing demand for conventional wood can make less expensive logging residues available to meet the biomass feedstock demand.

There are, however, limitations to applying this model to estimate available biomass feedstocks. The years 2014 to 2040—a span of only 27 years—is considered a short time period for some timber types, especially for stands in the West. Since data are limited regarding stand age and quadratic mean diameters, they are assumed to be constant for each stand diameter class group and tree type. Improvements could be made if, in the future, age and quadratic mean diameter distributions could be determined. This would likely increase the precision of estimates; but it might not affect the results for estimating woody biomass supply because it takes at least 7 years, and sometimes as long as 27 years, for a class 3 stand to become a class 2 stand or for replanted acres to grow to a pulpwood or class 2 stand. The current estimates of biomass feedstocks potentially harvested are probably a conservative estimate.

Many of the assumptions can be changed and adjusted with improved regional parameters or other information. Currently, assumptions regarding harvest intensity, growth, and replanting provide a more conservative estimate; yet the results are robust, and harvest activity intensities reflect the current location of abundant timber resources. Only a very small percentage of the available timberland is used to meet the supply target annually. The model shows the potential for increasing biomass feedstocks supply from forests in the next 20 years or so.

3.5 Wood Energy Demand in the Context of Southern Forest Resource Markets

3.5.1 Introduction

Conditions in the forests of the South[7] and the existence of active forest products markets have contributed to the development of a new wood-pellet-for-export industry, which has the potential to dwarf all current domestic uses of southern wood for energy in the near term (Abt et al. 2014). About 46% of the South is forested, compared with only 34% of the United States as a whole (Oswalt et al. 2014). The South includes more than 40% of all U.S. timberland[8] and contains more than 72% of all planted U.S. timberland (Oswalt et al. 2014). The region is easily

[7] Throughout section 3.5, the South is defined as including all of the 13 states of Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, and Virginia.

[8] "Forestland" is defined on p. 31 of appendix A of Oswalt et al. (2014). Timberland is a subset of forestland that can produce timber volume at a rate of 20 cubic feet/acre/year and is not legally or administratively restricted from timber harvest.

accessible for transport of wood to both domestic (rail and roads) and international (ports) destinations. The timberland in the South has provided about 63% of all U.S. timber harvested since 1996, nearly all of it from private land (Oswalt et al. 2014). The existing demands on the forests for wood for lumber, paper, composites, and other uses, in addition to these new energy demands, interact with the existing forest conditions and lead to changes in both timber markets and future forest conditions.

In this section, we discuss the factors influencing demand for wood (USDA Forest Service 2015a) and the factors influencing the supply of wood (USDA Forest Service 2015b) for both energy and conventional products in the South. We then use a partial equilibrium timber market model to evaluate a set of combinations of these factors to illustrate the impacts of the supply and demand factors on market outcomes. Using subregions of the U.S. Coastal South, we evaluate (1) competing pulpwood demands, (2) declines in sawtimber harvest (i.e., the "sawtimber overhang"), (3) substitution of mill residues for small roundwood, and (4) changes in timberland area. The simulations of market impacts on the prices, inventory, and removals of timber, and timberland area by management type are discussed.

3.5.2 Demand Factors

Historically, wood energy use in the United States has primarily consisted of (1) residential wood use for heat and (2) coproduction of heat and energy in the wood products industry (Ince et al. 2011a). More recently, domestic and international renewable energy policies are key drivers of the demands for wood for use for energy and, in particular, of the demands for bulk industrial pellets for export. Other demand factors—including those influencing conventional wood products—that have impacts on the markets for wood biomass feedstocks are illustrated using timber use data from recent surveys (USDA Forest Service 2015b). This section also discusses projections of new wood energy facilities in the South as developed by Forisk Consulting (2015).

3.5.3 International Policies

The 2009 European Union (EU) Renewable Energy Directive[9] and related guidance are likely the most significant international policies affecting U.S. pellet manufacturing and thus U.S. forests. These policies require (1) a 20% EU-wide renewable energy component, with each member state generating a set share of renewable energy; (2) a 20% reduction in GHG emissions[10] and in member state annual emission allocations for the period from 2013 to 2020;[11] and (3) a 20% improvement in efficiency.[12] Combined, these policy initiatives seek to promote renewable, low-GHG, efficient sources of energy.

[9] Directive 2009/28/EC of the European Parliament and of the Council of April 23, 2009, on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC (known as the Renewable Energy Directive). OJ L 140/16, http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009L0028&-from=EN.

[10] Decision 406/2009/EC of the European Parliament and of the Council of April 23, 2009, on the efforts of member states to reduce their GHG emissions to meet the Community's GHG emission reduction commitments by up to 2020. OJ L 140/136, http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0136:0148:EN:PDF.

[11] Decision 2013/162/EU. Commission decision of March 26, 2013, on determining member states' annual emission allocations for the period from 2013 to 2020 pursuant to Decision No 406/2009/EC of the European Parliament and of the Council. OJ L 90/106, http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2013:090:0106:0110:EN:PDF.

[12] Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC. OJ L 315/1. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:315:0001:0056:EN:PDF.

EU renewable energy policy continues to evolve. On January 22, 2014, the EU announced its 2030 energy framework and objectives, which include a requirement for 40% GHG reduction, a minimum renewable contribution of 27% at the EU level (but not translated to member state targets), and a target energy efficiency improvement of 25% (European Commission 2014a, 2014b). The effect of the new objectives on pellet markets is unclear and will likely remain so until the European Commission, Parliament, and/or Council provides further clarification. A recent EU Commission staff working document (European Commission 2014c) evaluated the current conditions with respect to the solid biomass guidelines and sustainability and concluded that the current array of member state policies did not pose a distortion risk to EU markets. The paper also reiterates the EU Commission position that solid biomass sustainability will continue to be monitored through 2020.

Three critical unknowns that could influence the use of southern timber for wood pellet production are (1) the GHG emissions reduction from the use of southern timber, (2) the ability of southern forests to meet other sustainability criteria set by the EU or member states, and (3) the availability of governmental subsidies for wood pellet use for energy in the EU.

Stephenson and MacKay (2014) evaluated GHG emissions, biogenic carbon, and indirect land use, using a life-cycle analysis tool and counterfactual scenarios to identify the most efficient pathways for biomass energy development in the United Kingdom (UK). Current EU GHG emissions accounting rules do not consider either indirect land use changes or changes in biogenic carbon stocks that could result from an increase in harvest to produce feedstocks for pellets to produce renewable energy. Stephenson and MacKay (2014) found that southern timber resources can meet UK GHG emissions reduction criteria in some cases (harvest of pine plantations or use of sawmill residues) but not in others (use of older hardwood stands where rotation ages are assumed to decline).

A second area of uncertainty in pellet market developments is the need to demonstrate compliance with land use restrictions and chain-of-custody provisions of the sustainability criteria. For many EU countries, including the UK, the sustainability requirements can be met through certification of the forest by independent third-party schemes, including the Forest Stewardship Council and the Pan-European Forest Certification. Several overviews of these schemes, including benchmarking them against UK regulations, have concluded that they may require additional inputs to meet the land and chain-of-custody requirements of the EU guidelines and member state regulations; see Kittler et al. (2012) and UK DECC (2014). In addition to the two approved certification schemes (Forest Stewardship Council and Pan-European Forest Certification), legality and sustainability can be demonstrated using specific evidence to meet each of the UK sustainability criteria (UK DECC 2014).

A third area of uncertainty results from the effects of governmental subsidies on the use of wood pellets alone or with co-firing for electricity production. These subsidies are a market intervention that could be interpreted to be either a cause or a result of market imperfections. For example, the policy and subsidy could be assumed to correct the imperfection that results from the free emission and sequestration of carbon, or the policy and subsidy could be assumed to cause a market imperfection by subsidizing one sector at the expense of another. Additional discussion of the scale of the subsidies can be found in Abt et al. (2014).

Subsidies for the use of wood biomass feedstocks are currently provided by governments in the UK and the Netherlands, although recently the UK government proposed some changes in policies that could affect the additional conversion of electricity facilities in the UK to use wood pellets as a feedstock.

3.5.4 Domestic Policies

No current policies specifically encourage or discourage the use of wood pellets in the United States, although there are many existing and potential future policies that could influence both the production and consumption of pellets or other wood for energy production. Historically, the U.S. pellet market has produced bagged pellets for use in residential wood pellet stoves, but the large-scale production of bulk pellets for export is a relatively new phenomenon. Both federal and state policies will influence the future of wood energy production and consumption in the United States.

EISA is the primary U.S. federal law that could indirectly influence pellet production, and thus U.S. forests.[13] EISA requires that any woody biomass used to meet the renewable fuels standard come only from non-federal and non–ecologically sensitive lands and from (a) roundwood and mill residue from existing plantations, (b) slash and pre-commercial thinnings, or (c) wildfire hazard reduction materials. EISA will affect pellet production if (1) cellulosic biofuels become a commercially viable product and begin to affect timber harvests and/or (2) international policies or subsequent domestic policies use the EISA feedstock limits as a basis for their own sustainability criteria. These outcomes would affect forests because limiting the type and location of inventory available for pellet production could change the procurement costs for some wood feedstocks.

Perhaps the most notable policies are taking the form of regulations promulgated by EPA. These policies include the following:

- Proposed new source performance standards[14]
- Proposed guidelines for regulating carbon emissions from fossil fuel power plants under section 111(d) of the Clean Air Act[15]
- The adopted Boiler Maximum Achievable Control Technology rule[16] under the Clean Air Act of 1970
- Non-Hazardous Secondary Material regulations[18] under the Resource Conservation and Recovery Act of 1976[19] (Probert 2012; Tarr and Adair 2014; EIA 2013).

The new source performance standards, as well as guidelines for regulating existing sources under section 111(d) of the Clean Air Act, have the potential to increase the demand for wood energy in the United States. The degree to which they influence domestic demand for wood energy production depends, in part, on rules governing biogenic carbon accounting processes, which are still under development by EPA. If these accounting processes show biomass to be GHG-beneficial relative to other fuels, there

[13] Energy Independence and Security Act of 2007, Pub. L. 110–140, 121 Stat. 1492, https://www.gpo.gov/fdsys/pkg/BILLS-110hr6enr.

[14] EPA National Emission Standards for Hazardous Air Pollutants: Off-Site Waste and Recovery Operations, Final Rule, 78 Fed. Reg.14248, 40 CFR pt. 63, http://www.regulations.gov/#!documentDetail;D=EPA-HQ-OAR-2012-0360-0077.

[15] EPA Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units—Proposed Rule, 79 Fed. Reg. 34830 (proposed June 18, 2014) (to be codified at 40 CFR pt. 60), http://www.regulations.gov/#!documentDetail;D=EPA-HQ-OAR-2013-0602-0001.

[16] EPA National Emissions Standards for Hazardous Air Pollutants for Area Sources: Industrial, Commercial, and Institutional Boilers, Final Rule, 78 Fed Reg. 7487, 40 CFR Part 63, https://federalregister.gov/a/2012-31645.

[17] Clean Air Act of 1970, Pub. L. 159 (July 14, 1955) 69 Stat. 322, and the amendments made by subsequent enactments, 42 U.S.C. 7401–7626, http://www.epw.senate.gov/envlaws/cleanair.pdf.

[18] EPA Commercial and Industrial Solid Waste Incineration Units: Non-Hazardous Secondary Materials That Are Solid Waste, Final Rule, 78 Fed. Reg. 9112 (February 7, 2013) 40 CFR Parts 60 and 241, http://www.regulations.gov/#!documentDetail;D=EPA-HQ-RCRA-2008-0329-1981.

[19] Resource Conservation and Recovery Act of 1976, Pub. L. 94–580, 90 Stat. 2795, 42 USC 82 part 6901, http://www.gpo.gov/fdsys/pkg/STATUTE-90/pdf/STATUTE-90-Pg2795.pdf.

will be increased incentive to use domestic biomass resources in electricity generation facilities within the United States. Alternatively, the Clean Air Act, Boiler Maximum Achievable Control Technology rule, and Non-Hazardous Secondary Material regulations have the potential to increase the costs of biomass use, including pellet production, by requiring additional pollution abatement practices or technology. The precise impacts of both sets of drivers are currently unknown.

A state-level renewable portfolio standard (RPS) also has the potential to influence pellet consumption for energy production. A summary of these policies and the potential and requirements for wood biomass use from a state RPS are presented as part of the *2014 Annual Energy Outlook* (Bredhoeft and Bowman 2014). The use of woody biomass for energy is still more expensive than the use of other carbon-based fuels, and state-level policies often do not provide subsidies for biomass use. Thus, the cost of biomass energy production may still exceed the cost of producing energy with natural gas even when a penalty is applied. Consumers in the United States have not demonstrated a strong financial commitment to the use of renewable, low-carbon energy (Neff 2012), and thus, utilities have little incentive to pass on added costs to consumers. In addition to state RPS policies, multiple regulations promulgated by or under consideration by EPA will affect how GHG emissions from biomass combustion are accounted for, which may in turn alter behavior and/or state requirements for biomass energy use.

3.5.5 Current and Projected U.S. Wood Demands

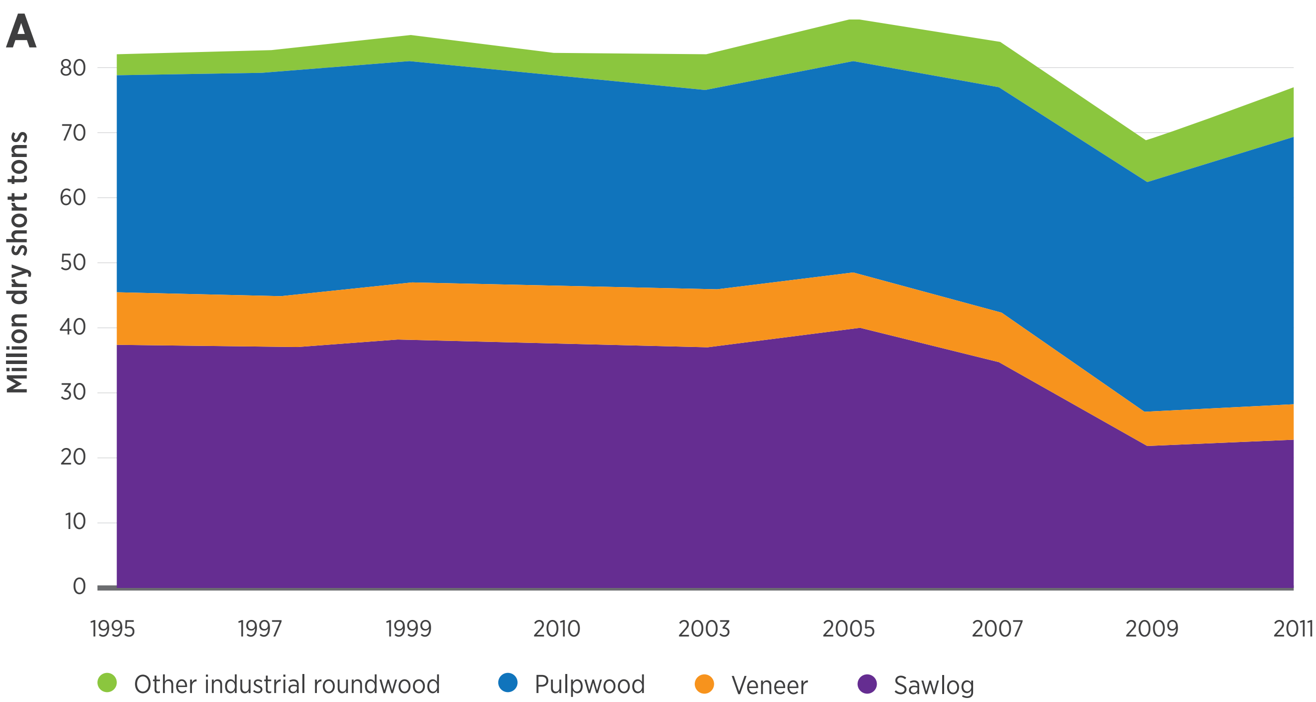
Timber in the U.S. South is harvested and used as inputs to conventional wood products, including the production of lumber, panels, paper products, and posts/poles/pilings. The Forest Service defines these inputs as sawlogs, veneer logs, composites, pulpwood, and a catch-all category called "other industrial roundwood" (USDA Forest Service 2015b). When there are fewer than three facilities producing wood products in any geography, the inputs to their processes are combined into a category referred to as "other industrial roundwood." Thus, most inputs to pellet production and other energy uses are categorized as other industrial roundwood. Before 2011, however, this was not a notable part of the measured timber use, comprising only about 1% of the total wood use in 2011 and only 2% of small-diameter wood uses (pulpwood and composites) (USDA Forest Service 2015b; Forisk Consulting 2015). Figure 3.22 shows the timber product use data for softwoods and hardwoods, South-wide, for 1995–2011 (not including Texas). Softwoods are the major timber product used (more than 75 million dry short tons through 2007 and in 2011), with a fairly level trend except for the effects of the 2007–2009 recession. In contrast, use of hardwood small roundwood for pulpwood has been declining since 1995, and hardwood sawlog use shows a marked recessionary falloff in use after 2007. Note that both softwood and hardwood veneer log use is declining, as veneer mills have closed across the South. Since 2011, hardwood lumber exports from the South have increased by nearly 60%, which will increase the production level somewhat even if domestic consumption has not recovered.

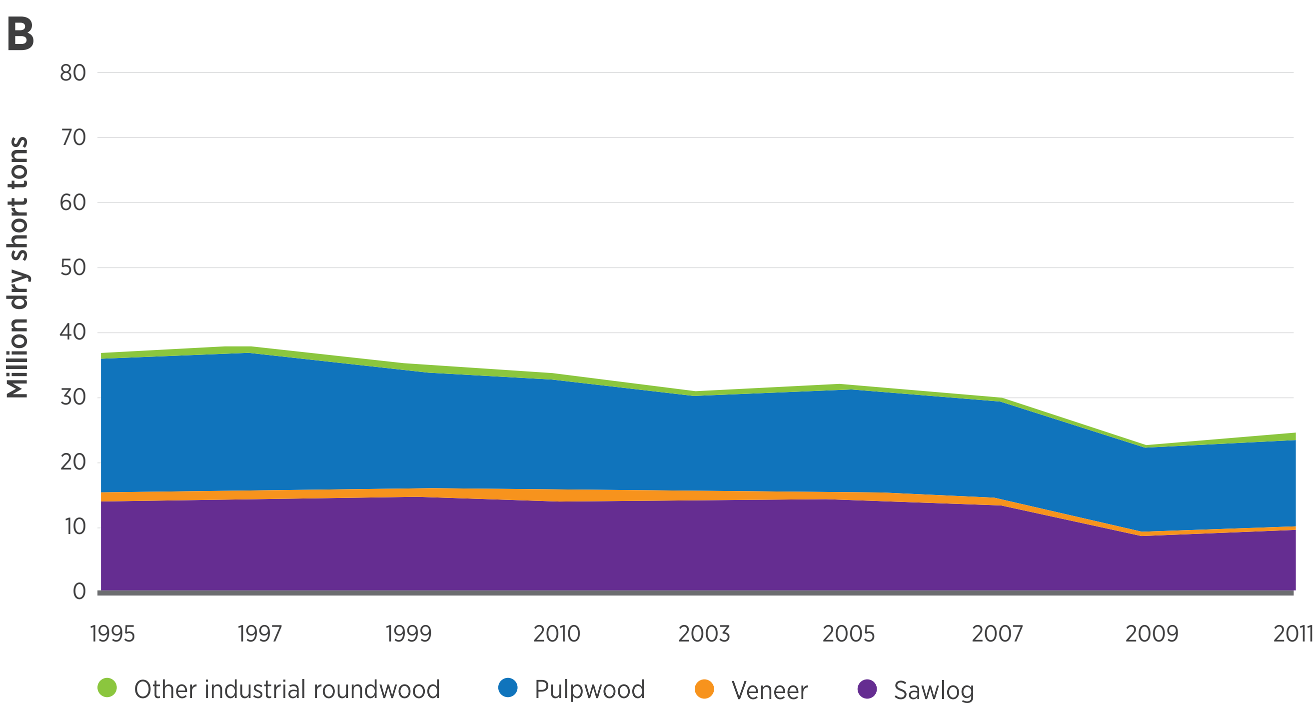
Although U.S. paper manufacturing has declined in recent years (Prestemon, Wear, and Foster 2015), data from 1953 to 2012 on inputs to paper manufacturing in the South indicate that the total use of southern wood for paper has leveled off since 2003 (fig. 3.22*A*) after a decline during the recession years of 2007–2009.[20] The leveling off, however, obscures that a decline in residues and hardwood inputs is counteracted by an increase in softwood inputs (fig. 3.22*B*). Softwood small roundwood inputs to paper manufacturing have increased steadily, rising to their highest level ever in 2011. Figure 3.22*A* also shows

[20] These data are derived from a series of Southern Pulpwood Production Reports, including Bentley and Cooper 2015; Bentley and Steppleton 2013 and 2011; Johnson and Steppleton 2011; Johnson et al. 2010, 2009, and 2008.

the input use per mill, which likely reflects increased output per mill, rising steadily through the years. Thus, although the number of mills has declined by 16% since 2000, total input use declined by only 4%, and softwood small roundwood use increased by 27% over that same time period. This has implications for a potentially growing wood energy sector because the competition for softwood small roundwood has increased, whereas the competition for hardwood small roundwood has decreased.

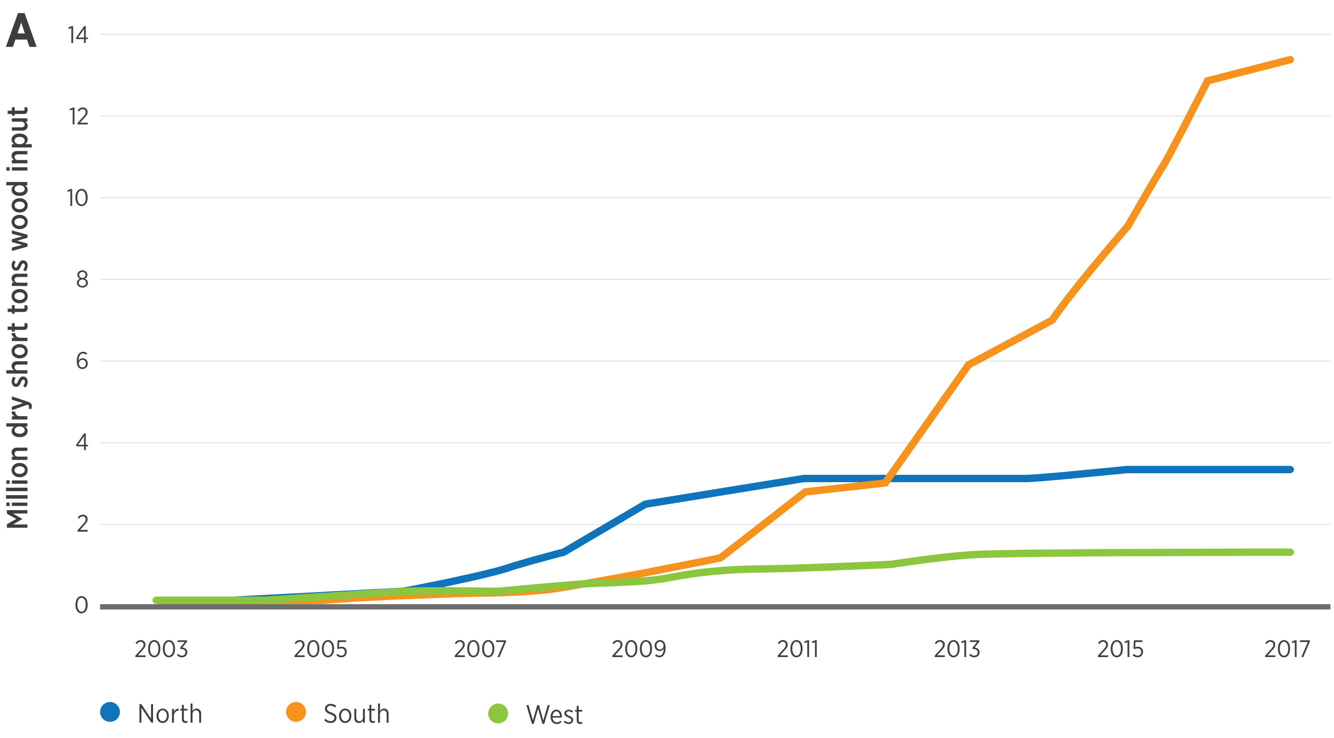
Figure 3.22 | Southern timber product use (excluding Texas), 1995–2011, for (*A*) softwood use and (*B*) hardwood use

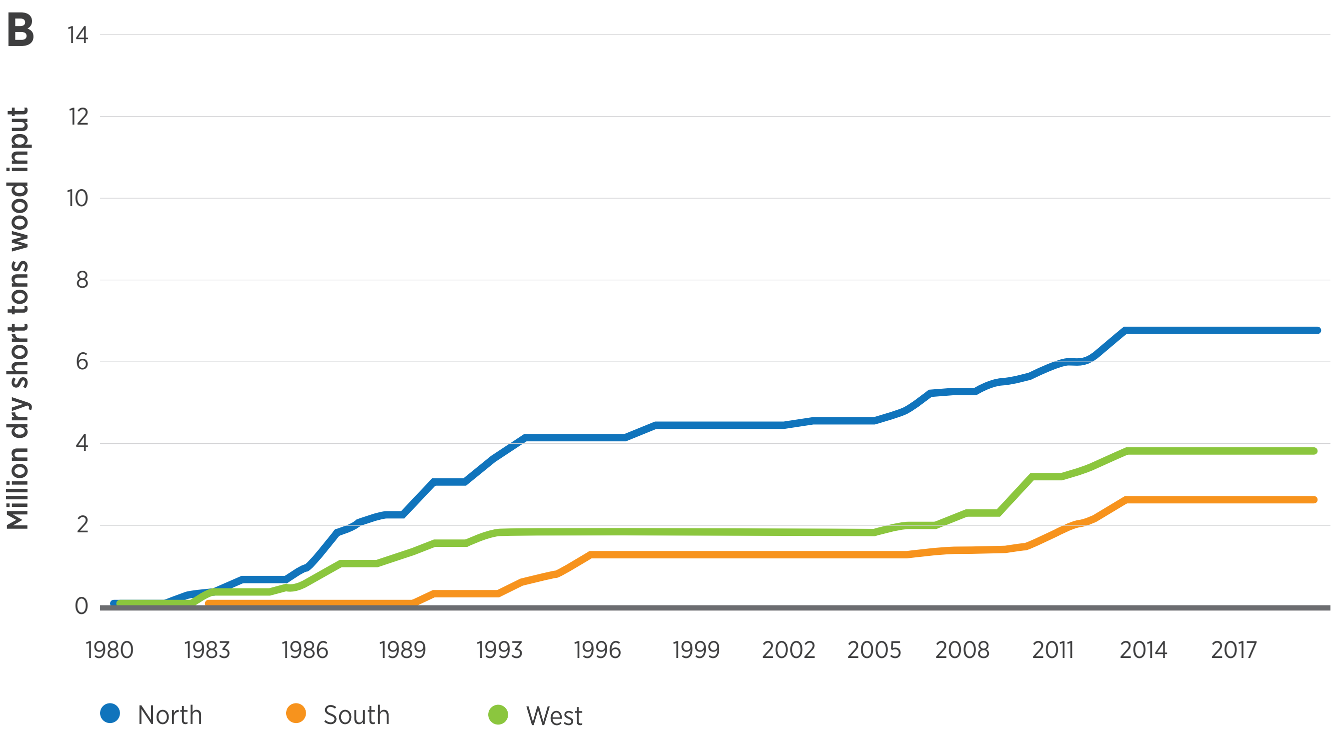




Source: Data from USDA Forest Service (2015b).

Figure 3.23 | Historical and projected (announced and meeting screens) wood input use by U.S. region, 2003–2017. *A*, Wood use for pellet production. *B*, Wood use for non-pellet energy production.



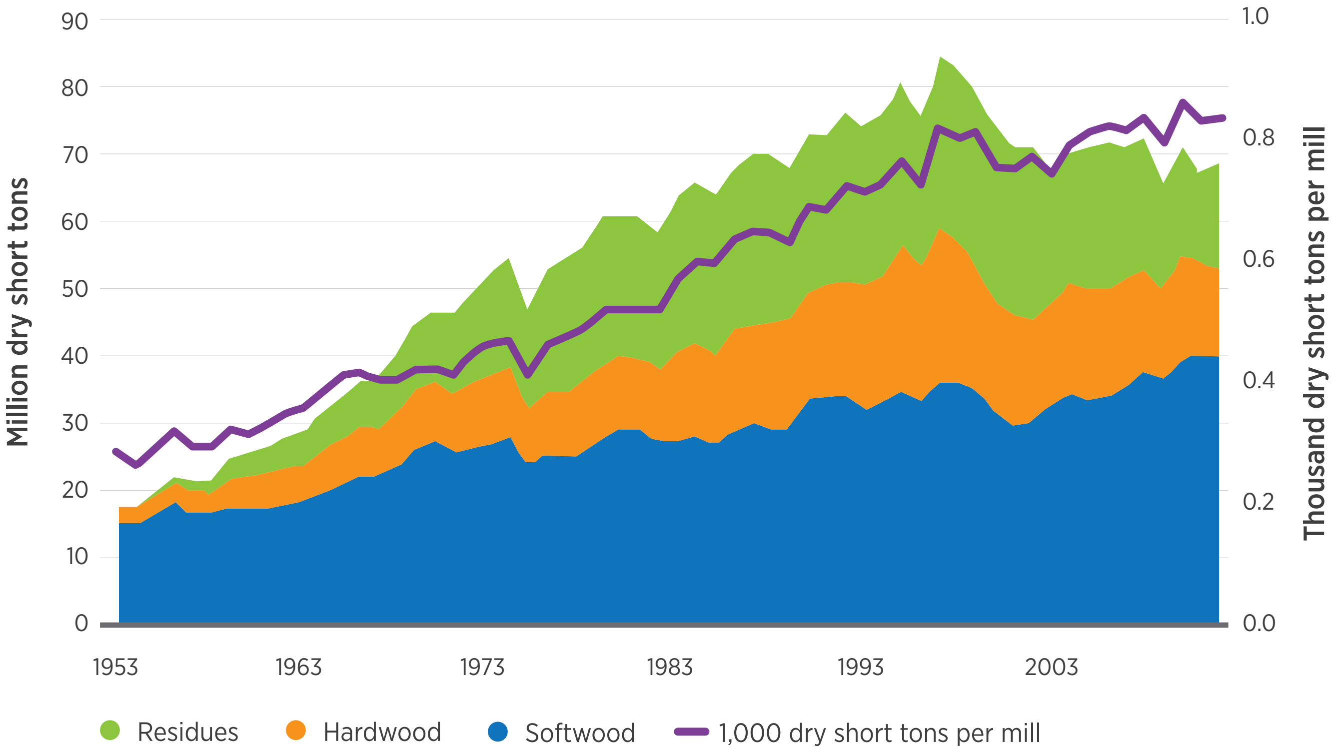


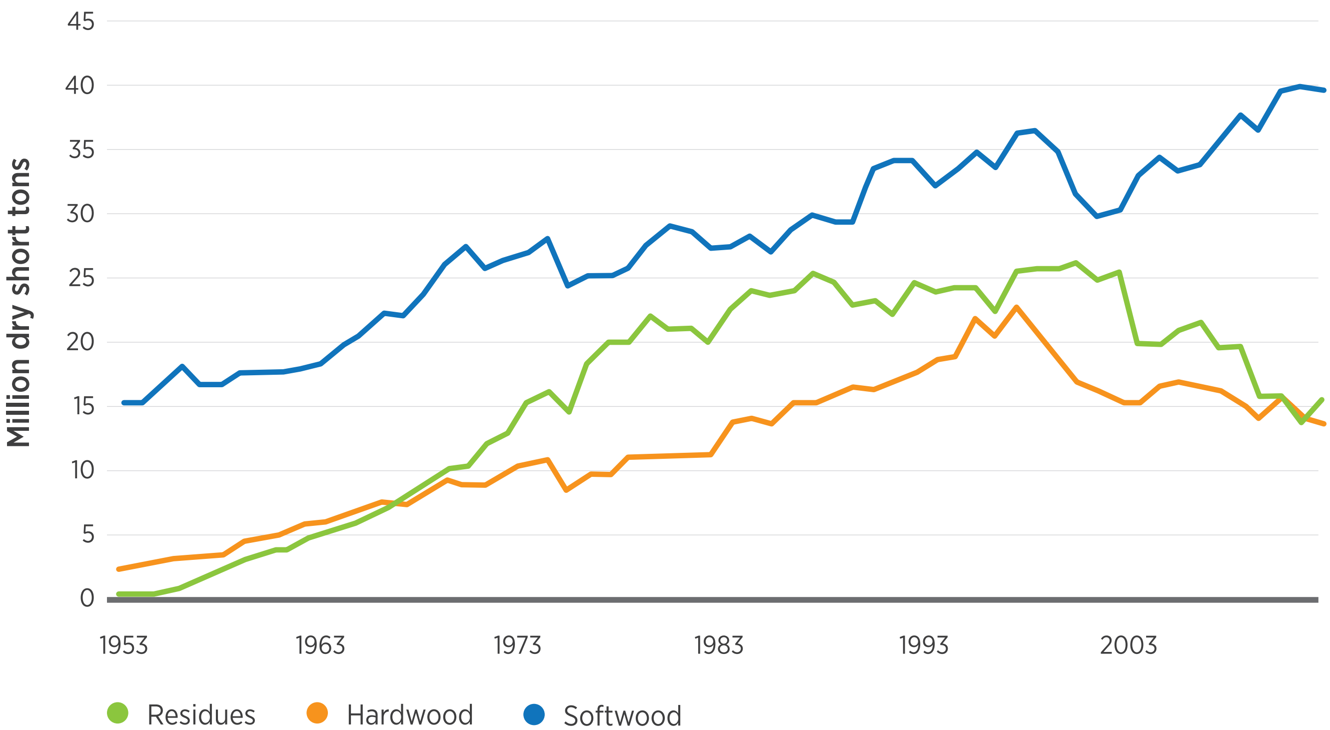
Source: Data from Forisk Consulting (2015).

For the purposes of this analysis, we use the projected pellet and non-pellet wood energy input demands from Forisk Consulting (2015). These inputs are derived from announcements made by energy and pellet producers and through follow-up surveys and analyses conducted by Forisk. The database of all U.S.-announced facilities is updated quarterly and is available by subscription. Generators and producers are asked to specify plant capacity, expected opening date, feedstock source, and progress to completion. Forisk uses various screens and conversion factors to develop the estimated wood input use by source. Note, however, that these feedstock sources are from the generators/producers at the time of announcement and are subject to change as prices and timber conditions in the market change. We did not adjust capacities for lower expected outputs in the starting year in these figures, although in the simulations discussed in this section we did reduce startup year capacities by 50% for each new facility. In this section, we use the Forisk announcements that passed the screens for both technology (uses a commercially viable technology) and status (made recent progress toward completion), which likely represent a more probable set of projects than the full announced list (fig. 3.23).

Figure 3.24*A* shows the actual and projected wood input use for pellet production by U.S. region for 2003–2017. Before 2011, this market was dominated by (mostly bagged) pellet production in the North, but it has since shifted to bulk production in the South. Nearly all of this bulk production is for export—there are few advantages to pelletizing for domestic consumption. In contrast, the wood used for non-pellet domestic energy production is dominated by the North and West, where most of the RPSs have been enacted, although it is not clear how much the RPSs have contributed to these announced facilities (fig. 3.24*B*).

Figure 3.24 | Southern pulpwood production (inputs to paper manufacturing), 1953–2012, by feedstock source and input per mill

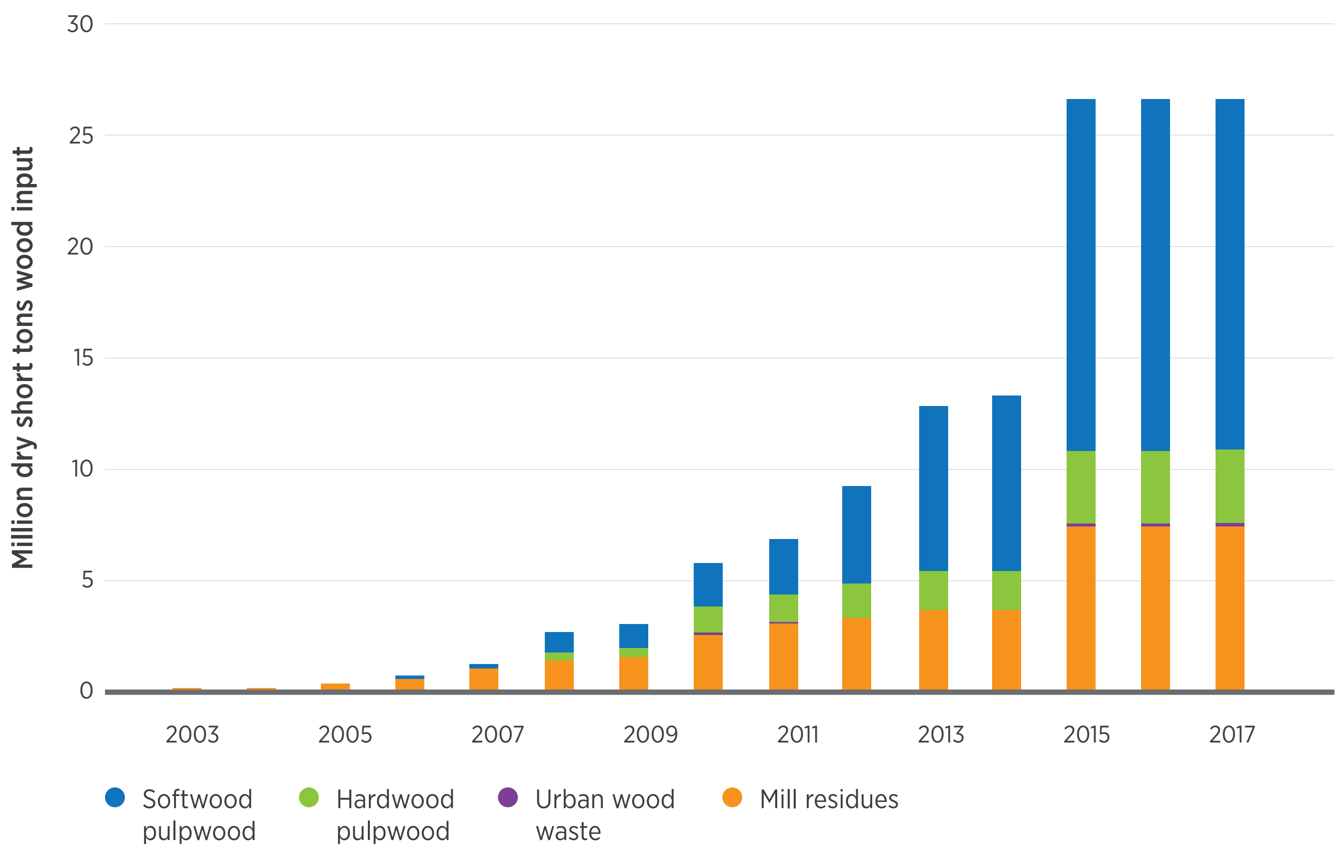




Source: These data are derived from a series of Southern Pulpwood Production Reports, including Bentley and Cooper (2015), Bentley and Stapleton (2012; 2013), Johnson and Stapleton (2011), and Johnson et al. (2008; 2009; 2010; 2011).

Inputs to the pellet production process can consist of softwood pulpwood, hardwood pulpwood, mill residues, urban wood waste, and logging residues. Figure 3.25 shows the expected inputs from the announced and screened facilities are dominated by softwood pulpwood, hardwood pulpwood and mill residues. Only very small amounts of input are expected to come from urban wood waste or logging residues.

Figure 3.25 | Historical and announced feedstock source for pellet production, 2003–2017, U.S. South

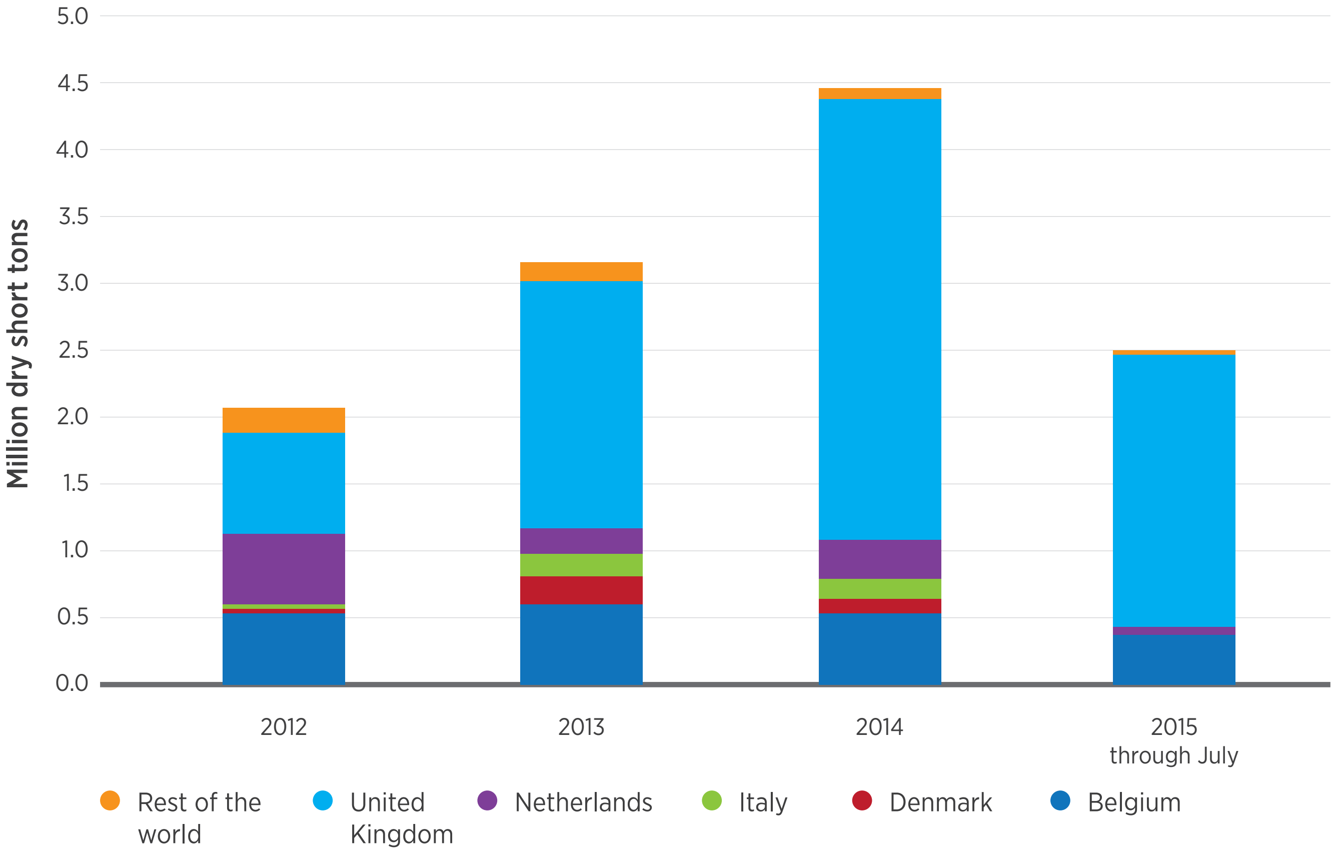


Source: Data from Forisk Consulting (2015).
Note: Quantities of logging residues and urban wood waste are small.

Much of the literature on wood energy assumes that logging residues will play a dominant role as a feedstock (Gan and Smith 2006; Perez-Verdin et al. 2009; Perlack et al. 2005). However, the Forisk survey shows that feedstocks for pellets will more likely be what is called "clean" feedstocks—softwood and hardwood small roundwood and mill residues, with only small amounts of input from logging residues and urban wood waste (fig. 3.25). These predictions from the announcing companies are subject to change, however, if future prices for small roundwood and mill residues rise, or if future prices for logging residues fall.

Output from the production of bulk pellets can be measured in the export statistics. According to the export data from the Bureau of the Census (2015), exports of wood pellets from the United States increased from 2.1 million dry short tons in 2012 to 4.5 million dry short tons in 2014, with more than 99% of those exports coming from southern ports.

Figure 3.26 | Exports of wood pellets from the United States by country of destination for 2012–2015



Source: Data from Census Bureau (2015).

Nearly all of these exports are going to the EU, rising from 94% in 2012 to 99.8% in the first half of 2015. The exports to the EU are dominated by exports to the UK, which increased from 36% of U.S. pellet exports in 2012 to more than 82% of U.S. exports in 2015 (fig. 3.26).

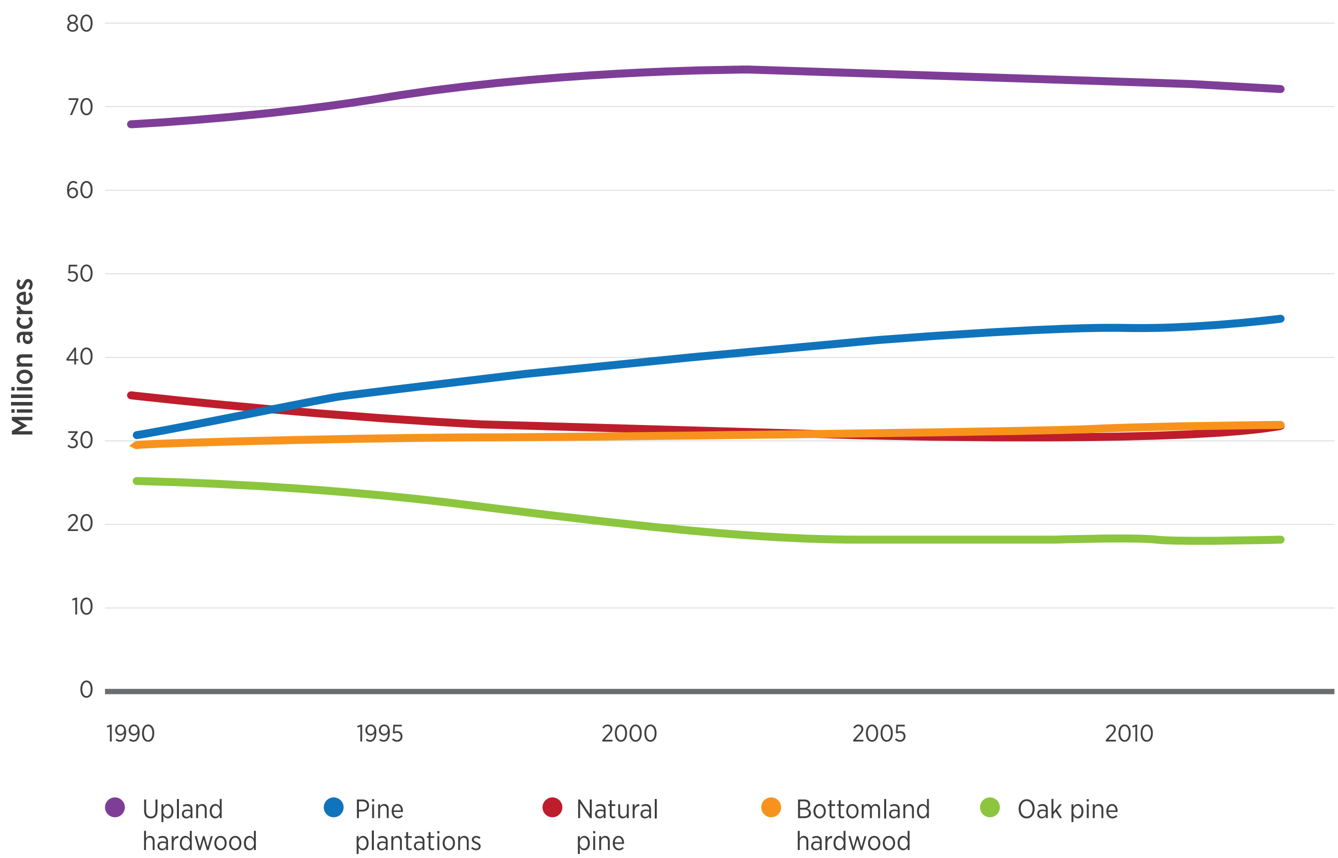
Overall, the pertinent demand factors are (1) the lack of a decline in total pulpwood demand, especially for softwood pulpwood; (2) the substitution of mill residues for small roundwood, making the output of the small roundwood–using sector a function of the demand for large roundwood; (3) the varying levels of large roundwood demand as affected by housing and lumber markets, both past and future; and (4) the influence of policies on the demand for wood pellets (international policies) and the demand for other wood as biomass feedstocks (domestic policies).

3.5.6 Supply Factors

The current and near-term (10–15-year) supply of timber is defined by what is already on the ground, what is harvested in the near term, and growth rates of existing timberland. Beyond 15 years, the supply will be influenced by landowner forest investment decisions (including planting of improved seedlings, intensive silviculture, conversion of nonforest to natural stands, and planting and replanting of pine plantations), as well as the loss of timberland to other land uses. In this section, we evaluate the forest conditions in the South that influence, currently and in the future, the supply of wood for both energy and conventional uses.

From the periodic and annual inventory records of the 13 southern states, we model[21] the South-wide timberland area by broad management type (fig. 3.27), inventory by species group (fig. 3.28), and annual removals and growth by species group (fig. 3.29). The broad management types are pine plantations, natural pine, oak-pine, upland hardwood, and bottomland hardwood; and the species groups are softwood and hardwood. Age class distribution area and inventory affect the current ability of the forest to respond to changes in demand (such as an increase in feedstock use for wood energy production), which in turn will affect the future response.

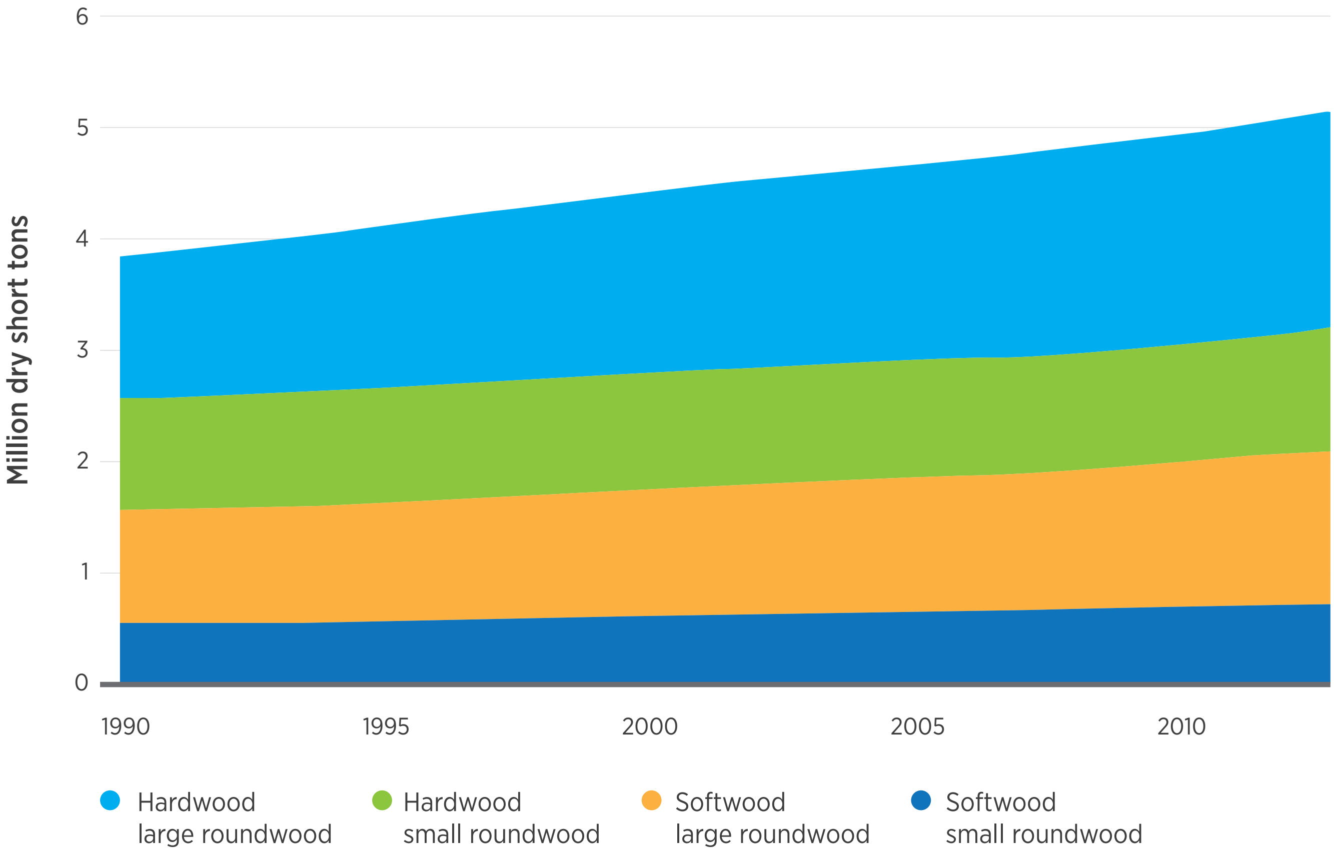
Figure 3.27 | Southern timberland acres by broad management type, 1990–2013 (excluding Kentucky)



Source: Data from SOFAC (2015) and USDA Forest Service (2015a).

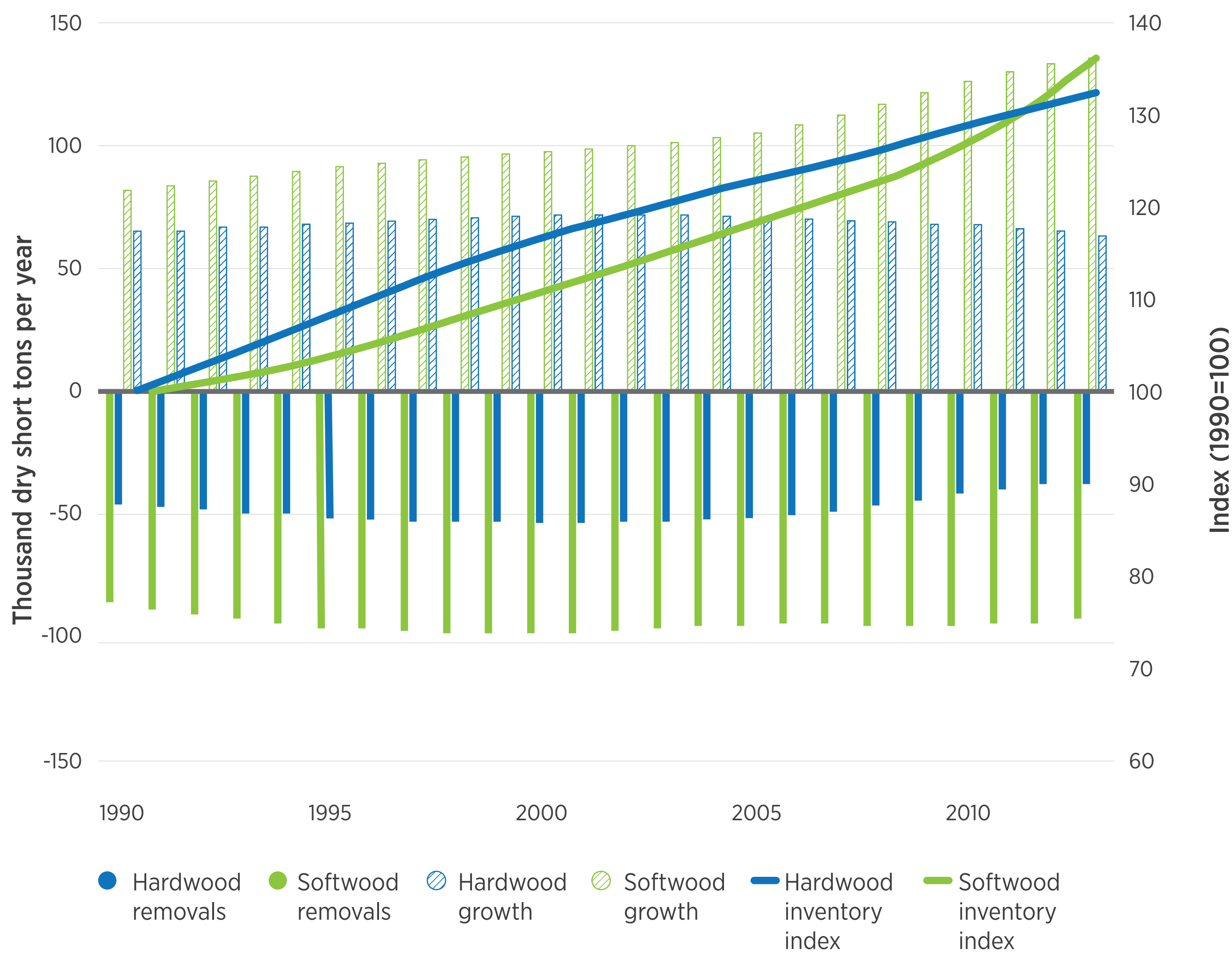
[21] We use Statistical Analysis System Proc Expand to fill in the between-survey-year estimates using a cubic spline function. This is for illustrative purposes only—these data are inadequate for use in any statistical modeling.

Figure 3.28 | Southern growing stock inventory, 1990–2013 (hardwood small ≤11 in. dbh, softwood small ≤9 in. dbh; excluding Kentucky)



Source: Data from SOFAC (2015) and USDA Forest Service (2015a).

Figure 3.29 | Southern growing stock growth and removals from timberland, and an inventory index, by species group, 1990–2013 (excluding Kentucky)



Source: Data from SOFAC (2015) and USDA Forest Service (2015a).

Overall, timberland area between 1990 and 2013 has been relatively stable, and large increases in pine plantations have generally been offset by declines in natural pine area.[22] Timber inventory, however, has been increasing steadily over this same time span—with hardwood inventories increasing by 32% and softwood inventories increasing by 36% (fig. 3.30). This picture of southern timberland area, however, obscures both the age class dynamics and the competing forces that could lead, all else held equal, to declining timberland area (increased agricultural rents or increased urbanization) or to increasing timberland area (increased timberland rents) (Hardie et al. 2000; Lubowski, Plantinga, and Stavins 2008). Given that urban land area is known to have increased over this time period, and that timber rents cannot realistically compete with

[22] Note that a data inconsistency in 2003–2004 in Kentucky led to exclusion of Kentucky from the area, inventory, growth, and removals charts; and incomplete timber product output data for Texas led to exclusion of Texas from the products discussion, although Texas is included in the Southern Pulpwood Production data.

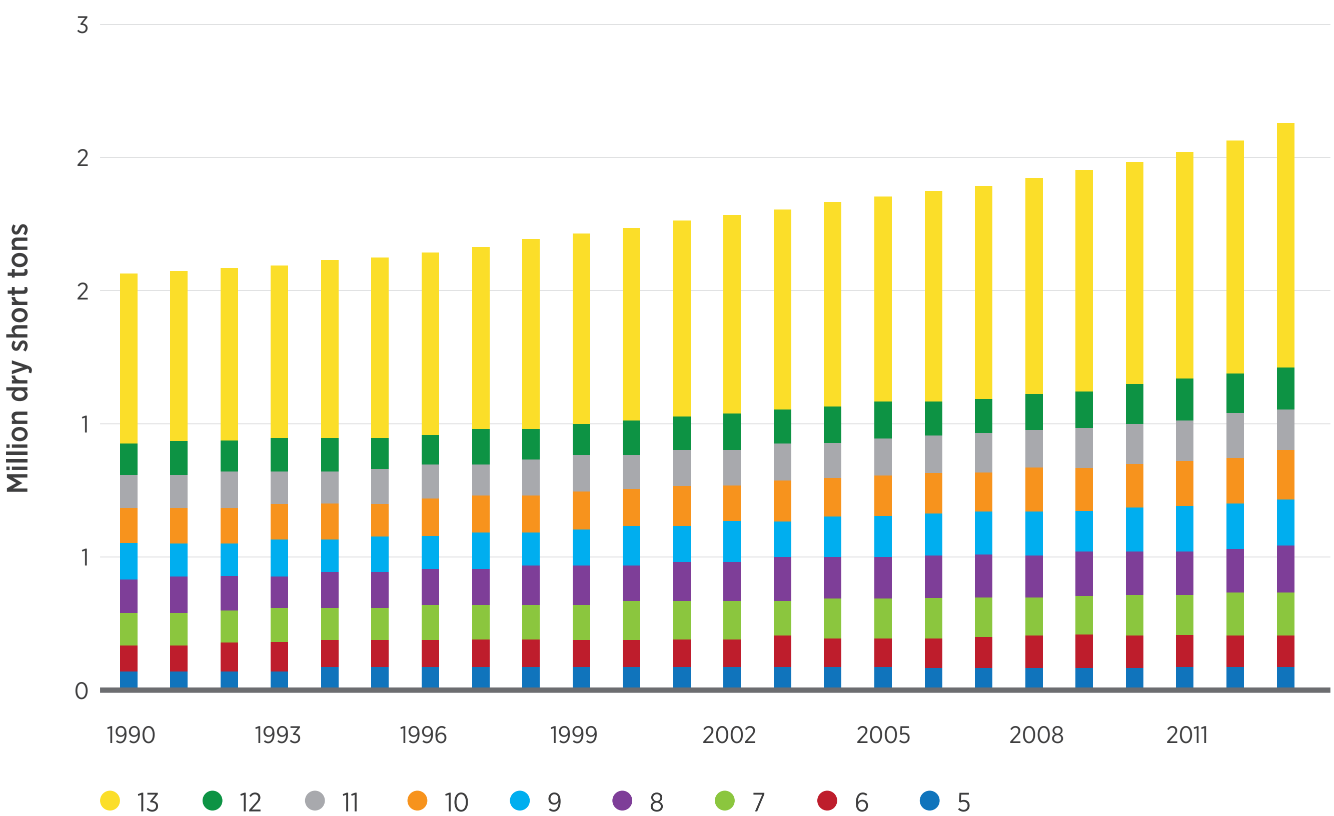
land values for development, the small changes in total timberland area imply that conversions of agricultural or pasture land into timberland have offset some or all of the declines in timberland area.

The age class dynamics can be seen, to some extent, by examining the changes in inventory by the size class of trees (fig. 3.30). Hardwood inventories are classed as large if they have >11 inches dbh and small otherwise; softwood inventories are classed as large if >9 inches dbh and small otherwise. Small-diameter hardwood inventory volume has increased at a rate of less than 0.03% rate per year since 1990, whereas large-diameter hardwood inventory has increased at a rate of more than 1.7% per year over 24 years, although this rate has fallen more recently (1% per year from 2005 to 2013). These data likely indicate that growth is slowing in older stands and that fewer acres have reverted to hardwoods in more recent years.

Softwood inventories, both large and small diameters, have increased at fairly steady rates of about 1% per year, although the softwood average annual rate of increase is nearly twice as high in recent years (2005–2013 compared with 1990–2005) (fig. 3.30). The overall increases can be attributed, in part, to the use of improved genetic stock and advanced silvicultural techniques. The more recent accelerated increase in softwood inventories is partly due to accumulating inventory in the larger diameter classes.

Figure 3.29 shows hardwood and softwood removals and growth in dry short tons per year (on the left axis) and an index of softwood and hardwood inventory (on the right axis). South-wide, (excluding

Figure 3.30 | Southern softwood growing stock inventory on timberland by diameter class (inches dbh), 1990–2013 (excluding Kentucky)



Source: Data from SOFAC (2015) and USDA Forest Service (2015a).

Kentucky), removals of both hardwood and softwood show the effects of the recession of 2007–2009. The rapid recent growth rates for softwood reflect the factors noted earlier as contributing to inventory gains. Growth rates for hardwood have returned to below 1990 levels after a brief spell at a higher rate. The recent decline in hardwood growth and the leveling off of hardwood removals can be seen in the leveling of the hardwood inventory index in more recent years.

These data show that timberland area has changed little over the last 24 years, but that the composition of timberland includes more planted timberland than in 1990. And more recently, hardwood removals are down, as are hardwood growth quantities. Timber inventories appear to be accumulating in the larger and older classes, in part because of the decline in use during and following the 2007–2009 recession. Although the increase in inventory and stable timberland area could be arguments for the use of timber in wood energy, there will likely be effects on existing markets, landowners, and forests.

3.5.7 Market Issues and Analysis

To illustrate the potential effects of an increase in wood energy demand under varying timber supply conditions, we use a partial equilibrium timber market model to show how price, removals, and inventory for different size and species of roundwood, as well as timberland, evolve over time in response to an increase in wood energy demand. The SRTS model (Abt, Cubbage, and Abt 2009) is used to evaluate a southern pellet supply region (U.S. Coastal South) as well as three smaller subregions of the South that have differing supply and demand characteristics. The subregions include the Gulf Coast (parts of Texas and Mississippi and all of Louisiana), the Mid-Atlantic Coast (parts of North Carolina and Virginia and all of South Carolina); and the Southeast Coast (parts of Georgia, Alabama, and Florida). More details on the modeling and the simulations can be found in Abt et al. (2014).

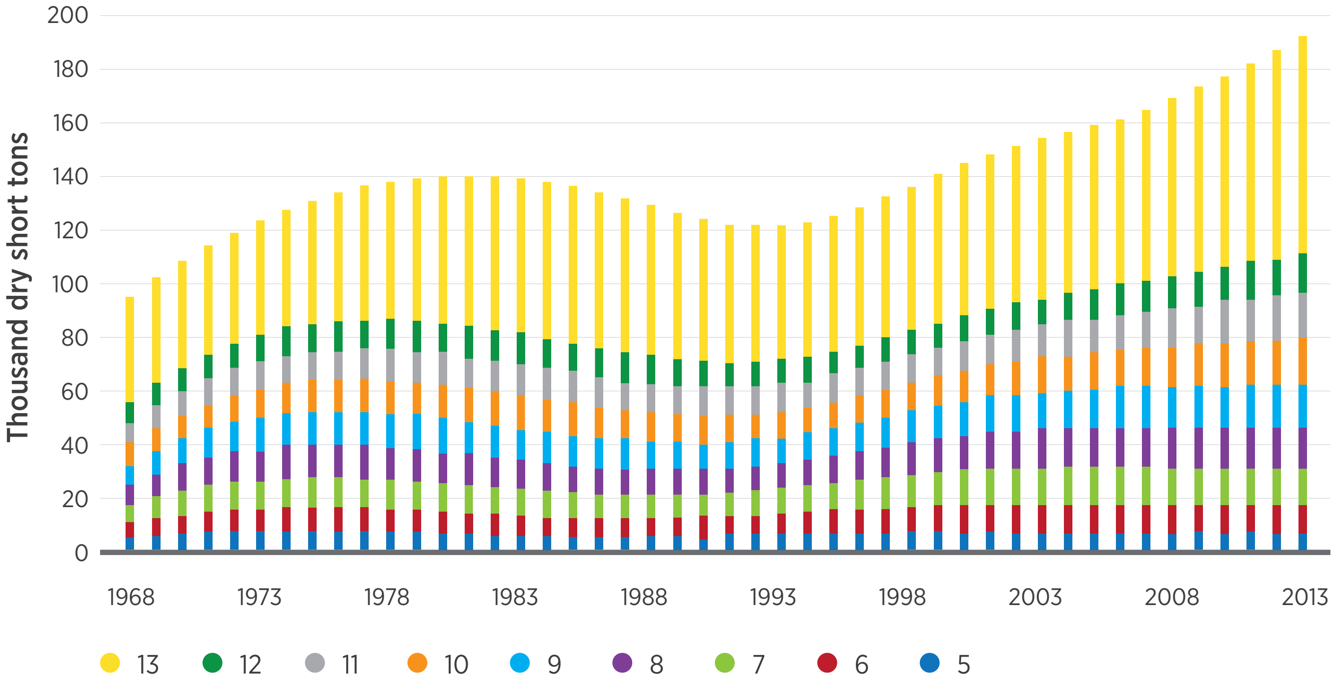
We use the historical data and the SRTS projections from Abt et al. (2014) to highlight the interactions between increasing wood energy demands and subregional specific timber supply factors and projected prices, inventory, and removals by species group and roundwood category (small or large). Using the announced facilities to represent potential demand for wood for energy (including pellets for both export and domestic wood energy), we compare two wood energy scenarios—a baseline scenario, which holds wood biomass feedstocks demand at 2010 levels, and an increased wood energy scenario. Both scenarios include constant demand for non-energy pulpwood and a moderately increasing demand for sawtimber, which are designed to reflect post-recession recovery levels.

3.5.8 Competing Pulpwood Demands—Mid-Atlantic Coast

The story of the Mid-Atlantic Coast is one of many little changes—closure of mills using hardwood pulpwood; an influx of new hardwood pellet manufacturers; increased exports of hardwood lumber to China; a Conservation Reserve Program planting boom; and a new panel milling industry. The sum total of these changes, even before the advent of the pellet industry, appeared to be rising removals of softwood small roundwood and falling removals of hardwood small roundwood. Outside the forestry sector, the growth in population and development along the I85/95 corridors and along the coast also have the potential to influence future timber markets in this area.

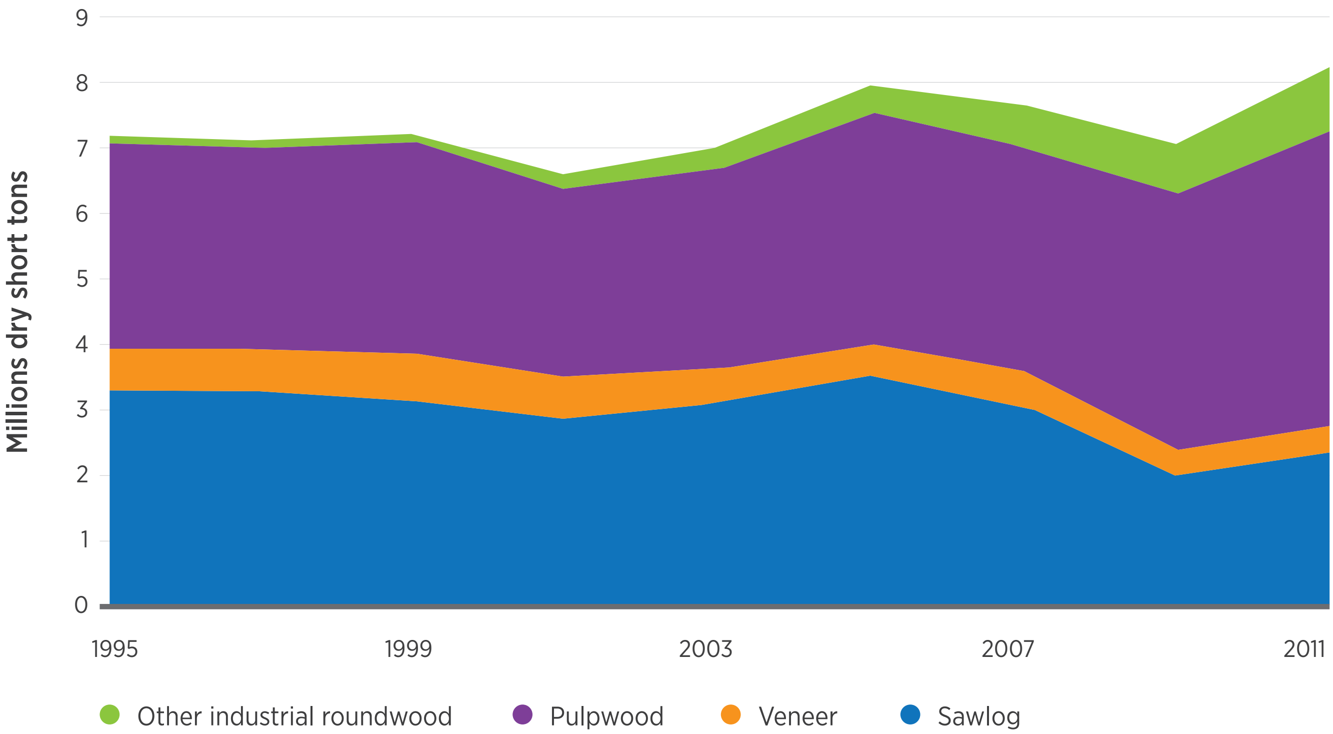
South Carolina is currently confronted with a fairly constant softwood small roundwood inventory (fig. 3.31) and rising softwood small roundwood demand (fig. 3.32). This combination of level small-diameter softwood production from forests, and increasing softwood small-diameter roundwood use (up 29% since 2005), would be expected to lead to increases in softwood pulpwood prices.

Figure 3.31 | Softwood growing stock inventory in South Carolina by diameter class (inches dbh), 1968 to 2013



Source: Data from SOFAC (2015) and USDA Forest Service (2015a).

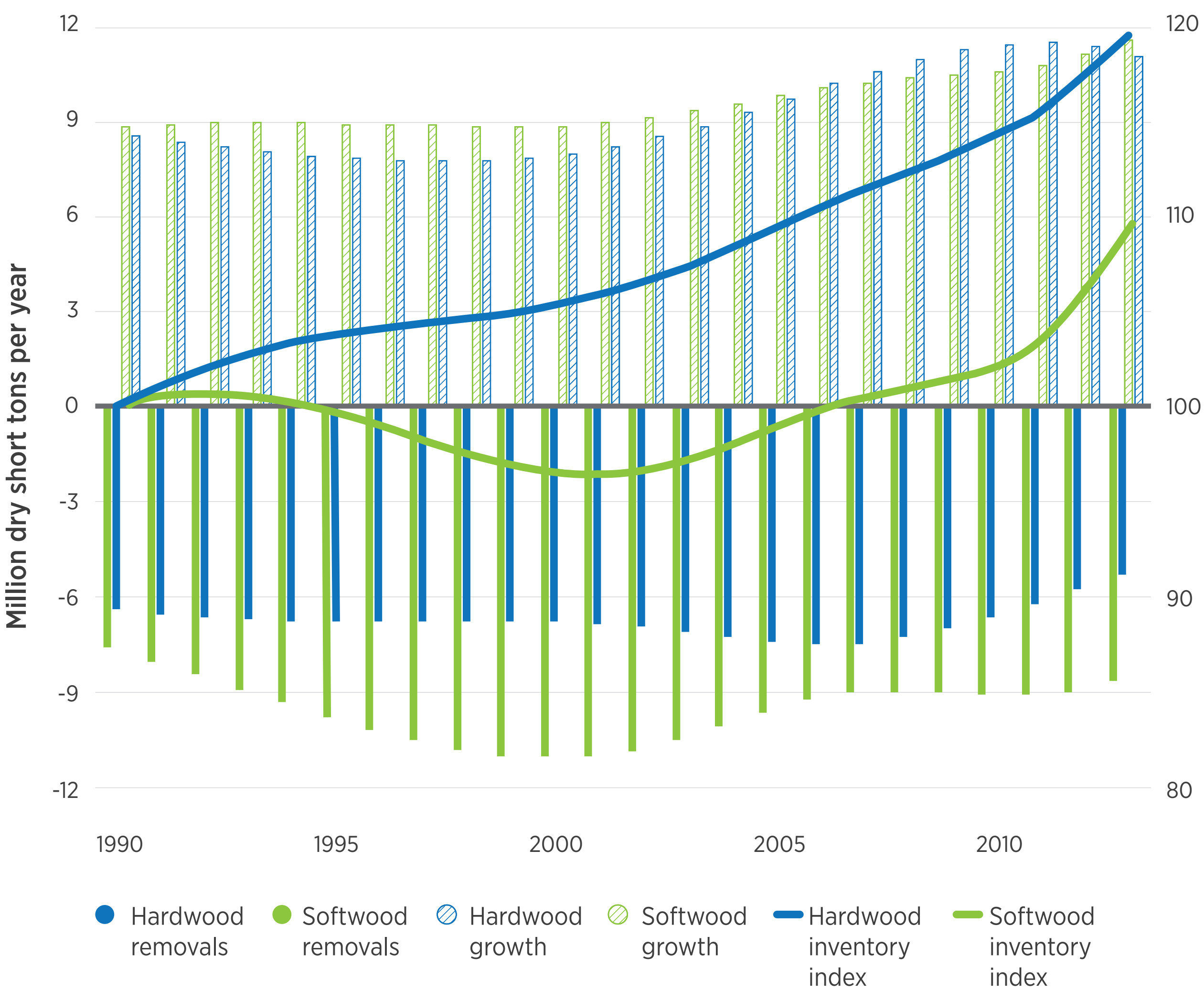
Figure 3.32 | South Carolina softwood timber product use, 1995–2011



Source: Data from USDA Forest Service (2015b).

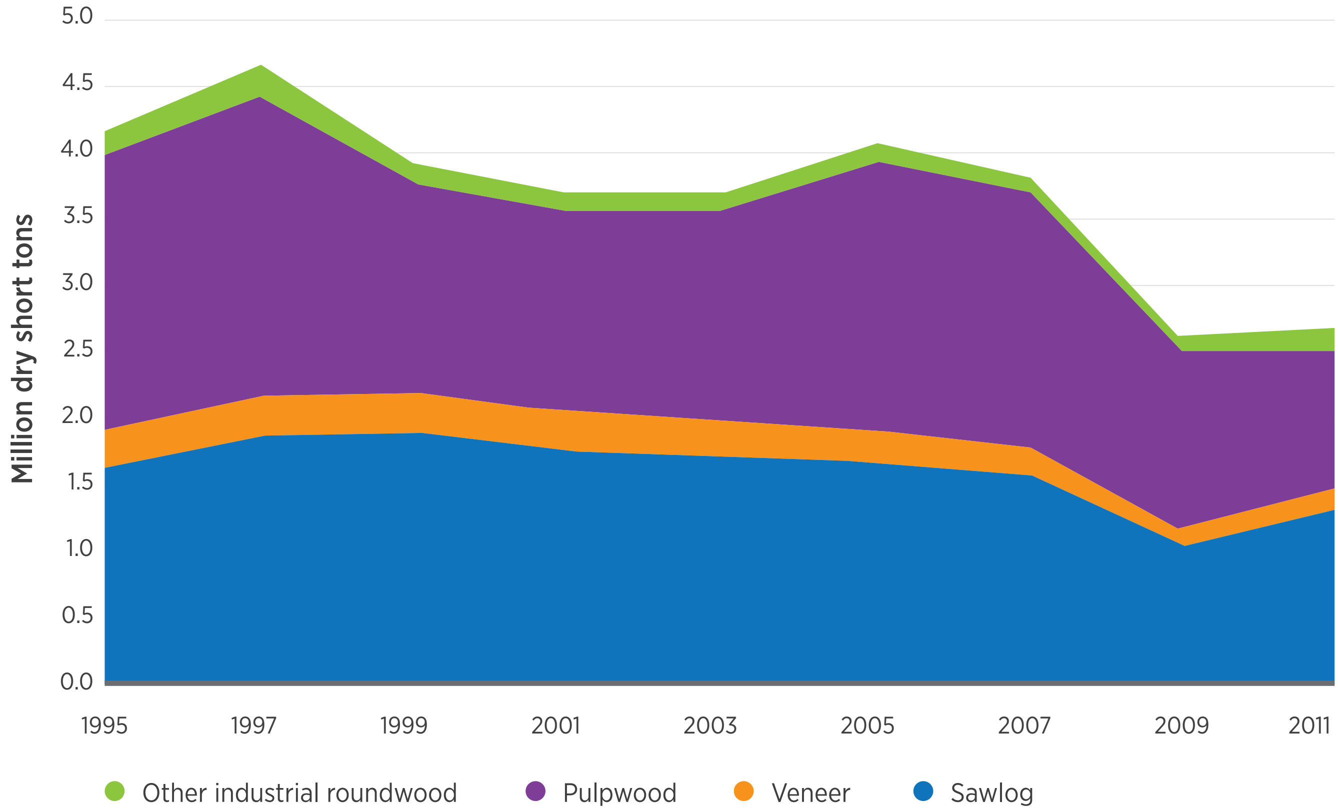
North Carolina illustrates a different situation, in which recent declines in hardwood growing stock removals (fig. 3.33) are reflected in declines in hardwood pulpwood use (fig. 3.34). This is leading to some increases in hardwood inventory—the hardwood inventory index shows a 20% increase since 1990. Softwood harvests were greater than softwood growth between 1995 and 2005 and led to the softwood inventory index falling below 100 for those years. Since then, however, reductions in removals and increases in growth have led to a 10% increase in softwood inventory over the 1990 values.

Figure 3.33 | Average annual growing stock growth and removals in North Carolina, and inventory index values for hardwood and softwood, 1990–2013



Source: Data from SOFAC (2015) and USDA Forest Service (2015a).

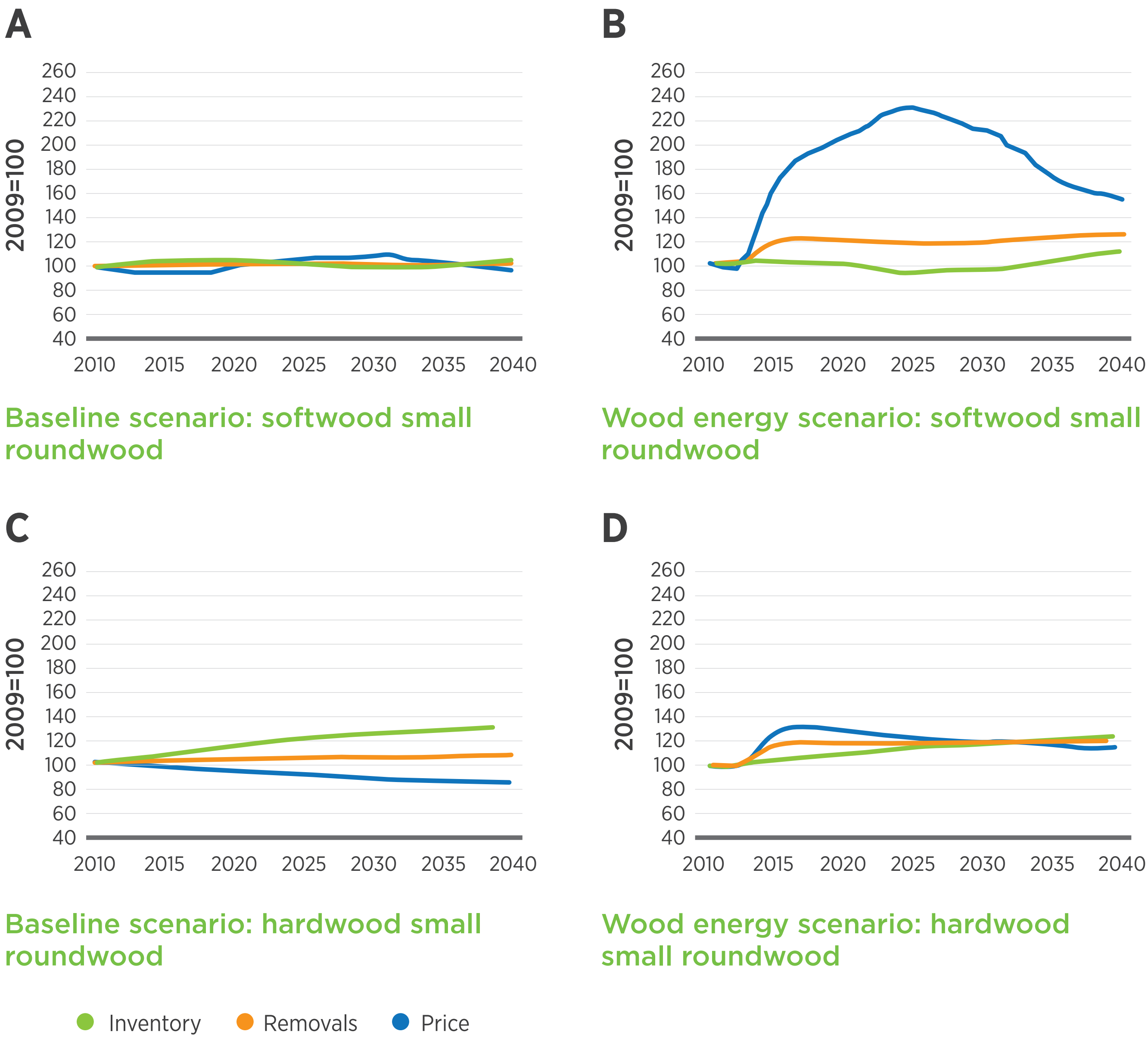
Figure 3.34 | North Carolina hardwood timber product use, 1995–2011



Source: Data from USDA Forest Service (2015b).

Projecting the current situation with modest increases in conventional products out to 2040, and no increase in wood biomass feedstocks use in the Mid-Atlantic coast region, results in a stable outlook for softwood small roundwood removals, prices, and inventory (fig. 3.35*A*). Projecting an increase in energy demand for softwood, however, leads to more than a doubling of stumpage prices and an accompanying increase in removals and decrease in inventory in the middle years of the projection (fig. 3.35*B*). The price and inventory recovery occur because the model assumes higher product prices lead to increased planting and increased timberland area; so after about 2025, available inventory rises and prices begin to fall. For small hardwoods in the baseline scenario, the decline in historical use contributes to continuing increases in inventory, with prices declining (fig. 3.35*C*). Projecting an increase in hardwood feedstock demand, however, results in increases in prices and harvest, and a slowing in the increase in inventory, though these are small relative to changes in the softwood market (fig. 3.35*D*).

Figure 3.35 | Mid-Atlantic Coast projection results showing inventory, removals, and price indices for small roundwood for 2010–2040 for both the baseline and wood energy scenarios and both softwood and hardwood



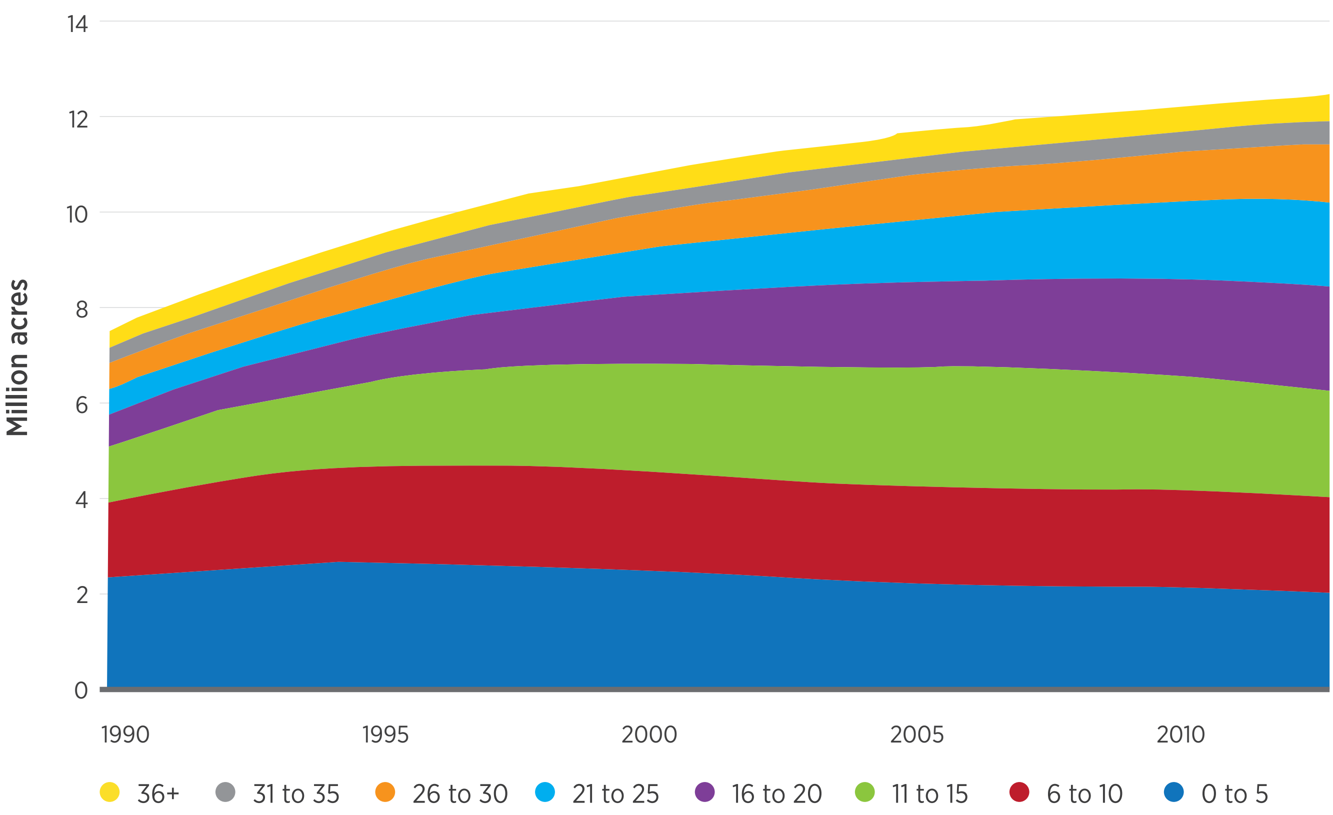
3.5.9 Decline in Sawtimber Harvest (the Sawtimber Overhang)—Gulf Coast

This region comprises the entire state of Louisiana, all but the Delta region of Mississippi, and the southeast coastal survey unit of Texas. The story in this region is the accumulation of softwood large roundwood inventory, sometimes called a "sawtimber overhang." The overhang results from a combination of two factors—a planting boom in the late 1980s (at least partially due to increased planting because of the Conservation Reserve Program) and a decline in harvest (at least partially due to the decline in sawtimber demand for housing since the start of the 2007–2009 recession).

Figure 3.36 shows the pine plantation acres by 5-year age classes in this subregion. The acres in the youngest age class (0–5 years) have been declining since 1995, and there are no acres in the oldest age classes (greater than 60, not specified in figure) before 2003—the pine plantation inventory average age is getting older. From 1990 to 2013, the acres in the 0–5-year age classes have declined by 7% while the acres in the older age classes have increased by 26%.

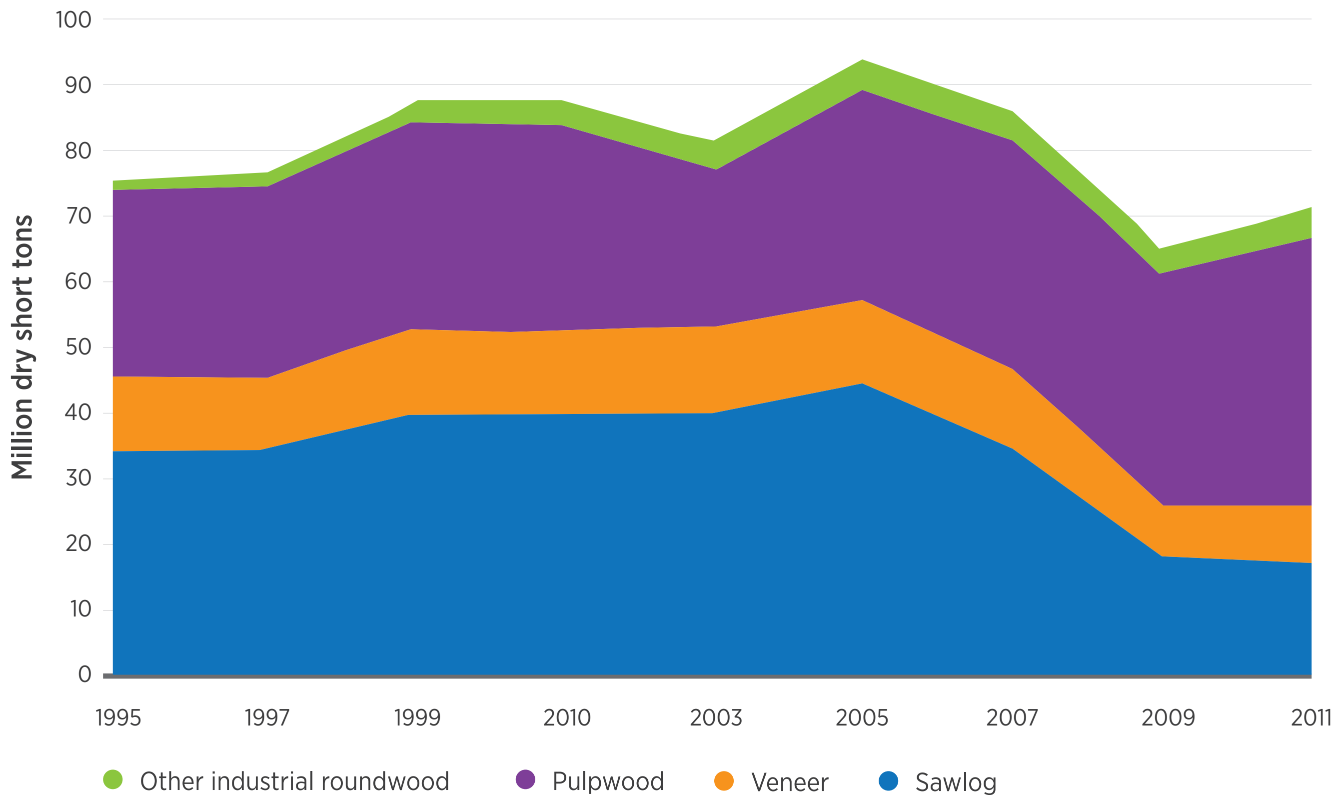
The use of this aging pine resource, however, has declined since 2005 and has not recovered following the recession (fig. 3.37). Between 1995 and 2005, sawlog use increased at an annual rate of 1.5%. Since then, however, sawlog use has decreased at 5.5% per year. As inventory accumulates in the large roundwood size because of lower demand, fewer acres are being planted because the lower sawtimber prices reduce expected landowner rents and fewer are willing to plant. In addition, with fewer final harvests, there are fewer areas available to plant.

Figure 3.36 | Pine plantation acres in Gulf Coast subregion by 5-year age classes, 1990–2013



Source: Data from SOFAC (2015) and USDA Forest Service (2015a).

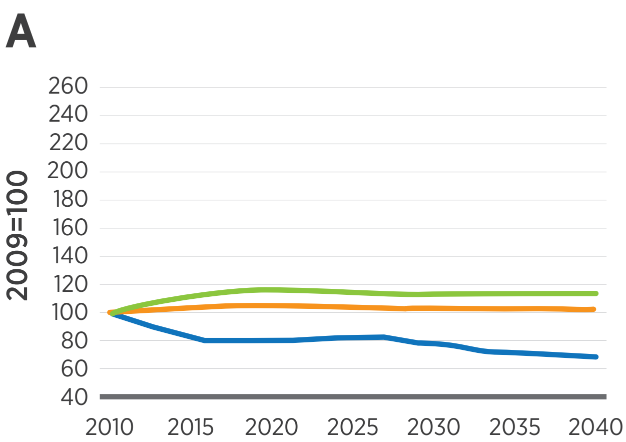
Figure 3.37 | Softwood timber product use in the Gulf Coast subregion (excluding Texas), 1995–2011



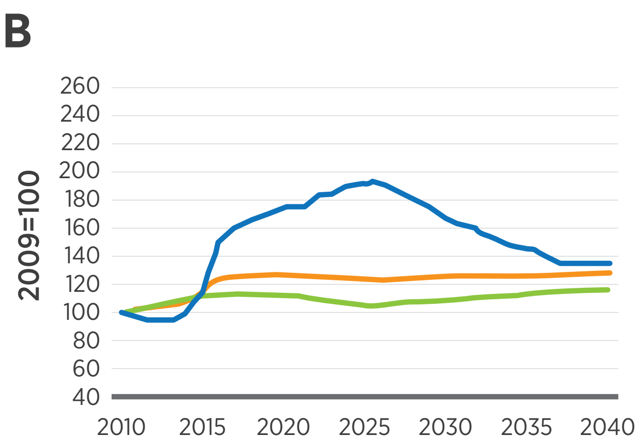
Source: Data from USDA Forest Service (2015b).

Projections of softwood small and large roundwood prices, removals, and inventory for this region, with and without additional wood biomass feedstocks demands, are shown in figure 3.38. The baseline scenario shows that both small (fig. 3.38*A*) and large (fig. 3.38*C*) roundwood inventories continue to increase and prices continue to fall. When increased wood energy demands are projected, however, figure 3.38*B* and *D* show that even as softwood small roundwood prices rise with the addition of new wood energy demands, there is almost no effect on softwood large roundwood markets. Even with increased harvests, the low large roundwood prices reduce landowner rents and so reduce incentives to plant trees either on recently harvested land or on converted agricultural land.

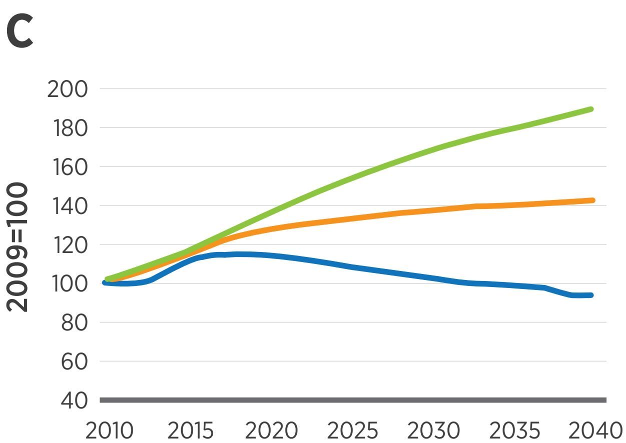
Figure 3.38 | Gulf Coast projection results showing inventory, removals, and price indices for softwood roundwood for 2010–2040 for both the baseline and wood energy scenarios



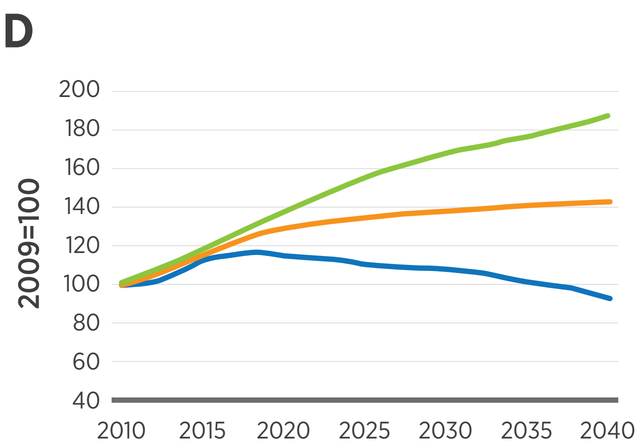
Baseline scenario: softwood small roundwood



Wood energy scenario: softwood small roundwood



Baseline scenario: hardwood small roundwood



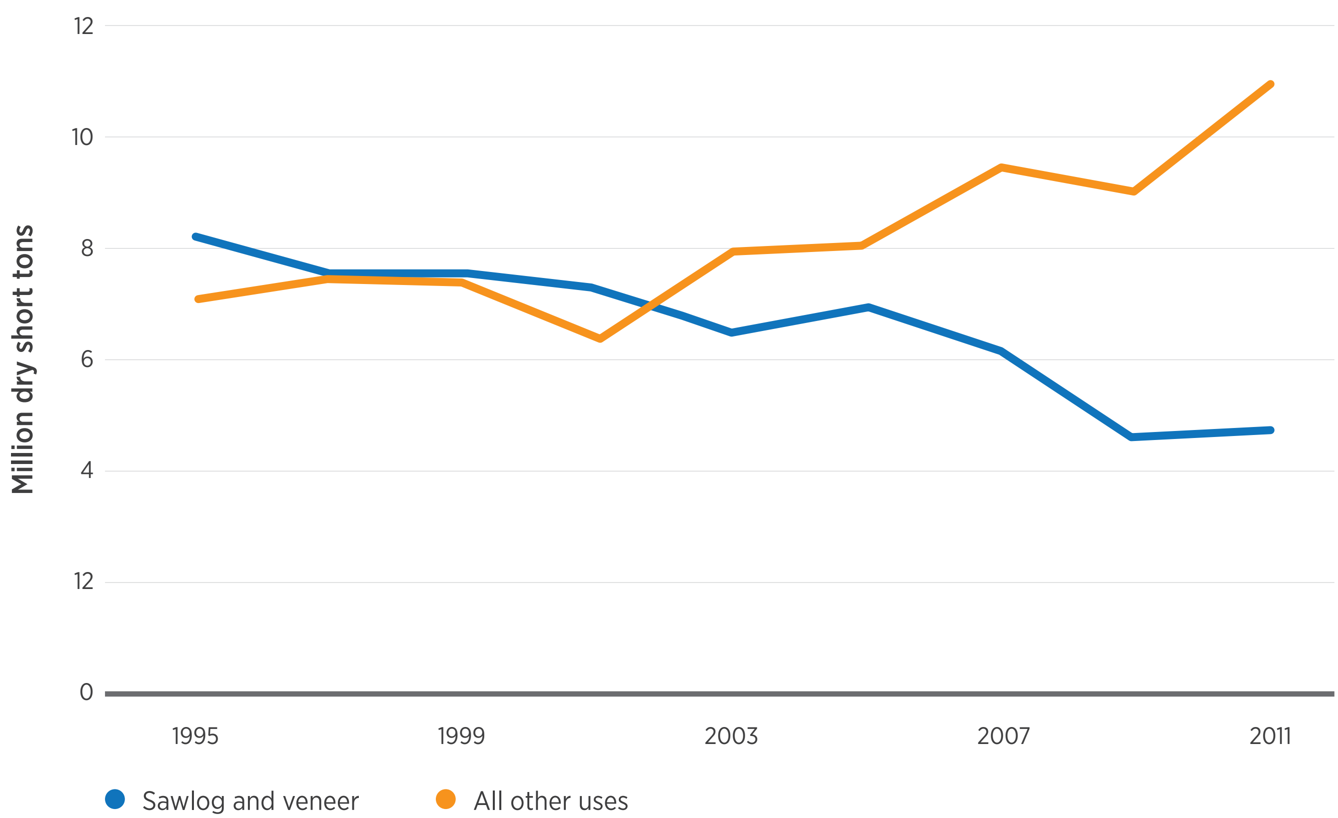
Wood energy scenario: hardwood small roundwood

Inventory Removals Price

Projected Recovery in Sawtimber Demand—Southeast Coast

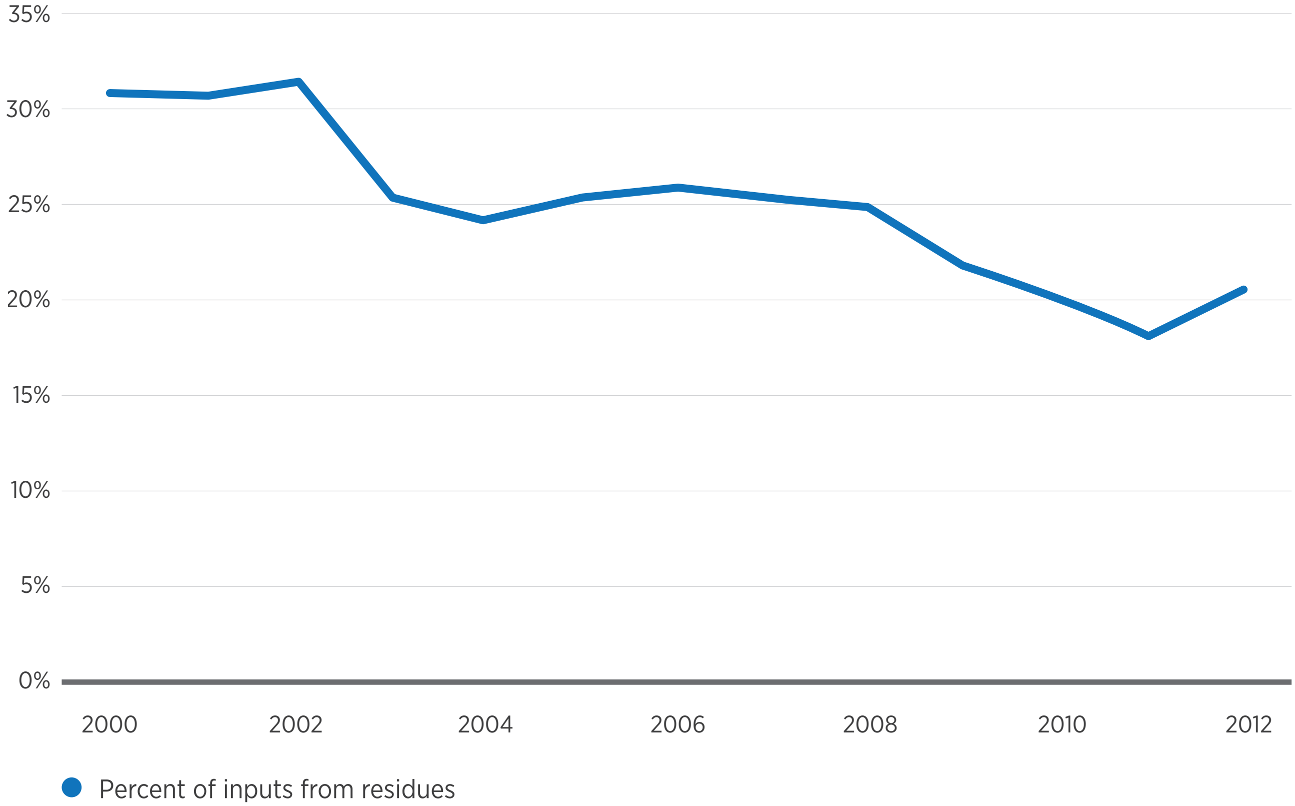
The Southeast Coastal region can be characterized by its productive forests and active markets for both small and large softwood roundwood. Similar to the other regions, this region had a significant falloff in use of sawlog and veneer timber diameter inputs (fig. 3.39) following the recession, while at the same time timber production for all other uses increased. Because national paper production did not increase during this period, we assume that the increase in small roundwood use was due to the decreased availability of sawmill residues—a result of decreased lumber demand for housing. Figure 3.40 shows the proportion of southern pulp mill wood input demand that was met by a combination of mill residues and remote chip mills from 2000 to 2012. The decline in 2002–2003 can be attributed, in part, to a decline in the use of remote chip mills, combined with an increase in composite panel production, which uses mill residues. The proportion of wood input met with residues continued to decline through the recession.

Figure 3.39 | Georgia softwood timber product use, 1995–2011



Source: Data from USDA Forest Service (2015b).

Figure 3.40 | Residue and chip use as a percent of total wood inputs to pulp production, U.S. South, 2000–2012

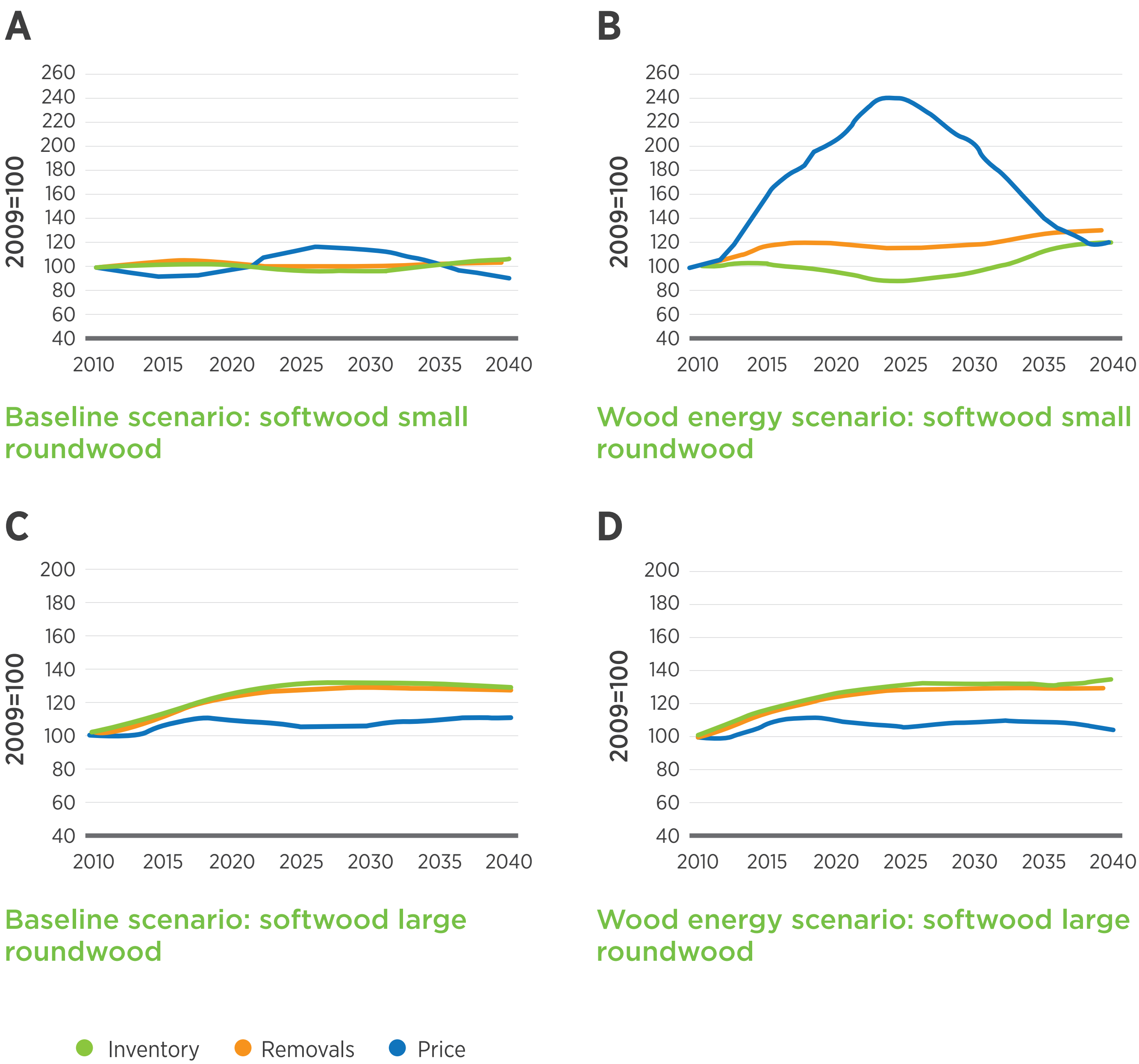


Source: Data from Bentley and Cooper (2015) and Bentley and Steppleton (2013).

In the projections for the Southeast Coast, we assume a 30% feedback between large roundwood input to sawmills, and residues. The actual rate of residue production depends on the diameter of the inputs to sawmills—larger diameter trees lead to lower levels of sawmill residue production. This means that regions where larger diameters of either hardwoods or softwoods are milled to lumber will have lower levels of residue production per unit of sawtimber input. The Southeast Coast has the lowest average diameter inputs in the South and thus has a higher rate of residue feedback. With a 30% feedback of mill residues to pulp or energy production, total sawmill residues from this region amount to between 7% and 10% of total wood energy demands. Thus, an increase in sawmill production would lead to further reductions in the impacts of net wood energy on the forest. This, in turn, would reduce the price pressure and the effect on small roundwood removals and inventory, but would also reduce the ultimate effect on timberland rents and thus reduce the effect on timberland area.

The baseline scenario (fig. 3.41*A*) projects that prices, inventory, and removals of softwood small roundwood stay fairly constant, consistent with the constant level of demand, while fluctuating slightly as inventories and prices rise and fall and removals fall and rise. The wood energy scenario shows more than a doubling of prices, higher removals, and lower inventories because of increased demand for wood biomass feedstocks (fig. 3.41*B*). Figure 3.41*C* and *D* show that the harvest of sawtimber is little affected by the increased wood energy demands, although there is some response in future years as timberland area increases in response to higher timberland rents under the wood energy scenario.

Figure 3.41 | Southeast Coast projection results showing inventory, removals, and price indices for softwood roundwood for 2010–2040 for both the baseline and wood energy scenarios

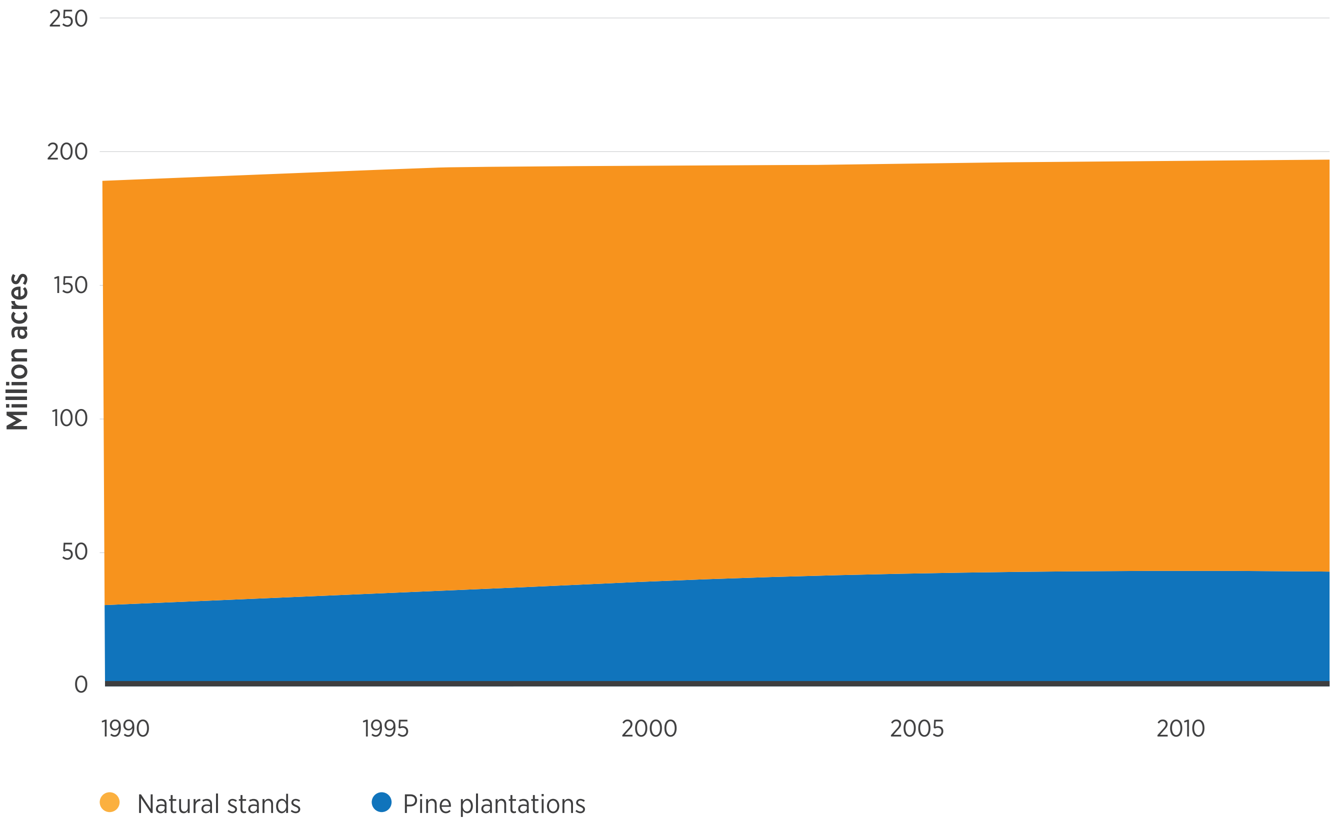


Timberland Area—U.S. Coastal South

As shown earlier in figure 3.12, and in figures 3.42 and 3.43, the area of planted pine in the South increased steadily from 1990 to 2013, increasing from 16% of U.S. Coastal South forests to 22% of those forests over 24 years. This rate of planting increase, however, has slowed in recent years; it is down from 1.3% per year during 1990–2005 to only 0.5% per year in 2005–2013. During that same time period, natural forests decreased by a total of 3%; the fastest period of decline (1990–2005 at -0.13%/year) coincided with the fastest period of growth in planted pine. In more recent years (2005–2013), this rate of loss has slowed to only -0.02%/year.

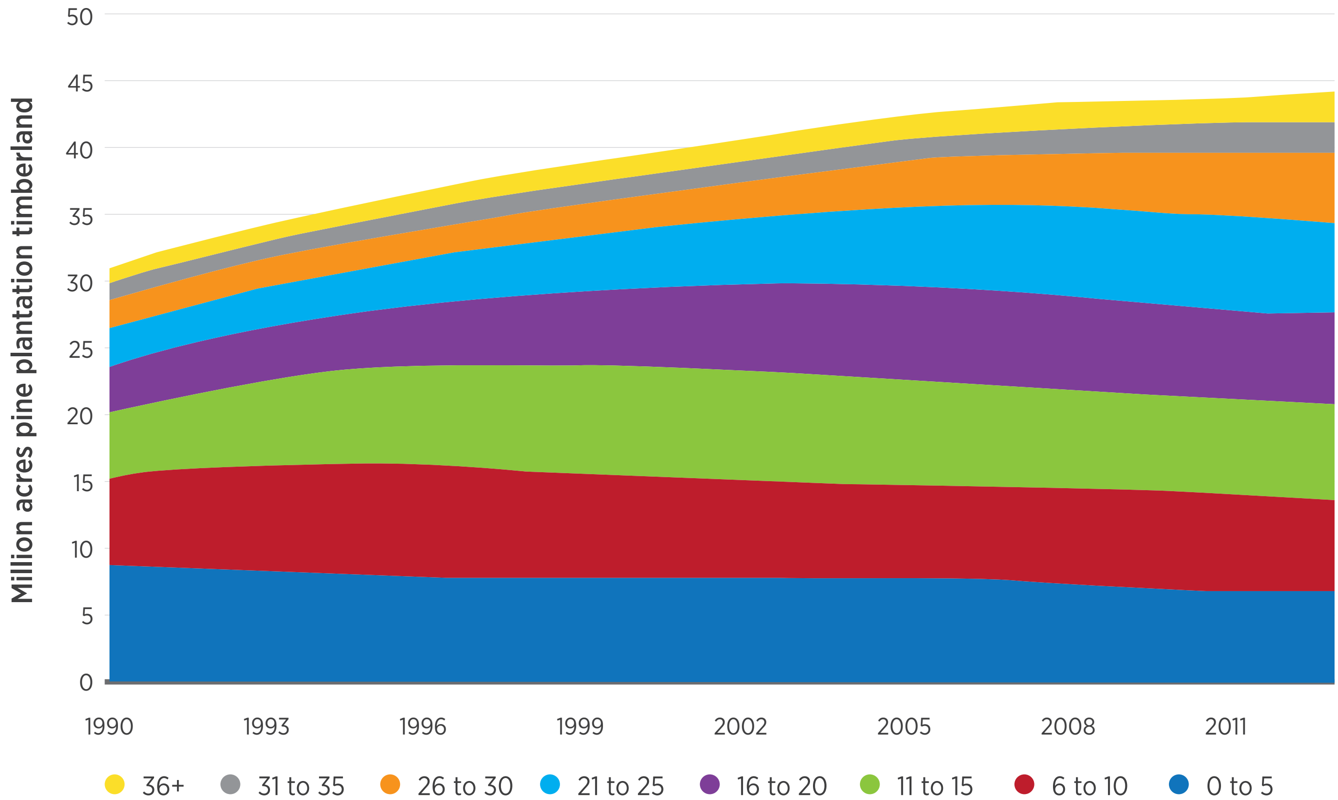
Figure 3.43 shows that the area of plantations in the youngest age class (0–5 years) has declined by the "lump" in age classes that resulted from planting subsidized by the Conservation Reserve Program. As this lump works its way through the age classes, we would expect total planted acres to decline unless additional assistance programs or increased sawtimber prices combine to increase landowner incentives to plant pine.

Figure 3.42 | Acres of natural stands and pine plantations in the Coastal South, 1990–2013



Source: Data from SOFAC (2015) and USDA Forest Service (2015a).

Figure 3.43 | Pine plantation acres in the Coastal South by age class



Source: Data from SOFAC (2015) and USDA Forest Service (2015a).

The projected effect of this falloff in planting can be seen in figures 3.44 and 3.45. Figure 3.44*A* and *C* show the baseline projections for softwood small and large roundwood, respectively. The projected baseline changes over time in the small roundwood market do not exceed 20% (up or down), similar to the subregional projections. The baseline changes in the softwood large roundwood market are also similar to the subregional projections, reflecting an accumulating large roundwood inventory, and corresponding low prices, even as removals rise to near pre-recession levels. Adding an increase in wood energy demands (fig. 3.44*B* and *D*) also produces projections similar to the subregional projections, with increases in small roundwood prices, especially in the middle of the projection, and then prices falling as inventory rises toward 2040. Inventory increases are a result of the projected increase in timberland acres, which is a result of the increased land rents resulting from increased softwood small roundwood prices. The addition of wood energy demands has little effect on the large roundwood markets, except that toward the end of the projection, prices fall slightly as the increases in planting lead to increased large roundwood inventories by 2040. Consistent with expectations, the changes in the projections for the Coastal South are smaller than the projections for the individual subregions.

Figure 3.44 | Total Coastal South projection results showing inventory, removals, and price indices for small round-wood for 2010–2040 for both the baseline and wood energy scenarios and both pine and hardwood

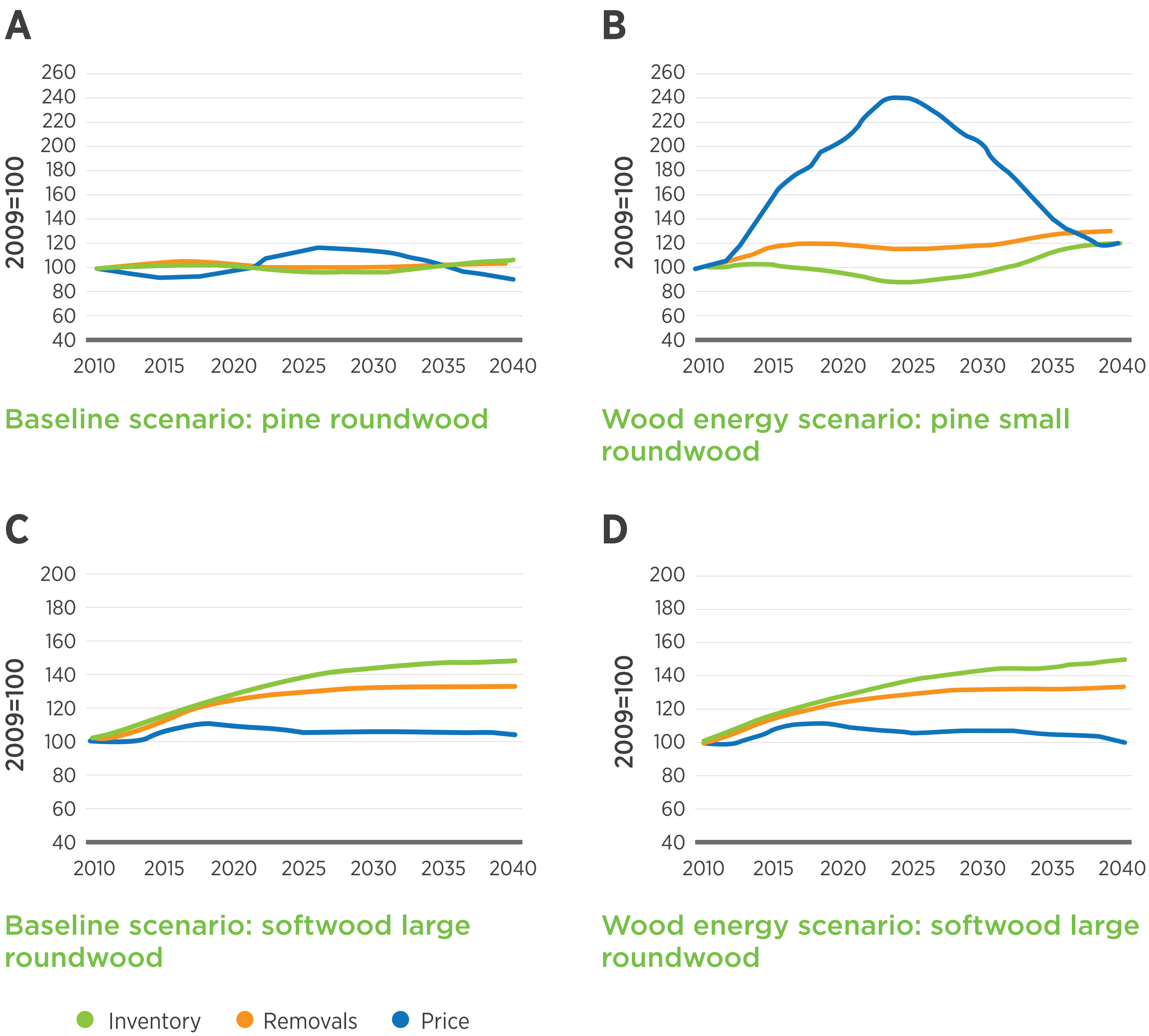
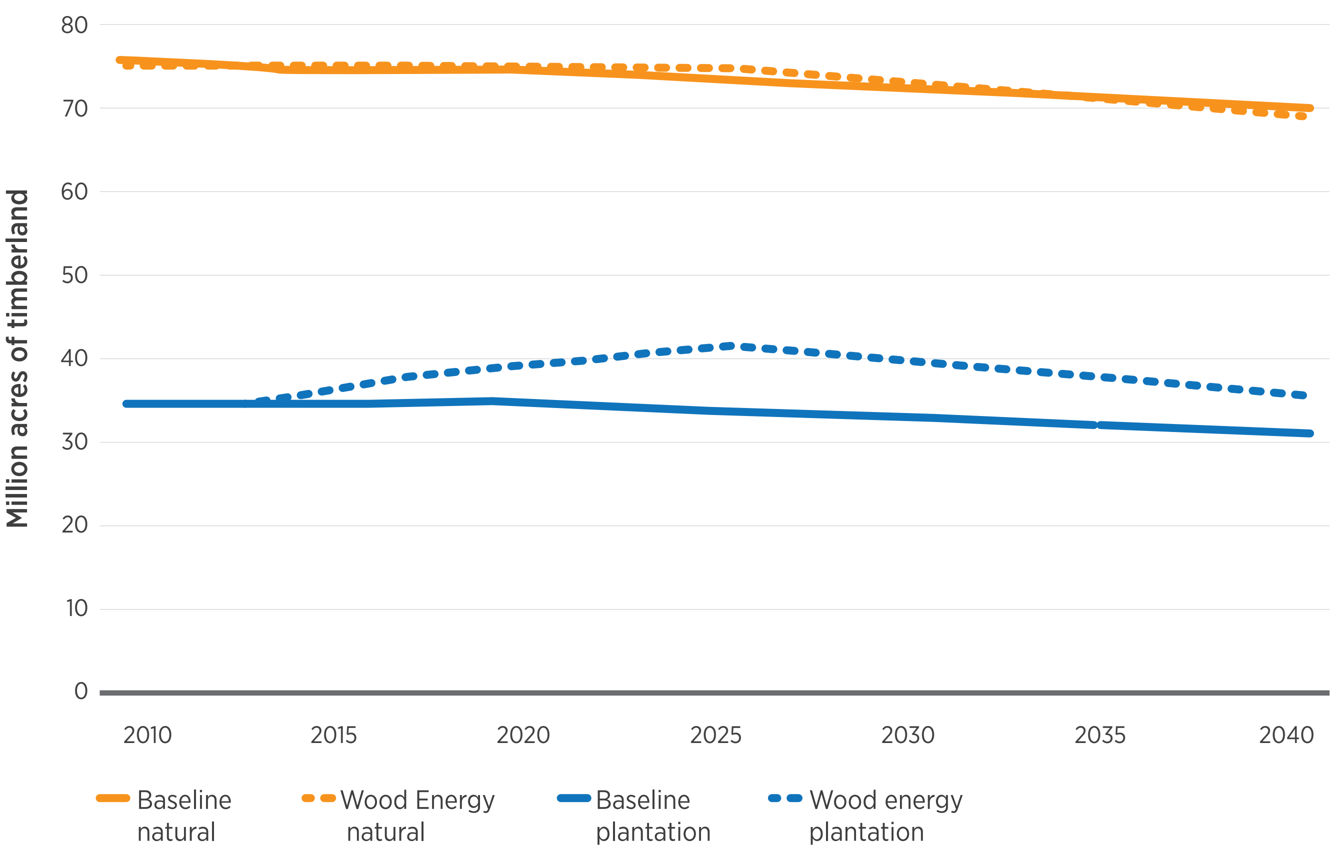


Figure 3.45 | Projected land use for Coastal South, 2011 to 2040, showing assumed split between pine plantations and natural forest for both the baseline and wood energy scenarios



3.5.10 Conclusions

Timber markets in the South are affected by the age class distribution and broad management types in the current forest, and these markets in turn affect future age class distributions and management types. Because both small- and large-diameter roundwood can be produced from a single acre of timberland (although they not always are), the product markets for large- and small-diameter timber are linked at each point in time. In addition, because the only way to get large-diameter timber stands is to allow small-diameter stands to age, markets are also linked over time.

Competition for pine small roundwood in some regions is likely to intensify with increased demands for wood biomass feedstocks, leading to higher prices and some potential reductions in other uses, as shown in the Mid-Atlantic subregion. Past reductions in conventional demands for hardwood small roundwood imply that prices for this feedstock are not likely to increase as rapidly as prices for pine small roundwood.

An increase in demand for small-diameter roundwood alone, however, is not likely to affect the demand for sawtimber. And as shown for the Gulf Coast subregion earlier, using projected demands, the prices for sawtimber will likely continue to stay low; this may reduce landowner incentives to replant, as well as the availability of land for replanting. This final harvest, which occurs for sawtimber production and provides planting opportunities, will affect the availability of “thinnable” acres in the 10–15 years following the harvest and thus affect the availability of the next generation of small-diameter softwood removals.

Potential recovery in the housing and lumber markets leading to renewed sawmilling has the potential to increase the availability of sawmill residues, which may ease the pressure on the small roundwood resources and thus ameliorate price increases and impacts on other uses. As shown for the Southeast Coast region earlier, this impact is greatest in areas that have active sawmilling industries and smaller average diameter sawmill inputs.

Finally, timberland has been shown to respond to land rents, and increased demand with a quasi-fixed inventory will lead to higher prices and thus higher land rents. In this way, increased demand for feedstock for wood energy can contribute to increased timberland area (or at least to smaller decreases in timberland area).

3.6 Summary and Discussion—Forest Resources to Roadside

This chapter considers only primary forest resources (i.e., those that come directly from the forests). These are logging residues and whole-tree biomass. Three other categories of forest feedstocks do come directly from forestland but are considered to be waste for the purpose of this report. They are described and quantified in chapter 5.

An economic model, ForSEAM, is used to develop supply curves for biomass from the land. The model simulates the annual harvest of commercial products as a way to estimate logging residues. These products include sawtimber, pulpwood, and roundwood for board products. In addition, the model provides estimates of whole-tree biomass harvested for biomass uses only. Logging residues are trees not meeting merchantable timber specifications and tree components, such as limbs, tops, and cull logs. Whole-tree biomass is a combination of merchantable trees and trees not meeting merchantable timber specifications. The whole-tree biomass comes from stand diameter classes without larger, merchantable sawtimber trees. The simulation uses two types of harvesting (cutting) options: clear cutting and thinning.

Only timberland is used in the model, rather than all forestland. Both private and federal timberlands are included, but there are restrictions on slope and reserved land.

Other parameters considered and included in the model are (1) wood type, (2) stand type, (3) land slope, (4) product types, (5) regions, (6) costs, and (7) time (year). All the outputs of the model by county will be made available in the Bioenergy KDF. For example, estimates of biomass availability by ton are developed as logging residues from clear cutting and thinning operations and as whole-tree biomass harvested from clear cutting and thinning operations to meet extra biomass demands as allocated down to a county. Appendix B discusses FIA estimates and sampling errors for forestland area and forest biomass. Estimates are aggregated into national estimates as reported, and the disaggregated estimates are in the Bioenergy KDF. Wood waste resource analyses are moved to chapter 5. Federal lands are included from the forest resource analysis—the model uses private industrial, private non-industrial, and federal timberlands.

Input costs are developed explicitly for the model. These costs are used for relative seeding of the model to account for different stumpage prices that indicate product value and to account for relative differences among harvesting systems, such as machinery types and the makeup of systems specific to stand, tree size, wood type, and land slope. Other differences include regional labor rates and whether the product is timber (roundwood in the model) or biomass (whole-tree chips in the model).

Cost curves are developed for the logging residues and the whole-tree biomass within the demands of six selected scenarios of wood use and possible increases in the use of wood for energy. The projections for U.S. forests and forest products markets are under varying market conditions. USFPM/GFPM and the SRTS inventory and harvest model for the South are used to project the harvest removals, inventory, price, and timberland area resulting from three levels of wood biomass feedstock demands. The scenarios range from a baseline to high wood/biomass demand scenarios: Baseline_ML, MM, MH, HL, HM, and HH.

Although a more in-depth analysis of the sustainability of forest resources from the land will be forthcoming, an effort is made to use assumptions and methods that provide some basis for sustainability in this report. A few of the cautions and constraints involved the following:

- Restricting harvest to timberland within private ownership, which excludes designated reserved land or protected areas
- Restricting the removal of logging residues to slopes less than 40%
- Assuming BMPs are used to harvest and assuming costs for such practices in the estimates.

Using these demands, ForSEAM is used to develop supply curves (appendix B) for which cumulative supply estimates in dry tons are developed as a function of marginal costs per ton for stumpage and harvest cost to the landing (i.e., roadside cost per ton). Summaries of aggregated forest biomass available for the analysis period and under selected parameters are shown in table 3.26.

A summary of forest resources to the roadside at a price of $60 per dry ton is shown in table 3.27 for the baseline and the representative high scenario. These are the selected forest resource availabilities used in the summary and total biomass of *BT16* in the executive summary, table ES.1. Although the HH scenario is used as the representative high-biomass scenario, some of the other scenarios actually produce more biomass (see all the scenarios in table 3.20). The decision was made to use the HH scenario as the high biomass scenario to remain consistent with the RPA 2010 assessment (USDA Forest Service 2012a) and the USFPM, GFPM, and SRTS Models used in the analysis. The decision not to establish biomass plantations in this study does not negate that the HH is the highest biomass scenario. The plantation restriction needs additional consideration and further analysis to evaluate the merits and concerns of establishing millions of acres of fast-growing energy plantations on forestland. As mentioned, such woody crops are considered to be a significant feedstock on agricultural land, as reported in chapter 4.

Another result in some cases is that the available biomass in the out years from the 2015 baseline decreases. The decrease is the result of the model restriction concerning the harvest of whole trees from the small-diameter stands. If stand diameter class 3 stands are allowed to be harvested every 7 years (i.e., the time to grow large enough to become a stand diameter class 3), then more biomass is available in the out-years. However, this would exclude any late seral or mature forest stands from the successional development of the small-diameter stands. To overcome the issue of maintaining much of the forest cover in repeating small-diameter stand development, stands are harvested only once for biomass (i.e., whole-tree biomass stands) and then put back into longer-term timber rotations. Since doing so takes considerable time, much longer than the 25-year modeling time span, it reduces the amount of biomass available for harvest toward the end of the modeling period. The model still maintains that state-level growth must always exceed harvest levels, and this longer outlook helps to ensure sufficient growth, as well as diverse, multiple-aged stands across the landscape.

Table 3.26 | Summary of Baseline and High Forest Resources by Cost, Year, and Feedstock Type

Stand species	$40				$60				$80			
	2017	2022	2030	2040	2017	2022	2030	2040	2017	2022	2030	2040
	Million dry tons											
Baseline_ML[a] (Baseline scenario)[b]												
All land												
Logging residues	17.9	19.4	21.4	20.8	17.9	19.4	21.4	20.7	17.9	19.4	21.4	20.8
Whole-tree biomass	3.1	1.0	0.3	0.0	69.9	73.7	59.8	60.7	98.1	96.6	94.6	95.2
Federal land excluded												
Logging residues	15.7	17.1	18.8	18.4	15.7	17.1	18.8	18.4	15.7	17.1	18.8	18.4
Whole-tree biomass	2.8	1.0	0.3	0.0	52.3	55.4	42.7	46.1	76.4	75.1	72.4	73.4
Total: Baseline (all land)	**21.0**	**20.5**	**21.7**	**20.8**	**87.8**	**93.1**	**81.1**	**81.5**	**116.0**	**116.0**	**116.0**	**116.0**
Total: Baseline (no federal)	**18.6**	**18.1**	**19.1**	**18.4**	**68.1**	**72.5**	**61.6**	**64.5**	**92.1**	**92.2**	**91.2**	**91.8**
HH[c] (High-yield scenario)												
All land												
Logging residues	18.0	19.3	20.7	19.9	18.0	19.3	20.7	19.8	18.0	19.3	20.7	19.9
Whole-tree biomass	2.7	0.7	0.1	0.0	61.3	63.7	51.0	40.7	65.0	63.7	62.3	63.1
Federal land excluded												
Logging residues	15.7	16.9	18.1	17.5	15.7	16.9	18.1	17.5	15.7	16.9	18.1	17.5
Whole-tree biomass	2.5	0.7	0.1	0.0	46.1	48.4	37.3	33.2	48.6	48.4	46.5	51.0
Total: High scenario (all land)	**20.6**	**20.0**	**20.8**	**19.9**	**79.3**	**83.0**	**71.7**	**60.6**	**83.0**	**83.0**	**83.0**	**83.0**
Total: High scenario (no federal)	**18.3**	**17.6**	**18.2**	**17.5**	**61.9**	**65.3**	**55.4**	**50.8**	**64.4**	**65.3**	**64.6**	**68.5**

[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]Baseline_ML is comparable to the base-case scenario in chapter 4.

[c]The HH scenario 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. HH is comparable to the high-yield scenario for agriculture at 3% in chapter 4.

The underlying assumptions are very important with regard to the available forest biomass. In each of the six scenarios, the amount of wood available for harvest to meet traditional and biomass demands is limited by three factors. The first factor is the growth constraint at the state level, which limits harvest to the estimated annual growth. The second factor limits the amount of harvest that could occur in any single POLYSYS region (modeling unit) to 5% of the available volume. This is to ensure that the model produces a patchwork of harvested sites across the landscape indicative of current timber harvests. The final constraint limits the re-harvest of land-once-harvested. Land-once-harvested in the model could not be harvested again until the land re-establishes a stand that has grown to a class 2 diameter size (i.e., a pulpwood-sized stand). As an example of the significance of the underlying assumptions, a sensitivity analysis is completed on two factors. In the first simulation, 5% of the available volume is allowed to increase to 10% (Increased Volume Scenario) in any one POLYSYS region. A second constraint change is to the re-establish stand rule to allow 1/4 of the harvested land to become available for harvest again once the stand grows to a stand class 3 diameter (Increased Volume Plus Scenario). The remainder of the stands are not harvested until the stands become at least a stand diameter class 2.

A comparison quantity of biomass available at $40, $60, and $80/dry ton in the Baseline_ML and HH scenarios with and without these changes is presented in appendix table B.8. Biomass availability expands (more tons are estimated available) as these constraints are eased. The sensitivity analysis shows that changing these assumptions (underlying assumptions) increases the amount of the biomass estimate at the $80/ton price from 83 million tons in the HH Scenario to 135 million tons in the Increased Volume Scenario. This occurs at the $60 price as well as the $40 price point.

Since the expectation is that the South will become the primary source of wood for biomass, additional analyses are completed to understand the shaping markets and changing supply. A continuing hypothesis is that conventional timber and biomass will be produced together. Associated with that assumption is that using biomass will provide management options that can lead to higher-value products and, finally, that all wood products will go to the highest value as long as markets are available. Markets for large- and small-diameter timber are linked at each point in time.

Competition for pine small roundwood in some regions is likely to intensify with increased demands for wood biomass feedstocks, leading to higher prices and some potential reductions in other uses. However, timberland has been shown to respond to land rents, and increased demand will lead to higher prices and thus higher land rents. In this way, an increased demand for feedstock for wood energy can contribute to increased timberland area (or, at least, to smaller decreases in timberland area) for all market demands.

Table 3.27 | 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[a] (Baseline scenario)[b]												
Logging residues	17.9	19.4	21.4	20.8	17.9	19.4	21.4	20.7	17.9	19.4	21.4	20.8
Whole-tree biomass	3.1	1.0	0.3	0.0	69.9	73.7	59.8	60.7	98.1	96.6	94.6	95.2
Total: Baseline	**21.0**	**20.5**	**21.7**	**20.8**	**87.8**	**93.1**	**81.1**	**81.5**	**116.0**	**116.0**	**116.0**	**116.0**
HH[c] (High-yield scenario)												
Logging residues	18.0	19.3	20.7	19.9	18.0	19.3	20.7	19.8	18.0	19.3	20.7	19.9
Whole-tree biomass	2.7	0.7	0.1	0.0	61.3	63.7	51.0	40.7	65.0	63.7	62.3	63.1
Total: High scenario	**20.6**	**20.0**	**20.8**	**19.9**	**79.3**	**83.0**	**71.7**	**60.6**	**83.0**	**83.0**	**83.0**	**83.0**

[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]Baseline_ML is comparable to the base-case scenario in chapter 4.

[c]The HH scenario 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. HH is comparable to the high-yield scenario for agriculture at 3% in chapter 4.

3.7 Discussion and Research Needs

The forest resource estimates presented in this report are only as good as the underlying data, and therefore are subject to assumptions in the use of the analytical tools. The forest biomass potential is assessed through an analytical process with estimates that are bounded by variables and assumptions. However, the authors have made every effort to reach the highest quality of data and to provide data sources, describe the models, and explain the assumptions. These data should be used and assessed along with FIA inventory data and the newest RPA report and its associated scenario assessment. Supplemental information in the Bioenergy KDF can further inform readers and help them use results of this report.

This analysis identifies several factors that merit additional discussion and development. These include a reevaluation of the underlying assumptions, technology improvement, and harvesting costs. For example, should plantations on forest sites be evaluated in the model and not just timberland? Technology improvement options could also be evaluated that were not considered in this analysis, such as increased growth rates or higher-production, lower-cost systems. Additionally, harvesting costs need to be updated and improved, as more experience in biomass harvest has occurred in the last few years. Readers are encouraged to continue to verify the analysis in this report, and to expand and improve upon it.

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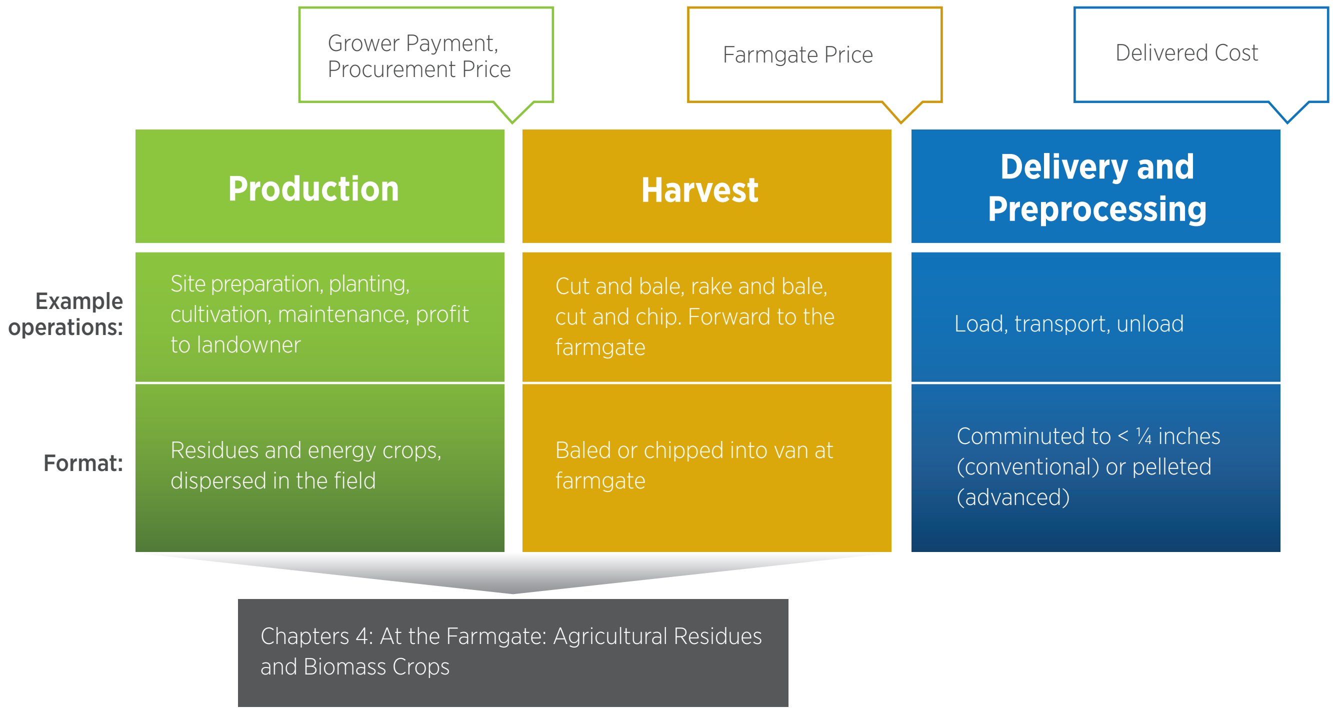
04 | At the Farmgate

Agricultural Residues and Biomass Energy Crops



4.1 Introduction

This chapter provides an updated assessment of the potential economic availability of biomass resources from agricultural lands reported at the farmgate. These farmgate results are in turn used in chapter 6, which characterizes these agricultural resources as delivered to potential biorefineries, along with the forestry resources and waste resources quantified in chapters 3 and 5, respectively.

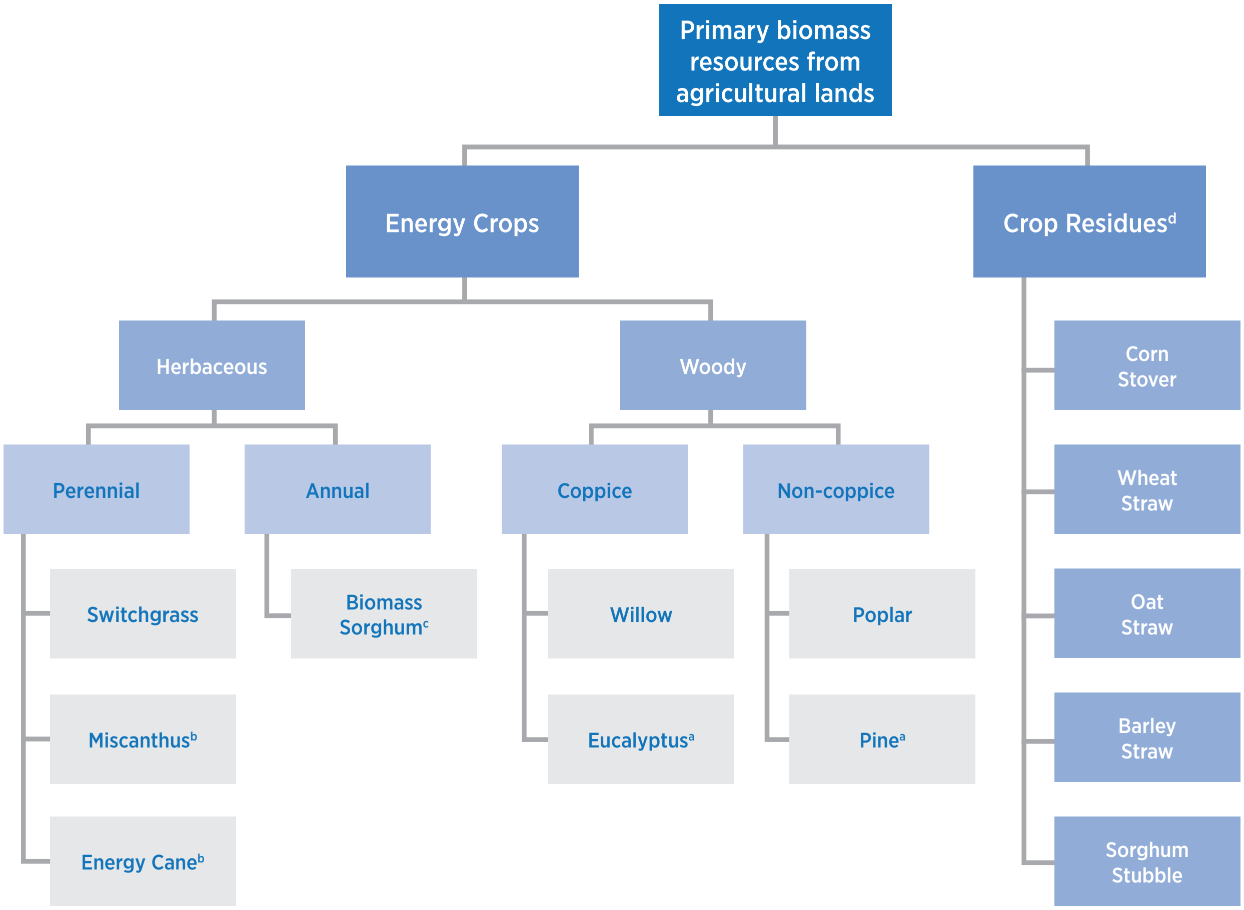
Resources evaluated in this chapter include crop residues and dedicated biomass energy crops (hereafter "energy crops") produced on agricultural land. Both of these biomass types can play a unique and important role in a national biofuels commercialization strategy. The 2011 *BT2* reported biomass resources from agricultural lands to be abundant, diverse, and widely distributed across the United States. The farmgate supplies reported here are derived using the same modeling approach as was used in the 2011 *BT2* but with updated input data and model enhancements (see appendix C.2).

Crop residues quantified here include corn stover, cereal (wheat, oats, and barley) straws, and sorghum stubble. These crop residues require no additional cultivation or land and represent near-term opportunity feedstocks. Most cellulosic biofuels commercialization strategies to date (of companies such as POET-DSM, Abengoa, and DuPont) have focused on agricultural residues, primarily corn stover. Secondary agricultural wastes, such as rice hulls, wheat dust, and sugar cane trash, are addressed in chapter 5.

Along with crop residues, dedicated energy crops are poised to complement the process to further commercialize biofuels, biopower, and bioproducts. These crops, such as switchgrass, miscanthus, and short-rotation woody crops, can improve supply security and help control feedstock quality characteristics. This can be achieved using energy crops alone or in combination with other feedstocks. Crop improvement programs are demonstrating energy crop yield gains and traits tailored to enhance conversion processes. Perennial energy crops can also complement the production of conventional crops, with potential for improved incomes and environmental benefits.

This chapter quantifies the potential availability of biomass feedstocks from primary agricultural residues and energy crops. Sources of each category evaluated are specified in figure 4.1.

Figure 4.1 | Taxonomy of modeled biomass resources from agricultural lands



[a]Eucalyptus and pine are newly added feedstocks. They were generalized in the 2011 *BT2* as 8-year rotation, short-rotation woody crops under single-stem management.

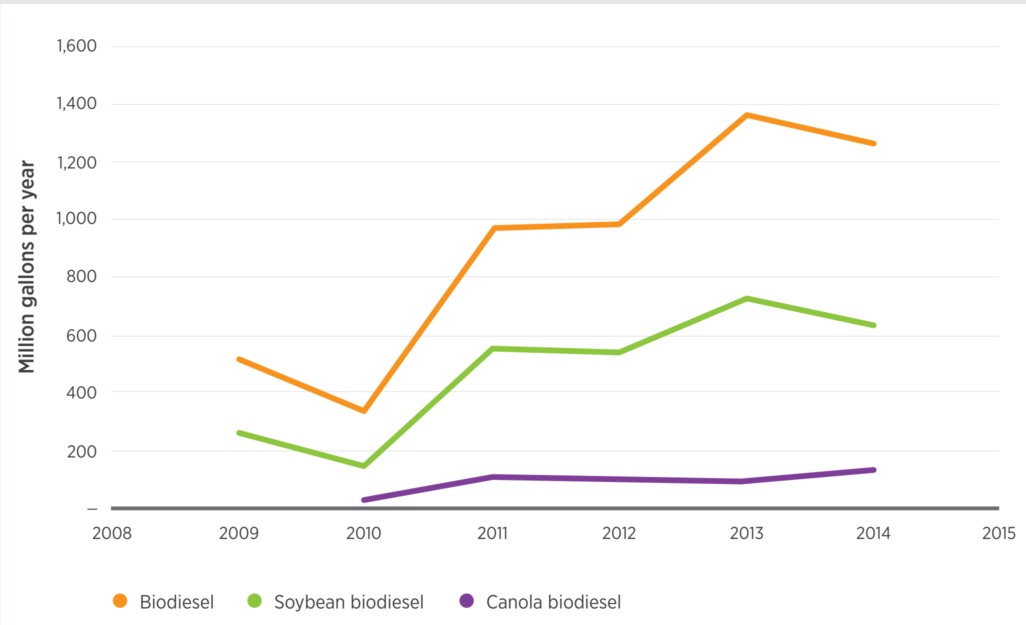
[b]Energy cane and miscanthus are newly added feedstocks to the billion-ton reporting. They were generalized in the 2011 *BT2* as perennial grasses, along with switchgrass.

[c]The 2011 *BT2* discussed several types of sorghum. For the purposes of this report, "biomass sorghum" depicts any variety developed for high biomass yields, and neither for grain nor sugar content. Budgets for biomass sorghum can represent biomass sorghum, forage sorghum, or sweet sorghum. Modeled yields represent either biomass or forage sorghum; the variety with the highest productivity in a certain region was used.

[d]Agricultural resources already used for biofuels or bioenergy, such as sugar cane bagasse, are reported in chapter 2.

Text Box 4.1 | Oilseeds for Use in Biodiesel and Drop-In Renewable Jet Fuel

Oilseeds, primarily soybean and canola, are currently used as feedstocks for biodiesel production. In 2014, soybean made up 51% and canola made up 11% of the feedstocks used in U.S. biodiesel production (EIA 2015). Other oilseeds include non-edible industrial rapeseed, camelina, Ethiopian mustard (carinata), condiment mustard, pennycress, sunflower, and safflower. The EISA targets for biodiesel have mandated at least 1 billion gallons of biodiesel per year since 2012 and are set for 2.0 billion gallons in 2017. USDA's ten-year projections (2016–2025) for U.S. soybean plantings remain above 80 million acres; and as growth in both domestic use and export demand lead to increases in prices, much of the required increase in production will be satisfied with expected yield improvement (USDA 2016). Soybean oil used to produce biodiesel in the United States is projected to rise from 5.2 billion pounds in 2015/2016 to 5.7 billion pounds in 2020/2021 and later years, supporting the production of about 800 million gallons of biodiesel annually in the second half of the projection period. These projections reflect a growing biomass-based diesel use requirement through 2017 under the RFS, and additional demand for biodiesel and renewable diesel to meet a portion of the RFS's advanced biofuel requirement (USDA 2016).



Source: Data from EIA (2015).
Note: Data assume 7.5 pounds per gallon for soybean and canola biodiesel.

Oilseeds can also be used to produce drop-in renewable jet fuel and diesel products, most commonly using a hydroprocessed esters and fatty acids conversion process. The Federal Aviation Adminstration has a goal of 1 billion gallons of alternative jet fuel by 2018. In addition, the U.S. Navy and U.S. Air Force have alternative energy goals that include the use of alternative jet fuels (50% blends by 2022). Oilseeds could be used as feedstocks in helping to meet these goals, and certified jet fuels have been made from several oilseeds. Initial alternative jet fuel production has been primarily from woody biomass, municipal solid waste, and waste grease, so it is unclear what portion might be supplied by oilseeds.

The 2011 *BT2* included a range of energy crop categories, including perennial grasses, annual herbaceous crops, and single-stem and coppicing short-rotation woody crops. The current analysis adds more specificity, reflecting advancements and understanding in the management of energy crop options. The following are brief descriptions of energy crops included in this analysis. More detail on these crops is provided in the 2011 *BT2* section 5.1 (DOE 2011, 87–117) and in appendix C.

- **Agricultural residues**—Conventional crop residues including corn stover and wheat, barley, oats, and sorghum straw.
- **Biomass sorghum**—An annual herbaceous crop, currently grown in rotation throughout the Southeast and Great Plains for grains and forage. Biomass sorghum exhibits non-photoperiod sensitivity and drought tolerance.
- **Energy cane**—A perennial tropical grass with high yield potential across the Gulf South. Low-sugar, high-cellulose varieties (a hybrid of commercial and wild sugar cane species) can be established, managed, and harvested using existing sugar-cane industry equipment.
- **Eucalyptus**—A short-rotation woody crop ideal for Gulf States as well as Georgia and South Carolina.
- **Miscanthus**—A sterile triploid with low nutrient requirements and wide adaptability across cropland.
- **Pine**—A tree representing the major commercial tree crop in the South, with 32 million acres of plantations (Fox, Jokela, and Allen 2007). This crop can be adapted to grow in high density on agricultural land assuming 8-year rotations.
- **Poplar**—A short-rotation woody crop with great potential in the Lake States, the Northwest, the Mississippi Delta, and other regions.
- **Switchgrass**—A model perennial native grass, with wide range and potential distribution.
- **Willow**—A short-rotation woody crop assumed to be managed on a 20-year cycle and harvested at 4-year growth stages. It is being commercialized widely in the Northeast.

4.2 Approach to Quantifying Farmgate Resources from Agricultural Lands

To evaluate potential farmgate supplies of agricultural resources, this study employs the Policy Analysis System (POLYSYS), a policy simulation model of the U.S. agricultural sector (De La Torre Ugarte and Ray 2000). The POLYSYS modeling framework, which can be conceptualized as a variant of an equilibrium displacement model, was previously developed to simulate changes in economic policy, agricultural management, and natural resource conditions, and to estimate the impacts to the U.S. agricultural sector from these changes. An important component of POLYSYS is its ability to simulate how commodity markets balance supply and demand via price adjustments based on known economic relationships. POLYSYS is used to estimate how agricultural producers may respond to new agricultural market opportunities, such as new demand for biomass, while simultaneously considering the impact on other non-energy crops. POLYSYS was used to quantify potential biomass resources in the 2011 *BT2* and has been used in other agricultural and biofuels analyses (Ray et al. 1998a; Langholtz et al. 2014; Ray et al. 1998b; Langholtz et al. 2012; Lin et al. 2000; De la Torre Ugarte et al. 2006; Larson et al. 2010; De La Torre Ugarte et al. 2003).

POLYSYS anchors its analyses to the USDA-published baseline of yield, acreage, and price projections for the agriculture sector, which are extended from the USDA 10-year baseline projection period through 2040 for this analysis (Hellwinckel et al. 2016). Conventional crops currently considered in

POLYSYS include corn, grain sorghum, oats, barley, wheat, soybeans, cotton, rice, and hay, which together comprise approximately 90% of the U.S. agricultural land acreage. Conventional crops simulated for residues include corn, grain sorghum, oats, barley, and wheat (winter plus spring). Production costs associated with residue removal from these crops include replacement of embodied nutrients and per-acre harvest costs associated with shredding, raking, and baling (with a large square baler; see appendix C.3) and transportation to the field edge. Second-generation biofuel crops specified in figure 4.1 are also considered. Production costs associated with these herbaceous and woody energy crops include establishment, maintenance, and per-acre harvest costs (see tables C.3 and C.4 of appendix C.3).

See appendix C.1 for more information on the POLYSYS modeling framework, including land base[1] and other input assumptions.

4.2.1 Enhancements and Modifications from *BT2*

Although this analysis follows the same general methodology for estimating farmgate supplies as was reported in the 2011 *BT2*, several changes have been made in this analysis. The changes include updating input data, adjusting for inflation, harmonizing with current and projected operational technology, and minor corrections in the modeling framework. Updated data sets and revised technical assumptions used in this analysis are described in more detail in appendix C.2.

4.2.2 Model Inputs, Assumptions, and Constraints for Energy Crops

The following general constraints, assumptions, and inputs apply to all energy crops discussed in section 4.1:

- **Yield improvements**: Field trial data to date provide validation (Owens et al. 2016) for higher biomass yields in the future (see appendix C.1). Base-case and high-yield scenarios are two scenarios for yield improvements over time that may be achieved with a mix of improved management practices and crop genotypes. These assumptions were derived from a series of workshops in 2010 drawing on expert opinion (DOE 2009). In the 2011 *BT2*, the base-case scenario assumed 1% yield improvements per year, with high-yield scenarios adding 2%, 3%, and 4% yield improvements per year. Yield improvement assumptions in this analysis, ranging from 1% to 4%, are specified by scenario (see table 4.1).
- **Land-use constraints**: In addition to the constraint of available land, as established by the USDA baseline (USDA-OCE/WAOB 2015, see appendix C.1), there are annual constraints (5% of permanent pasture, 20% of cropland pasture, 10% of cropland) and cumulative constraints (40% of permanent pasture, 40% of cropland pasture, 10% of cropland) applied to the model regarding land that can be converted to energy crops. These constraints are also bound by the management-intensive grazing (MiG) constraint of 1.5 acres of MiG required for one acre of pasture converted to energy crops. Eligible pasture is defined as having greater than or equal to 25 inches of annual precipitation, which excludes irrigated pasture acres amounting to 47.1 million acres of land nationally (see appendix C, fig. C.1).
- **Budgets**: Energy crop budgets include establishment and maintenance, excluding land rent. (See 2011 *BT2* tables 5.3 and 5.4 [DOE 2011, 128–129] and appendix C.3 for a summary of crop budgets, as well as a discussion of land rent

[1] Our analyses are limited to the continental United States. Hawaii and Alaska were excluded because of a lack of conventional crops grown in these areas and in turn the inapplicability of our modeling approach to these states.

Table 4.1 | Specified-Price Simulation Scenario Descriptions at County Scale

Scenario name		Short description	Tillage flexibility constraint	Energy crop yield improvements[a]	Conventional crop yield
Base case (1%)	BC1	Cumulative base-case	1	1%	Baseline for all crops[b]
High yield (2%)	HH2	Cumulative high-yield run	3	2%	High corn grain[c]
High yield (3%)	HH3	Cumulative high-yield run	3	3%	High corn grain
High yield (4%)	HH4	Cumulative high-yield run	3	4%	High corn grain

[a]Energy crop yield improvements are applied as annual yield increases, compounded beginning in 2015 (see section 4.5).

[b]The base-case scenarios follow the USDA baseline projection (USDA-OCE/WAOB 2015) and demands, extrapolated to 2040 (see appendix C.1).

[c]High-yield scenarios use assumptions derived from the high-yield workshops (DOE 2009). The high-yield scenarios assume corn grain yield grows at a higher rate to achieve 265 bushels per acre in 2040 (national average) and allows greater farmer adoption of no-till management.

exclusion in appendix C.1.) Harvest costs in this report were added to the crop budgets to calculate the break-even cost of production at the farmgate.

See appendix C for more information on the yield modeling framework, as well as detailed budgets and land use assumptions and constraints.

4.2.3 Agricultural Residue Modeling Assumptions

Quantities of agricultural residues are based on estimates of total aboveground biomass produced as byproducts of conventional crops, which are then limited by sustainability and economic constraints. Total aboveground biomass residue produced (before sustainability, operational, and economic constraints) is calculated in POLYSYS based on a 1:1 harvest index or ratio of residue to grain for corn, and on a 1:1.57 ratio for barley, oats, sorghum, and wheat (spring and winter). There are many harvest options for residues; but for each crop, this study models and costs one machinery complement. For more information, see appendix C.1.

Crop residues provide important environmental benefits, such as protection from wind and water erosion, maintenance of soil organic carbon, and soil nutrient recycling. Thus, not all crop residues produced are sustainably available. Sustainably available removals are constrained to not exceed the tolerable soil loss limit of the USDA Natural Resources Conservation Service (NRCS 2016a; 2016b), and to not allow long-term reduction of soil organic carbon. The following models were used in this analysis: Revised Universal Soil Loss Equation 2 (USDA 2016), the Wind Erosion Prediction System (NRCS 2012), and the Soil Conditioning Index. County-level average retention coefficients are calculated for wind, rain, and soil carbon for each rotation and tillage combination by crop management zone (see Muth et al. [2013] for more details).

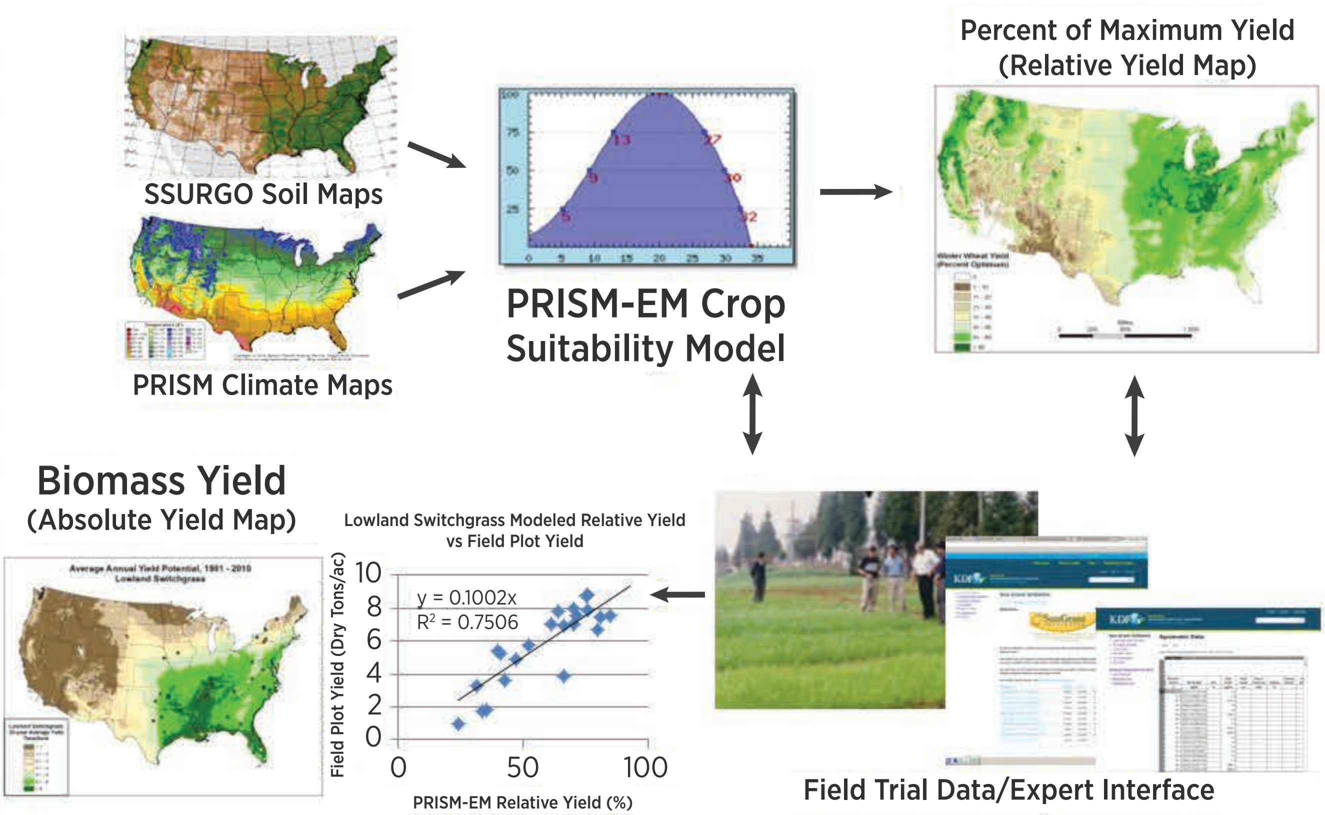
In the 2011 *BT2*, 100% of sustainably available agricultural residues were also assumed to be operationally available. In this report, operationally available residues are limited to 50% of total residue yield starting in 2015, increasing linearly to 90% of available residue yield in 2040, for each county.

Subsequently, collection of residues is assumed to be limited to operationally available removals or sustainably available removals, whichever is most limiting. This operational efficiency change was made to reflect the near-term technical challenges of harvesting variable levels of available field and sub-field residue, while acknowledging technological advancements in harvesting equipment in the long term that can be developed to mobilize greater proportions of the sustainable supply.[2]

4.2.4 Energy Crop Modeling Assumptions

Empirically modeled energy crop yields are new to this analysis. Energy crop yields were derived from modeling of crop yields based on data from the Sun Grant Regional Feedstock Partnership in coordination with the Oregon State University PRISM (Parameter-elevation Relationships on Independent Slopes Model) modeling group. Following six crop-specific

Figure 4.2 | Crop yield mapping work flow using PRISM-EM with the Regional Feedstock Partnership



Source: Daly and Halbleib (2014), "Potential Yield Mapping of Dedicated Energy Crops," energy.gov/sites/prod/files/2014/11/f19/daly_biomass_2014.pdf.

Note: Acronyms from top left to bottom right are as follows: SSURGO = Soil Survey Geographic Database; PRISM = Parameter-elevation Relationships on Independent Slopes Model; PRISM-EM is an environmental suitability modeling framework.

[2] This constraint is not meant to capture willingness to participate in residue collection.

workshops, the data from more than 110 field trials were used to estimate county-specific per-acre yields based on 30-year historic weather data (fig. 4.2).

Modeled crop yield is generated with PRISM-EM (Halbleib, Daly, and Hannaway 2012) based upon PRISM biweekly climate variables including precipitation, minimum temperature, maximum temperature, and Soil Survey Geographic Database soil pH, drainage, and salinity. The process of creating potential yield begins with calibrating PRISM-EM model settings for crop-specific water use and temperature tolerance values (such as optimal temperature growth and water use efficiency). Initial calibrations for these functions are based on known relative tolerances for warm- or cool-season crops and whether they are grown as annuals or perennials. These functions are used with soil characteristics and historical weather patterns to generate "first-guess" average annual relative yield values (0%–100%). The relative values are regressed with average field trial yield values to create a transfer function that is used to estimate absolute yield. Since yield data are available for only a few years, in some cases PRISM-EM is run for the individual years that match those of the data; and the estimated yields are adjusted to reflect those under 1981–2010 thirty-year average climate conditions. The process of modeling relative yield and estimating absolute yield is done in an iterative fashion during face-to-face meetings with species experts, in which yield outliers from the regression function are examined and model calibrations modified as needed.

The field trial potential yield values are derived from plot-level data, which are averaged across top-producing and/or commercially recommended varieties (when available) or nutrient applications that reflect best management practices (BMPs) via pre-establishment soil sampling. In the former case, however, BMPs are assumed to have been applied to all variety trials. Note that small-scale test plot yields are typically much higher than field-level production values; therefore, small-plot values are reduced by 20% to account for this bias according to Knörzer et. al (2013). Additionally, the fidelity of soils data used in the model is limiting, and the process acknowledges that two identical soils in different locations may behave differently.

4.3 Scenarios

Consistent with the 2011 *BT2*, this *BT16* report introduces markets for biomass feedstocks as specified farmgate prices offered (≤\$40, ≤\$60 and ≤\$80 per ton).[3] These prices (\$2014) are adjusted for inflation and are applied to all counties for all years in the simulation period. The exception is for specified demand scenarios, in which POLYSYS targets specified levels of production and solves for the least-cost resource mix needed to meet the specified demand. The 2011 *BT2* reported potential county-level feedstocks as a function of price, year, and yield scenario ("base-case" with a 1% annual yield increase or one of three "high-yield" scenarios with a 2%, 3%, or 4% annual yield increase). In addition to a "baseline scenario" (BL0) that establishes initial and future crop supply and demand, we expand the number of scenarios and market simulations in this analysis to include the following:

4.3.1 Supplies at Specified Prices

Exogenous price simulations (hereafter "specified-price" simulations) introduce a farmgate price, and POLYSYS solves for biomass supplies that may be brought to market in response to these prices. In specified-price scenarios, a specified farmgate price is offered constantly in all counties over all years of the simulation. For example, at a ≤\$60 specified price, the resulting supply potential in 2040 is achieved by

[3] A broader range of offered prices (\$30–\$100 in \$5 increments) were simulated and are available online in the Bioenergy KDF.

Text Box 4.2 | Observed Energy Crop Yield Improvements

The Regional Feedstock Partnership provided critical information related to potential yields of energy crops at locations across the country. Yields forecasted in the High-Yield Scenario workshops are becoming realized in the field. The development of poplar as an energy crop has advanced rapidly. Yields of the fastest-growing new poplar clones ranged from 1.3–1.6 times those of currently-available commercial clones, and they are capable of producing up to 8 tons per acre per year. As development of the poplar energy crop continues, it is estimated that gains in biomass yield of roughly 20% to 30% can be expected through each breeding cycle. Yield increases associated with new willow cultivars have typically ranged from 15% to 25%, with the yield of the top three cultivars across all research sites ranging from 1.3 to 6.3 tons per acre per year. Sorghum and energy cane cultivars have been identified that are capable of yields in excess of 8.9 and 20 tons per acre, respectively.

In addition to the identification of new high-yielding clones, fertilization and nitrogen addition were found to enhance yields dramatically in some crops. Switchgrass yields were improved by up to 88% with the addition of moderate amounts of fertilizer. In miscanthus field trials in Illinois, yields increased from 4.7 to 8.1 tons per acre with the addition of moderate amounts of nitrogen. In some locations, miscanthus yields were more than 8.9 tons per acre, especially with a moderate fertilizer treatment.

As energy crop development continues, higher-yielding cultivars can be expected, and continued improvement in agronomic practices will enable these energy crops to make significant contributions to the nation's energy portfolio.

the constant presence of a ≤$60 market price in all preceding years as well (2015–2039 for residues and 2019–2039 for energy crops). Constant prices allow farmers to respond by changing crops and practices gradually over time. Indeed, some biomass crops, such as poplars, require years to reach maturity. The same supply would not result from a sudden offer of ≤$60 solely in year 2040 but not in the preceding years. Specified price runs represent the potential if a national market were in place beginning in the near term and offering constant prices until 2040 (see text box 4.4). Consistent with the 2011 *BT2,* these simulations are for all feedstocks combined (i.e., energy crops were simulated to compete both with conventional crops and with other energy crops).[4]

4.3.2 Prices at Specified Production Targets

New to the billion-ton report series, exogenous demand simulations (hereinafter "production-target" simulations) introduce a national supply target, and POLYSYS solves for prices needed to realize the least-cost mix of biomass resources to meet that demand. This approach simulates markets that develop using least-cost resources first, producing higher-cost resources only when necessary to meet demand targets. In this sense, production-target simulations better represent current biofuels commercialization efforts, which capitalize on least-cost feedstock opportunities and lack the support of a commodity infrastructure for biomass delivery. Even production-target scenarios may somewhat overestimate actual supply paths because of the potential for some of the estimated production to be geographically dispersed and uneconomical to transport to biorefineries. The specified-production scenarios are outlined in table 4.2. Selected quantities and target years are chosen based on potential real-world scenarios (e.g.,

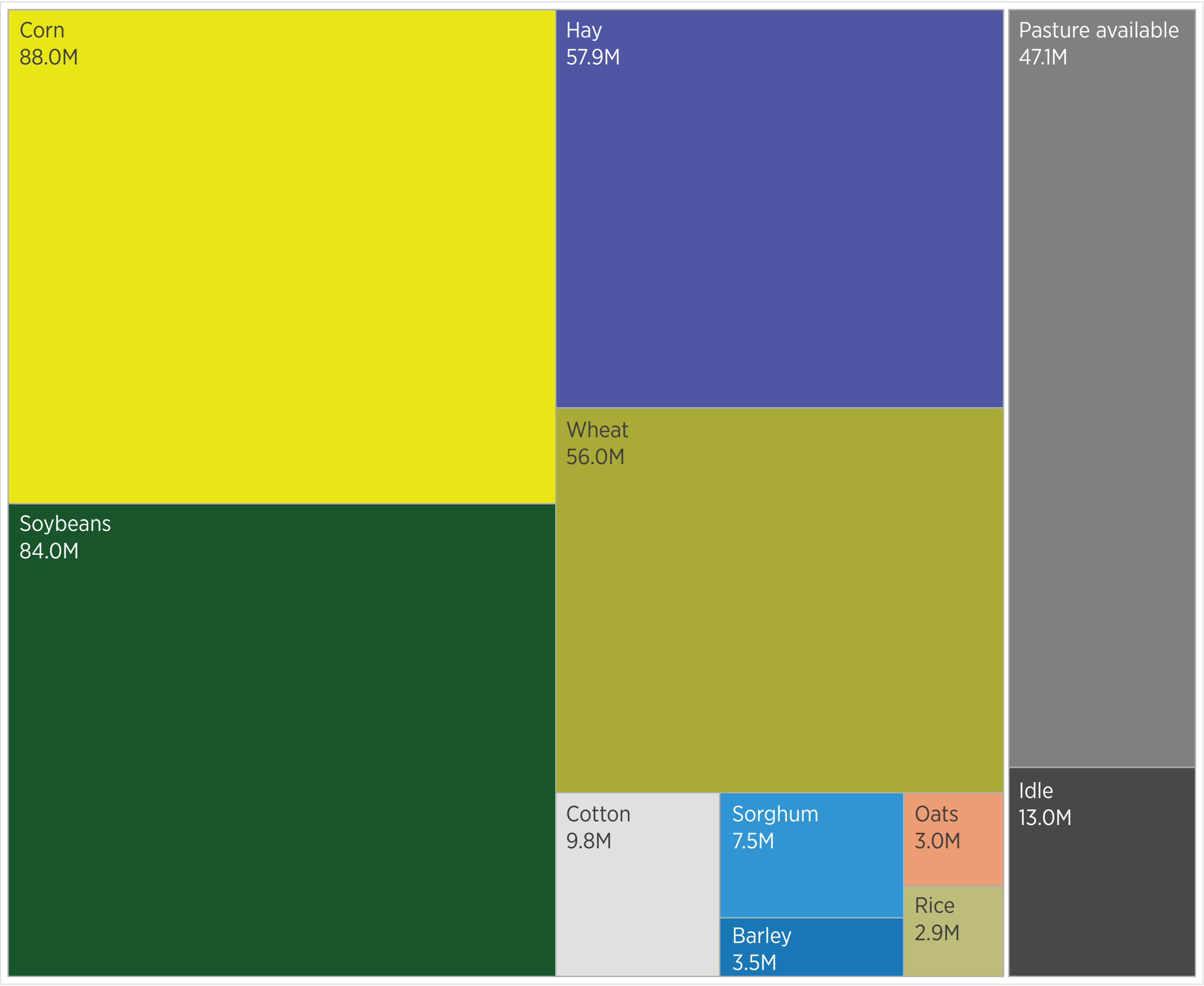
[4] In addition to specified-price simulations of all feedstocks combined, our simulations include feedstock-specific scenarios, which simulate each dedicated energy crop in the absence of the other energy crops, elucidating each energy crop's full potential if it is not competing with other energy crops. These specified-price simulations are further described in appendix C and are available online in the Bioenergy KDF.

RFS levels). These targets are slightly exceeded when POLYSYS solves for biomass supplies that will enter at simulated prices. Higher-quantity scenarios do not include earlier years (e.g., 2022) because of the time necessary to achieve these higher targets. These higher-quantity scenarios often bring prices exceeding offered prices under specified-price simulations at corresponding biomass levels because of delays in production of some high-yielding crops (e.g., no production of miscanthus in year 1). See appendix C.

4.4 Baseline (BLO) Results: Primary Agricultural Resources

To establish a baseline for comparison, we completed a simulation without offering any farmgate prices to energy crops or residues (i.e., continuation of the USDA baseline). The resulting planted acres are presented in figure 4.3 for the initial simulation year of

Figure 4.3 | Baseline land use by conventional crops in 2015, idle land, and pasture available in 2015 (pasture available is 11% of the total pastureland)[5]



[5] Interactive visualization: https://bioenergykdf.net/billionton2016/4/8/tableau

2015. The available land base for this simulation and all others discussed below is described in appendix C with other agricultural land modeling assumptions.

4.5 Specified-Price Simulation Results

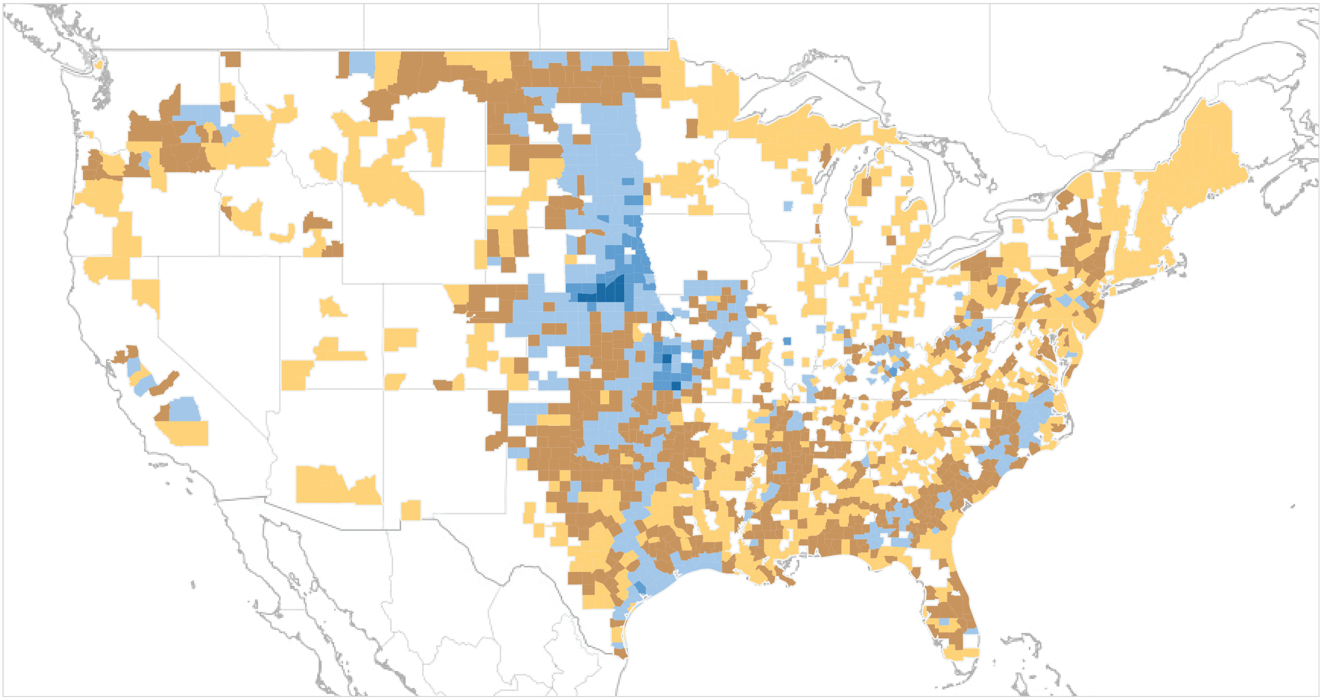
Two scenarios of specified-price simulations are highlighted in this report: a base-case scenario with a 1% yield increase annually and a high-yield scenario with a 3% annual yield increase. The simulations begin in 2015 with an offered farmgate price for primary crop residues only between 2015 and 2018 and long-term contracts for dedicated crops beginning in 2019, as discussed in appendix C. Expected mature energy crop yield grows at a compounding rate beginning in 2016 as specified by scenario. For example, woody crops planted in 2022 according to base-case yield growth assumptions would expect mature yield increase of 7.2% above the assumed base year value. For example, a county with a 2015 expected yield of 5 dry tons per acre mean annual increment (or 40 dry tons per acre at the end of an 8-year rotation) would have an expected yield if planted in 2022 of 5.36 dry tons per acre mean annual increment (or 42.9 dry tons per acre at the end of an 8-year rotation) when harvested in 2030. For the high-yield 3% scenario, the expected yield at planting is 6.1 dry tons per acre mean annual increment (or 49.2 dry tons per acre at the end of an 8-year rotation) when harvested in 2030. The yield growth assumptions are fixed after crops are planted such that yield gains do not apply to crops already planted, but new plantings do take advantage of the gains in expected yield growth.

4.5.1 Base-Case Scenario (1%)

Under this base-case scenario, at offered farmgate prices less than $35, supply is found to be available only from residues (96%–100% of total supply) and woody energy crops (0%–4% of total supply). At ≤$40, 30 million tons of total biomass resources from agricultural lands are available in 2017, consisting completely of residues because of the constraints discussed earlier, and 38 million tons by 2022, also completely from residues because of low offered prices and the high cost of energy crops under these base-case assumptions. The total reaches 59 million tons with both residues and energy crops in 2030 and 108 million tons in 2040, the final year of the simulation as displayed in figure 4.4. A total of 79% of this production is from residues in 2030 and only 54% in 2040, with herbaceous energy crops dominating the market in later years (11% in 2030, 31% in 2040) as planted acreage reaches maturity and is ready for harvest, along with some woody energy crops (11% in 2030 and 15% in 2040). In these later years and at these lower prices, herbaceous energy crops are coming primarily from switchgrass, with some miscanthus (a higher-yielding, but higher-cost crop). Less than one million tons of energy sorghum is coming into production by 2040. Woody energy crops contribute about half the total energy crop production in 2030 but decrease to 32% of energy crop production by 2040 as switchgrass production continues to rise with realized yield increases.

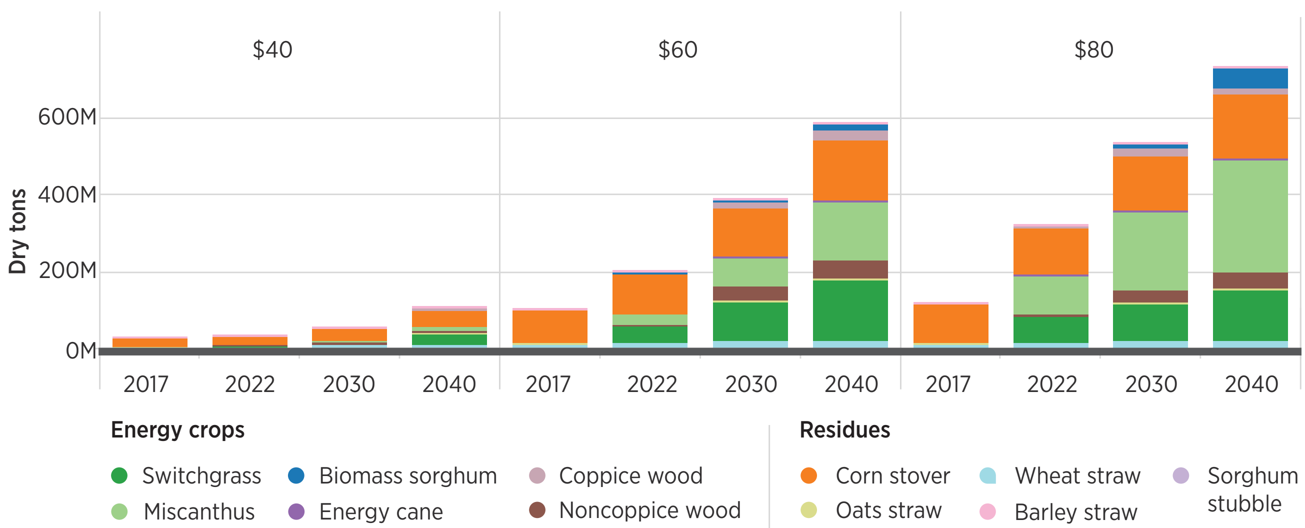
At a ≤$60 offered farmgate price, 104 million tons of residues are available in 2017 and 201 million tons of residues and energy crops in 2022. In later years, 388 million tons of residues and energy crops are available in 2030 and 588 million tons in 2040 from residues and energy crops. At this price point, 49% of total supply is available from herbaceous energy crops in 2030, increasing to 58% by 2040. Another 13% is available from woody energy crops in 2030, which decreases to 12% in 2040. Increasing the offered farmgate price further to ≤$80 yields 117 million tons of available residues in 2017. Herbaceous energy crops continue to dominate the market at this price point, with residues taking a smaller share of the 323 million tons of total potential feedstocks in 2022 than under a ≤$60 offered farmgate price scenario (fig. 4.5). In 2030 and 2040, the total energy

Figure 4.4 | Production of residues and energy crops at an offered farmgate price of $40 in 2040 under a base-case (1%) scenario[6]



Note: dt/SqMile = dry tons per square mile.

Figure 4.5 | Production of herbaceous and woody energy crops under ≤$40, ≤$60, and ≤$80 offered farmgate prices under a base-case (1%) scenario for select years[7]



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

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

crops and residues reach 537 and 734 million tons, respectively. This supply comprises 60% in 2030 and 67% in 2040 for herbaceous energy crops. Woody energy crops are limited to 10% of the market in 2030 and 8% in 2040, and residues make up the rest. The total potential availability of biomass feedstocks under the base-case scenario in selected years is outlined in figures 4.6, 4.7, and 4.8.

Under this base-case scenario at an offered farmgate price of ≤\$40, land planted under dedicated energy crops begins at 0.9 million acres in 2022, advancing to 2.4 in 2030 and 9.4 in 2040. In comparison, at a higher offered farmgate price of ≤\$60, the acres under production at the launch of energy crops (2019) are higher and accelerate at a faster pace: 21.4 million acres are planted in 2022, 42.4 million acres in 2030, and 64.4 in 2040. Similarly, at a ≤\$80 offered farmgate price, the planted acres begin at 41.5 million acres in 2022 and grow to 62.1 million acres in 2030 and 80 million acres in 2040. Figure 4.9, which shows acres in production in selected years and prices under the base-case (1%) scenario, depicts two other crop categories: conventional crops (as discussed earlier, this includes eight crops shown in figure 4.3) and "other," which consists of pasture land[8] and idle land,[9] as well as land under production for energy crops. For example, other land covers 468.3 million acres in 2017 under a ≤\$40 offered farmgate price and shrinks to 467.0 million acres in 2040. As we transition to a ≤\$60 offered price with 303.6 million acres under production for conventional crops in 2017, for example, a total change of -28.1 million acres planted occurs for conventional crops by 2040. This gives way to energy crops coming into production during this timeframe on a total of 64.3 million acres across all land types (42% cropland, 4% cropland pasture, 54% permanent pasture) by 2040.[10] The distribution of land use under base-case assumptions for select years at \$60 per ton farmgate prices is shown in table 4.3.

Text Box 4.3 | Constructing Supply Curves From Independent Exogenous Price Simulations

Each simulation of a different price is an independent model simulation. The mix of feedstocks supplied at each price will change based on the offered price. For example, when markets are offered at ≤\$40 in 2019, farmers respond differently than if they were offered ≤\$80 in 2019. Each price increase does not look back at the previous simulation (e.g., recursive dynamics) to determine land allocation due to existing programming of the model. Therefore, supply curves constructed from these separate simulations for individual or combined biomass crops shown later in this chapter may have anomalies (e.g., backward bends) for certain feedstocks.

The energy crop category of land use depicted in figure 4.9 at the ≤\$40 offered farmgate price consists primarily of coppice and non-coppice wood (0.9 million acres in 2022, 1.6 million acres in 2030, and 4 million acres in 2040) with some switchgrass and miscanthus entering in later years (e.g., 4.4 million acres of switchgrass in 2040). However, at higher offered prices, the use of land for these dedicated energy crops changes to primarily switchgrass and miscanthus (e.g., 13.7 million acres under production for these two crops at an offered farmgate price of ≤\$60

8 Pasture land excluded from POLYSYS land base includes 399.2 million acres out of 446.2 million acres total pasture (see appendix C.1 for more details).

9 Idle land is fixed across all scenarios beginning at 12.3 million acres in 2015 and ending at 23.3 million acres in 2040 (see appendix C.1 for more details).

10 Note: In a baseline scenario (BL0, a continuation of the USDA baseline), other land decreases, although less severe than the modeled change described in this scenario example.

Figure 4.6 | Supply curves of potential production from major crop residues for select years under base-case assumptions

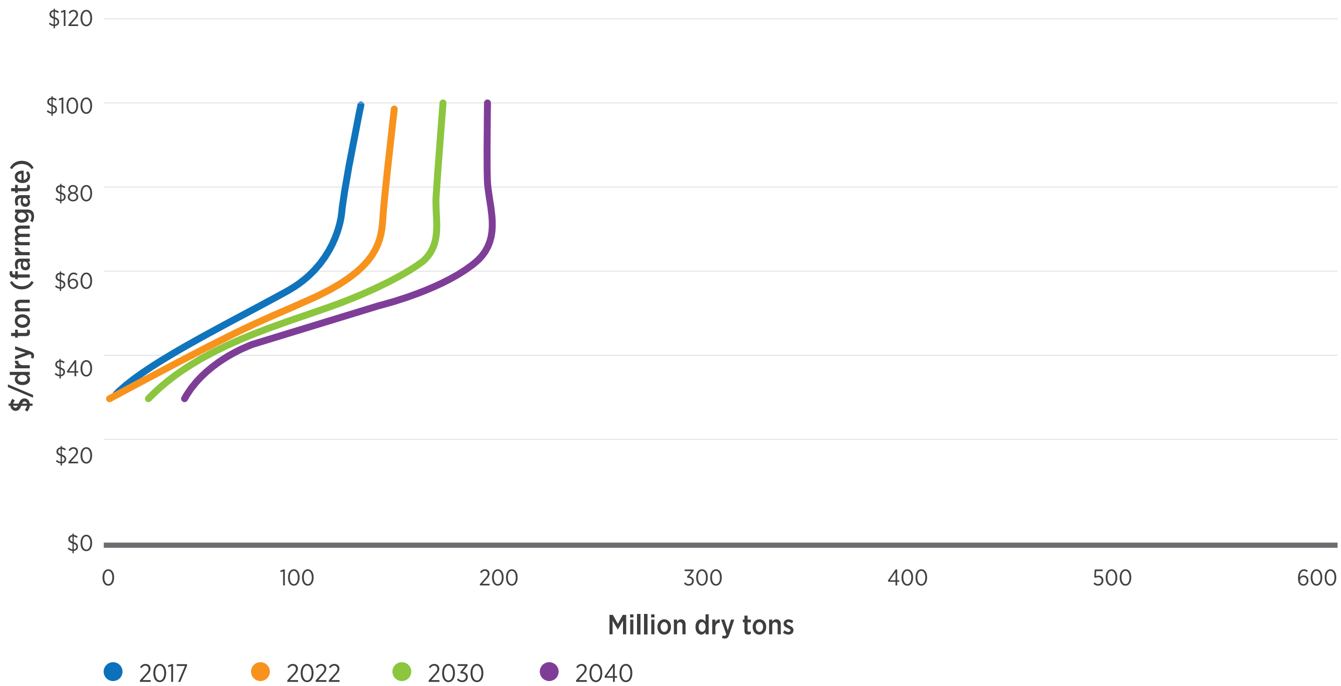


Figure 4.7 | Supply curves of potential herbaceous energy crop production for select years under base-case assumptions

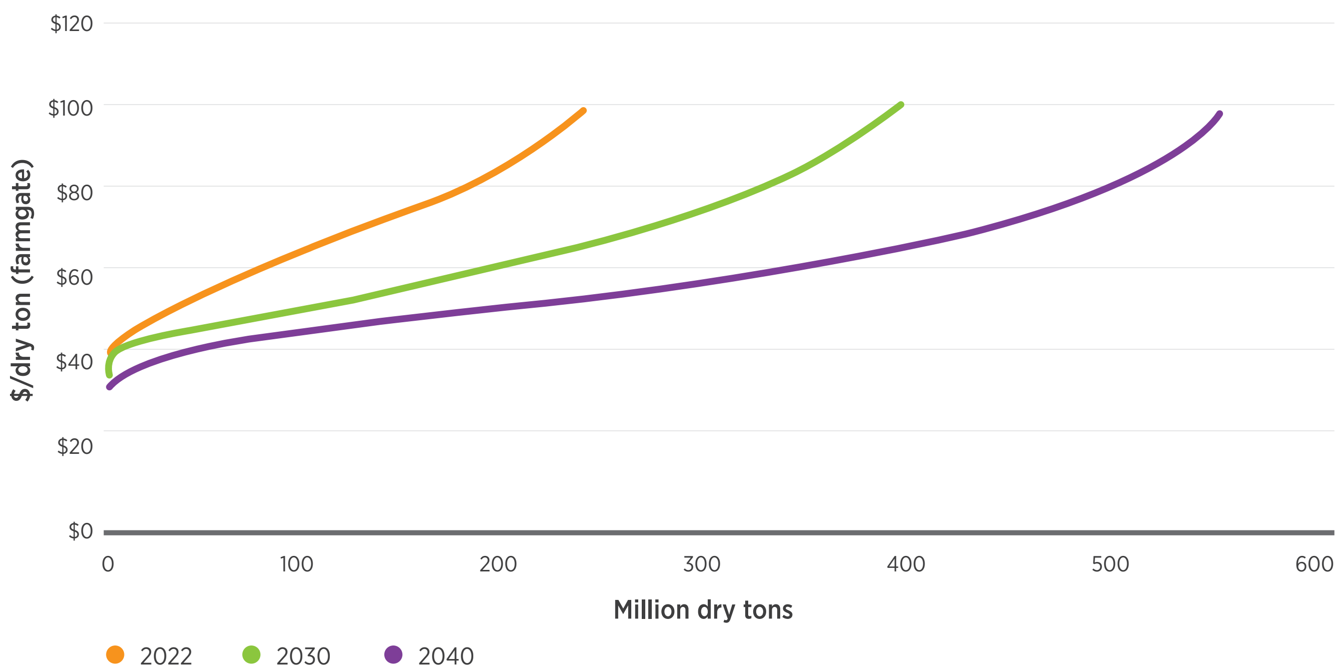
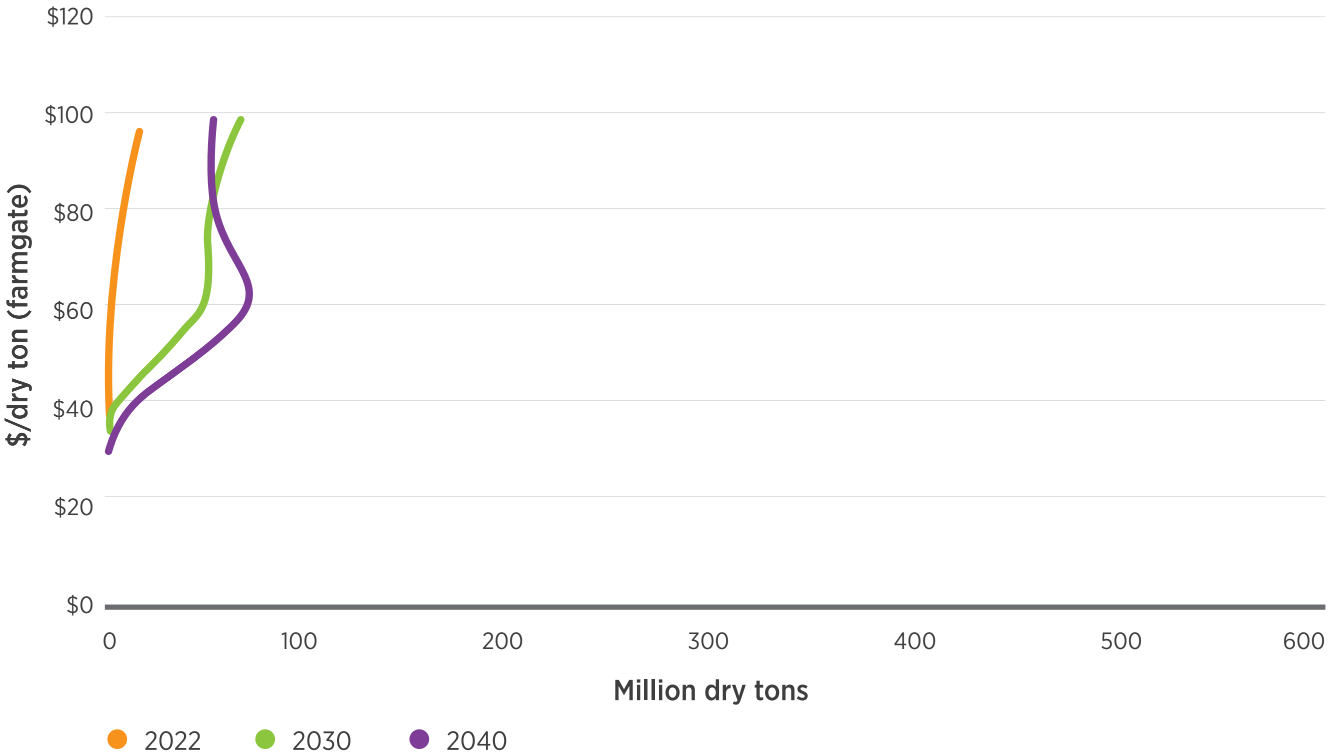


Figure 4.8 | Supply curves of potential woody energy crop production for select years under base-case assumptions



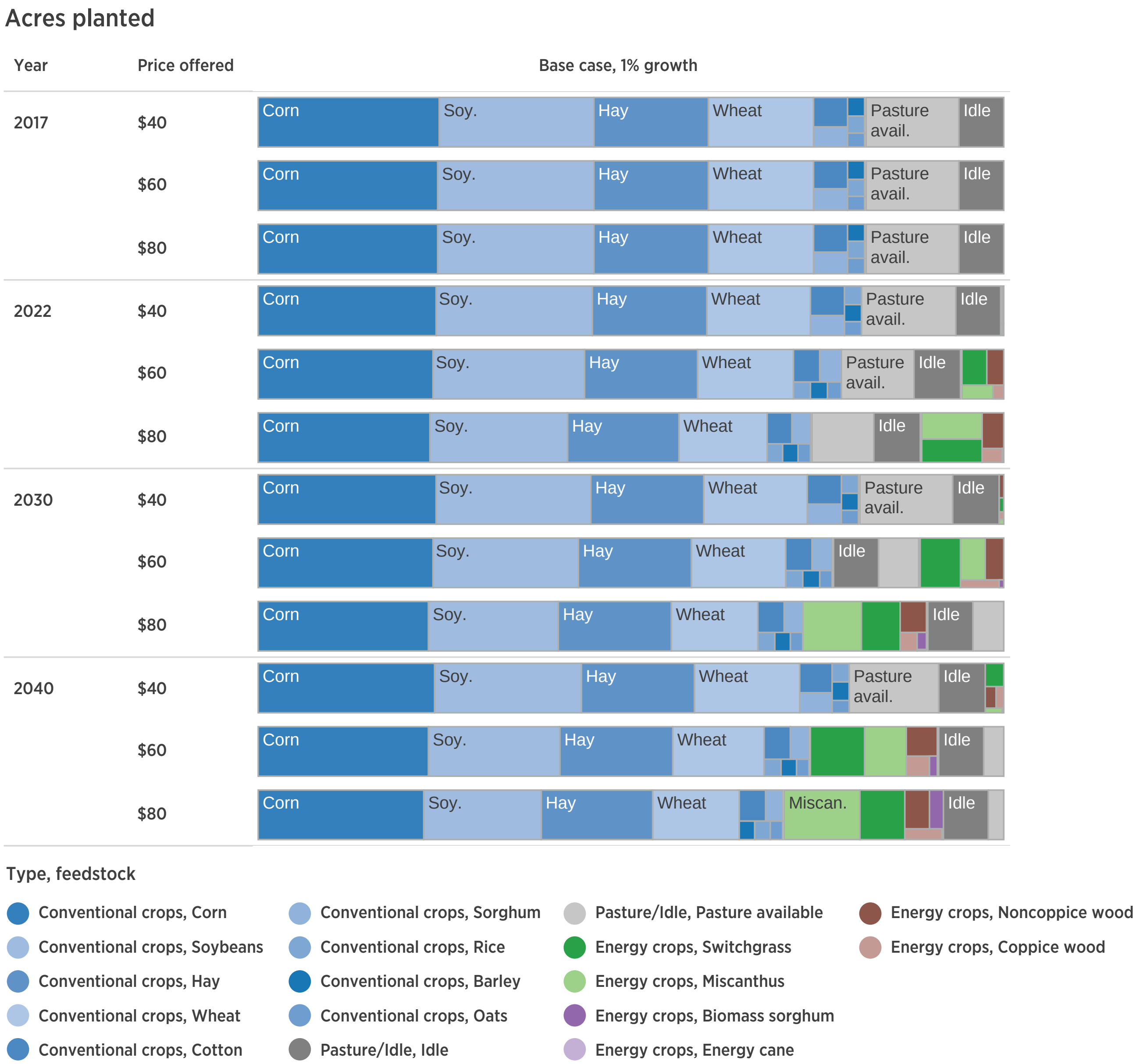
in 2022), which demonstrates the decreasing supplies at higher prices as depicted in figure 4.8 and text box 4.3. The share of coppice woody crops remains nearly constant at higher offered prices (e.g., in 2030: 3.2 million acres at ≤$60 versus 3.5 million acres at ≤$80), but more land comes into production for non-coppice (e.g., less than 7.9 million acres at ≤$60 and 8.5 million acres at ≤$80 in 2030) as depicted in figure 4.9. Biomass sorghum claims more area for production under the ≤$80 scenario, beginning at 130 thousand acres in 2022 and increasing to 5.1 million acres in 2040 as yield improvements begin to accumulate and make biomass sorghum more competitive, and as land is freed up from the transition of other energy crops out of production (e.g., as acres in switchgrass production end their rotation and are eligible for transitioning to another crop or land use). The ramp-up of planted acres, mirroring production as discussed earlier, is replicated and even compounded under the high-yield scenarios discussed below.

4.5.2 High-Yield Scenario (3%)

A high-yield scenario initiates a 3% yield improvement for all energy crops beginning in year 2016 as well as high-yielding corn and a high flexibility of tillage options to accommodate no-till adoption for agricultural residue generation. Figure 4.10 depicts the acres under production for selected years and prices for the high-yield scenario as well as the base-case scenario for comparison.

Total planted acres under energy crops after constraints are met encompass slightly more under this more aggressive scenario at an offered farmgate price of ≤$40 than under the base-case at this same price: 2.2 million acres in 2022, 9 million acres in 2030, and 38.5 million acres in 2040. Likewise, acres under production are higher at ≤$60 and ≤$80 offered farmgate prices: ≤$60 brings 28.3 million acres into production in 2022, 57.9 million acres in 2030, and 88 million acres in 2040; ≤$80 brings in 49.9 million

Figure 4.9 | Total planted acres by crop type after constraints are met at select prices under base-case assumptions[11]

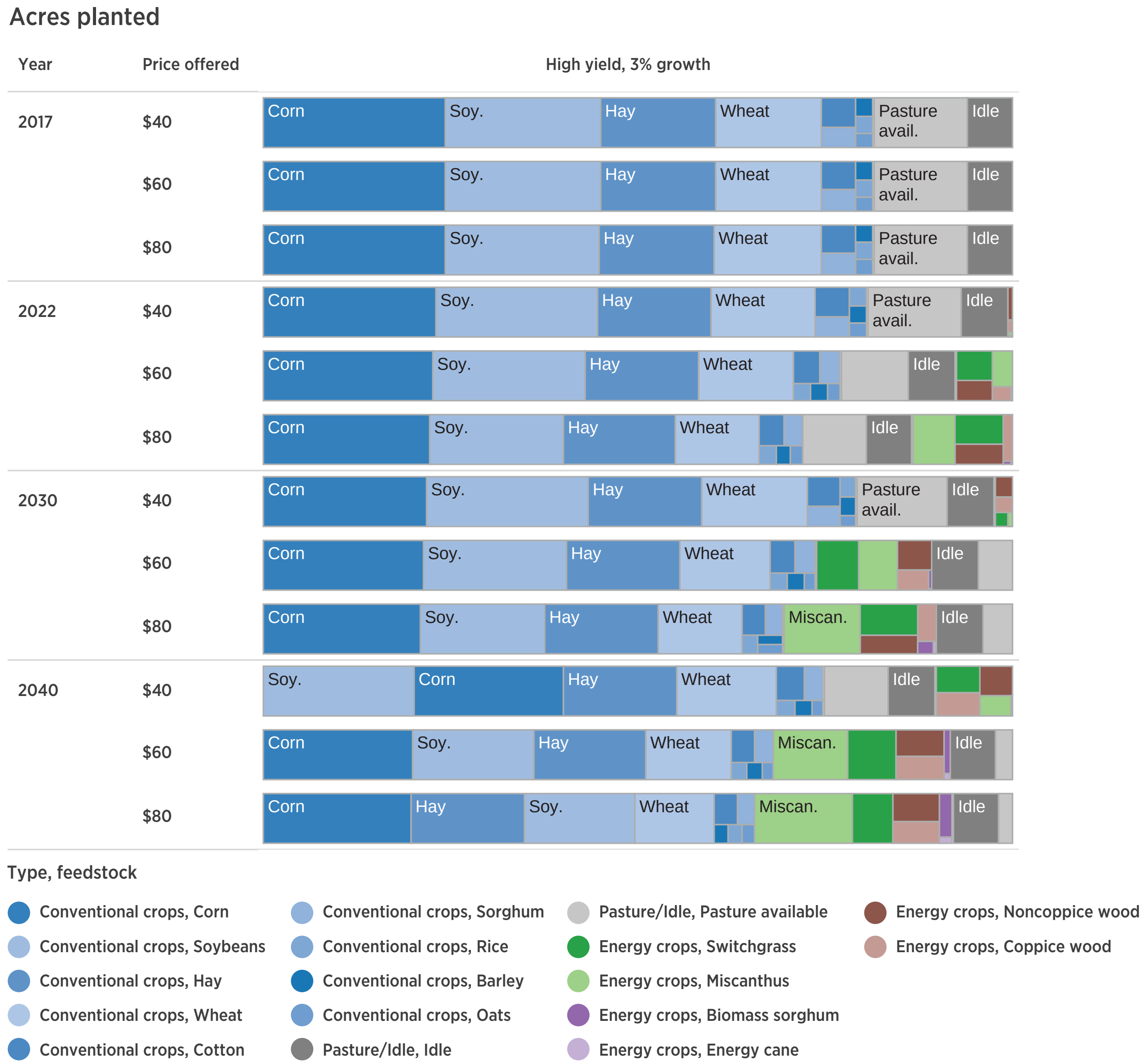


[11] Interactive visualization: https://bioenergykdf.net/billionton2016/4/6/tableau

Table 4.3 | Distribution of Land Use Under Base-Case Assumptions for Select Years at ≤$60 Offered Farmgate Price

Land use type	2017	2022	2030	2040
	Million acres			
Energy crops land allocation (planted)	N/A	21.41	42.38	64.34
Cropland allocation (planted)	N/A	11.01	15.30	27.10
Cropland used as pasture allocation (planted)	N/A	1.11	2.20	2.48
Permanent pastureland allocation (planted)	N/A	9.29	24.88	34.76
Energy crops (harvested/fraction)	N/A	13.2/0.62	31.95/0.75	50.00/0.78
Corn (planted)	89.85	87.6	86.92	84.76
Corn stover (harvested)	47.68	50.36	54.63	56.53
Other crops with residues (planted)	65.79	59.72	59.08	56.91
Other crops with residues (harvested)	16.34	17.89	20.26	22.05
Percent of total U.S. cropland (325.6 million acres) allocated to energy crops	N/A	3.4%	4.7%	8.3%
Percent of total U.S. pastureland (446.2 million acres) allocated to energy crops	N/A	2.3%	6.1%	8.3%
U.S. major crops with residues (acreage), percentage harvested for biomass	155.60, 41.1%	147.30, 46.3%	146.00, 51.3%	141.70, 55.5%
Percentage of U.S. cropland contributing to biomass production (energy crops planted and residue harvested)	19.7%	24.3%	27.7%	32.5%

Figure 4.10 | Total planted acres by crop type after constraints are met at select prices under high-yield (3%) assumptions[12]



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

acres in 2022, 76.1 million acres in 2030, and 98.6 million acres in 2040. For comparison, under this aggressive scenario (high yield 3%, ≤$80), 303.6 million acres are in production for conventional crops in 2017; this decreases to 268.3 million acres in 2022 and finally by 2040 decreases to 244.3 million acres (a 20% reduction from 2017). The distribution of land use under high-yield assumptions for select years at $60 per ton farmgate prices is shown in table 4.4.

As depicted in figure 4.11 and consistent with constraints discussed earlier, in 2017, production of 30 million tons was simulated to be available from residues only at an offered farmgate price of ≤$40. The total available biomass resources associated with planted acres discussed earlier at an offered farmgate price of ≤$40 are simulated to be 2 million tons from energy crops in 2022, which was 5% of 44 million tons of total production. Compared with the base-case scenario, which had no energy crops entering at ≤$40 in 2022, the onset of energy crops at this low price demonstrates the impact that yield improvements (3% per year) have on the profitability of these crops. In 2030, 40 million tons from energy crops are available, and in 2040, 276 million tons from energy crops are available at an offered farmgate price of ≤$40. In this high-yield but low-price scenario, herbaceous energy crops and woody energy crops come into production in 2019 and reach a potential supply of 18 million tons for herbaceous energy crops and 22 million tons for woody energy crops in 2030. Later years see further increases to 170 million tons for herbaceous energy crops and 106 million tons for woody energy crops in 2040. Residues are capped at 83 million tons in 2040, which constitutes just 23% of total production; herbaceous energy crops dominate at 47% of total production.

At a ≤$60 offered farmgate price, 105 million tons of residues are available in 2017, and 245 million tons of biomass resources from agricultural lands are available in 2022 (55% residues, 42% herbaceous energy crops). The surge in herbaceous energy crops when the simulation transitions from ≤$40 to ≤$60 demonstrates the minimum profitability needed under these simulations for herbaceous crops. In later years, 554 million tons become available in 2030 (54% herbaceous energy crops, 15% woody energy crops, and 31% from residues) and 937 million tons in 2040 (64% herbaceous energy crops, 15% woody energy crops, and 21% residues) at ≤$60. A ≤$80 price yields 121 million tons of residues in 2017. In 2022, herbaceous energy crops begin to dominate the market at this higher price, comprising 59% of 394 million tons of total production in 2022. In 2030 and 2040, woody energy crops increase to 12% of total production: 85 million tons in 2030 and 125 million tons in 2040. The production of herbaceous energy crops continues to rise from 62% of total production (446 million tons) in 2030 to 68% of total production (729 million tons) available in 2040. Total production reaches 1.07 billion tons at a ≤$80 offered farmgate price in 2040, with just 20% (214 million tons) of this production coming from residues. The total potential availability of biomass feedstocks under the high-yield (3%) scenario at selected years is shown in figures 4.11, 4.12, 4.13, and 4.14.

4.5.3 Economic Impacts

Changes in crop prices, planted acres, and crop net returns compared to the 2015 base year are summarized in tables C-8 and C-9 of appendix C for the base-case and high-yield scenario at $60 per dry ton or less. Relative to the USDA projections, simulated results show a loss of crop acres to energy crops; 2040 crop prices relative to the baseline are generally higher in nominal terms but lower than near-term prices in real terms. For producers, the higher crop prices more than compensate for the loss in crop acres, as reflected in higher net crop returns relative to the base year. In the base case, the cross price elasticity of supply of corn when biomass prices increase from $40 to $60 is 0.7 in 2030 and 1.8 in 2040. This suggests the responsiveness of corn price to biomass

Table 4.4 | Distribution of Land Use Under High-Yield Assumptions for Select Years at ≤$60 Offered Farmgate Price[13]

Land use type	2017	2022	2030	2040
	(million acres)			
Energy crops land allocation (planted)	N/A	28.3	57.87	87.95
Cropland allocation (planted)	N/A	15.39	27.8	48.95
Cropland used as pasture allocation (planted)	N/A	1.29	2.31	2.54
Permanent pastureland allocation (planted)	N/A	11.62	27.76	36.46
Energy crops (harvested/fraction)	N/A	17.11/0.60	41.63/0.72	64.12/0.73
Corn (planted)	90.36	84.55	79.67	74.33
Corn stover (harvested)	46.76	51.93	53.45	50.38
Other crops with residues (planted)	65.87	58.72	56.35	52.48
Other crops with residues (harvested)	19.41	23.37	28.02	29.51
Percent of total U.S. cropland (325.6 million acres) allocated to energy crops	N/A	4.7%	8.5%	15%
Percent of total U.S. pastureland (446.2 million acres) allocated to energy crops	0%	2.9%	6.7%	8.7%
U.S. major crops with residues (acreage), % harvested for biomass	156.20, 42.4%	143.30, 52.6%	136.00, 59.9%	126.80, 63%
% of U.S. cropland contributing to biomass production (energy crops planted and residue harvested)	20.3%	27.9%	33.6%	39.6%

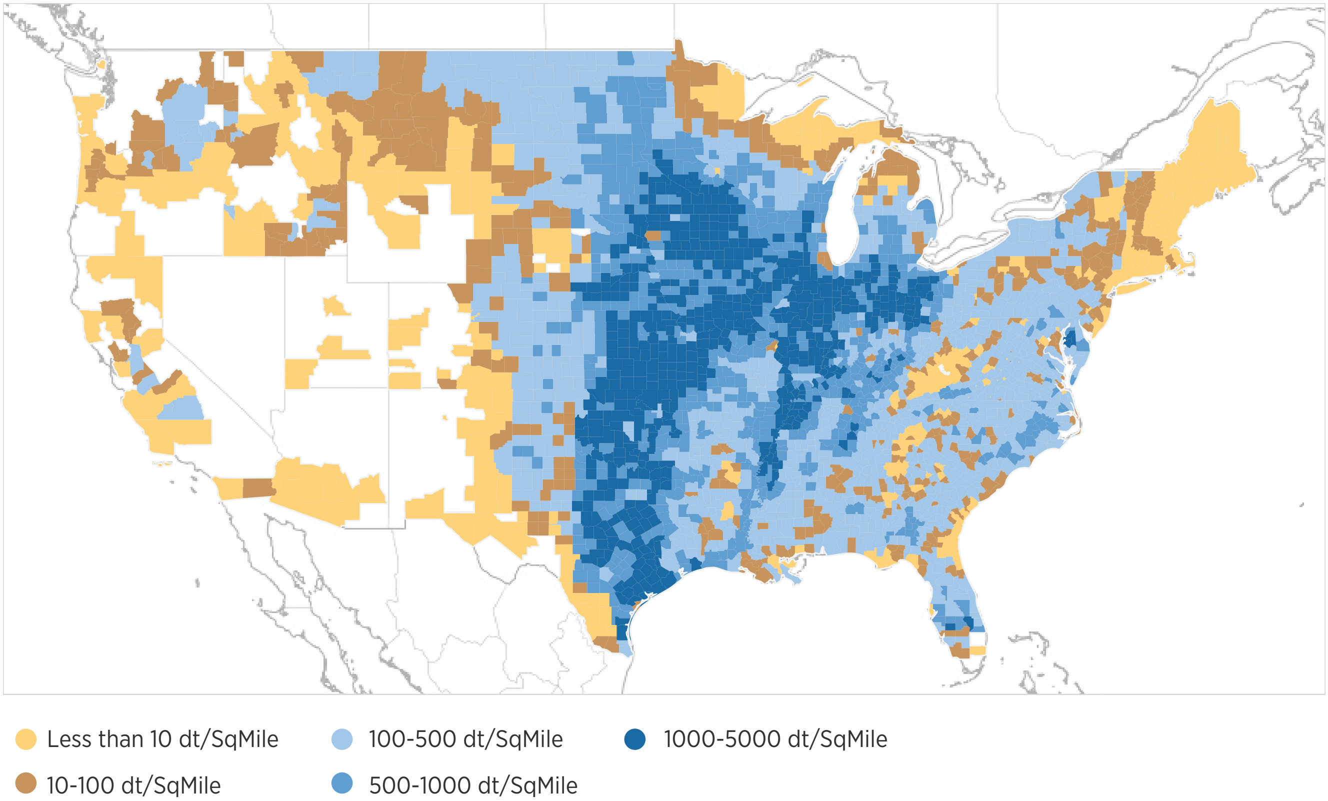
price is increasing over time. The price of corn is lower due to the excess grain produced under the 3% high-yield scenario.

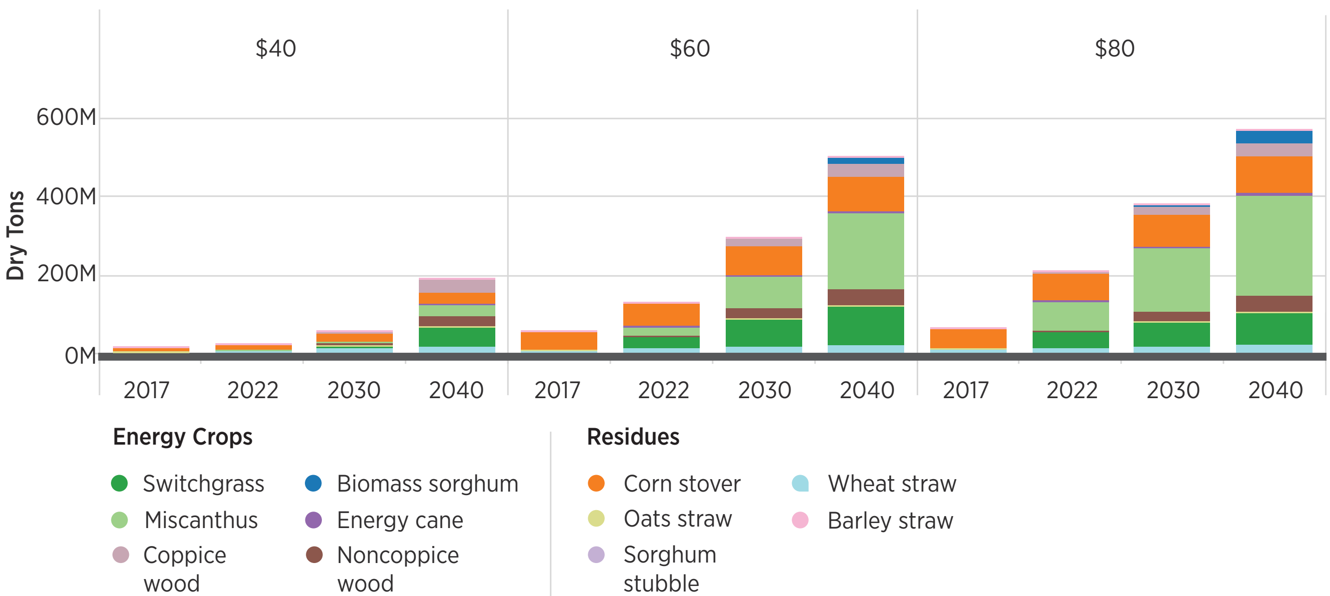
Comparing the simulated results to the USDA projections shows only minor changes in total livestock production, beef cattle farm prices, and inventories of cattle. The key assumption is that increased forage productivity compensates for losses because of the presence of energy crops on pastureland.

Total net crop returns increase significantly under the USDA baseline scenario where crop residues are collected and energy crops produced. Total net returns from livestock production are unaffected. Overall, total net returns to major crops and livestock in the *BT16* base-case scenario increase by about $16.5 billion by 2040 compared to the extended baseline. Under the high-yield scenario, total net returns are nearly $14.5 billion higher by 2040.

[13] Interactive visualization: https://bioenergykdf.net/billionton2016/4/5/table

Figure 4.11 | Production of residues and energy crops at an offered farmgate price of ≤$60 in 2040 under a high-yield (3%) scenario[14]





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

Figure 4.12 | Supply curves of potential production from major crop residues for select years under high-yield (3%) assumptions

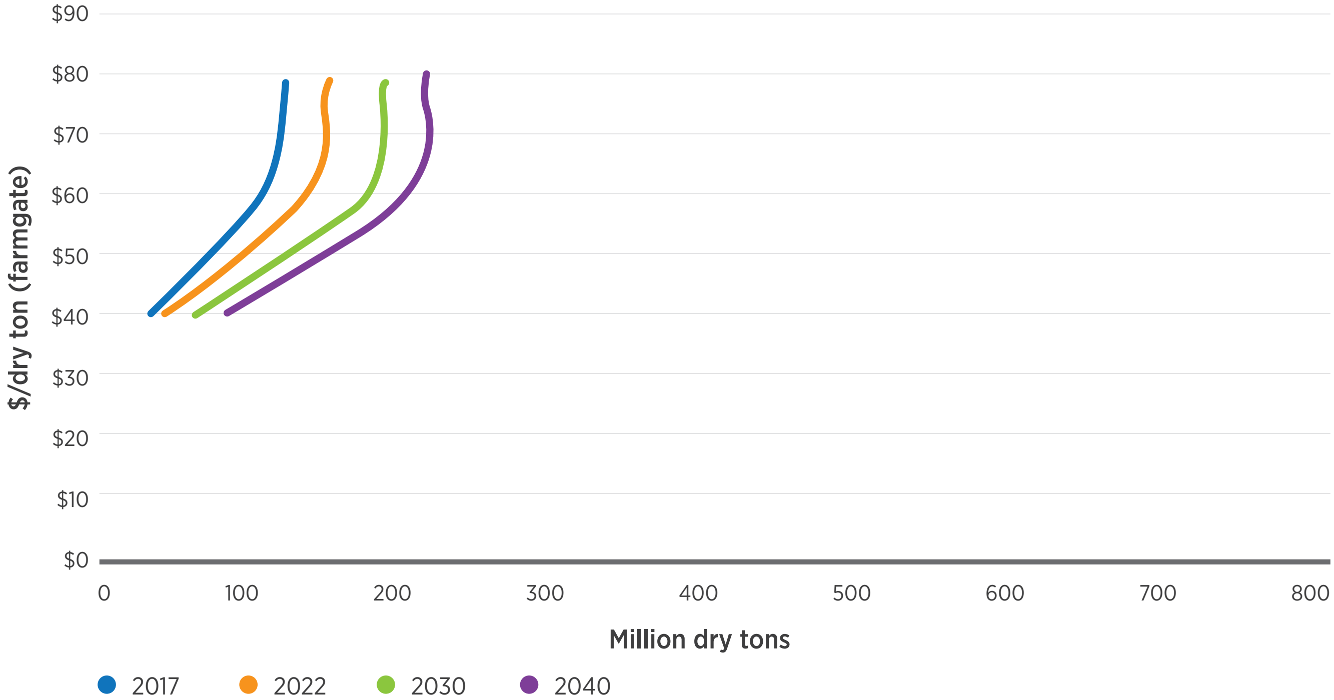


Figure 4.13 | Supply curves of potential herbaceous energy crop production for select years under high-yield (3%) assumptions

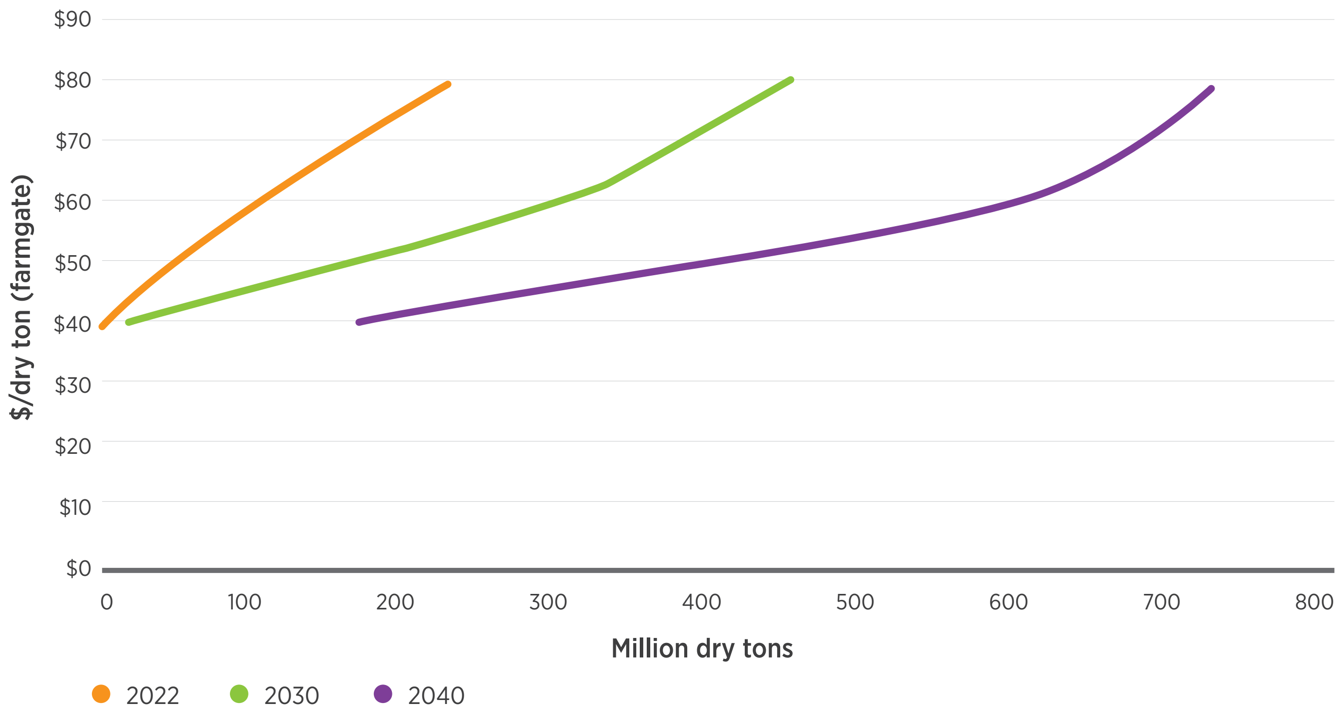
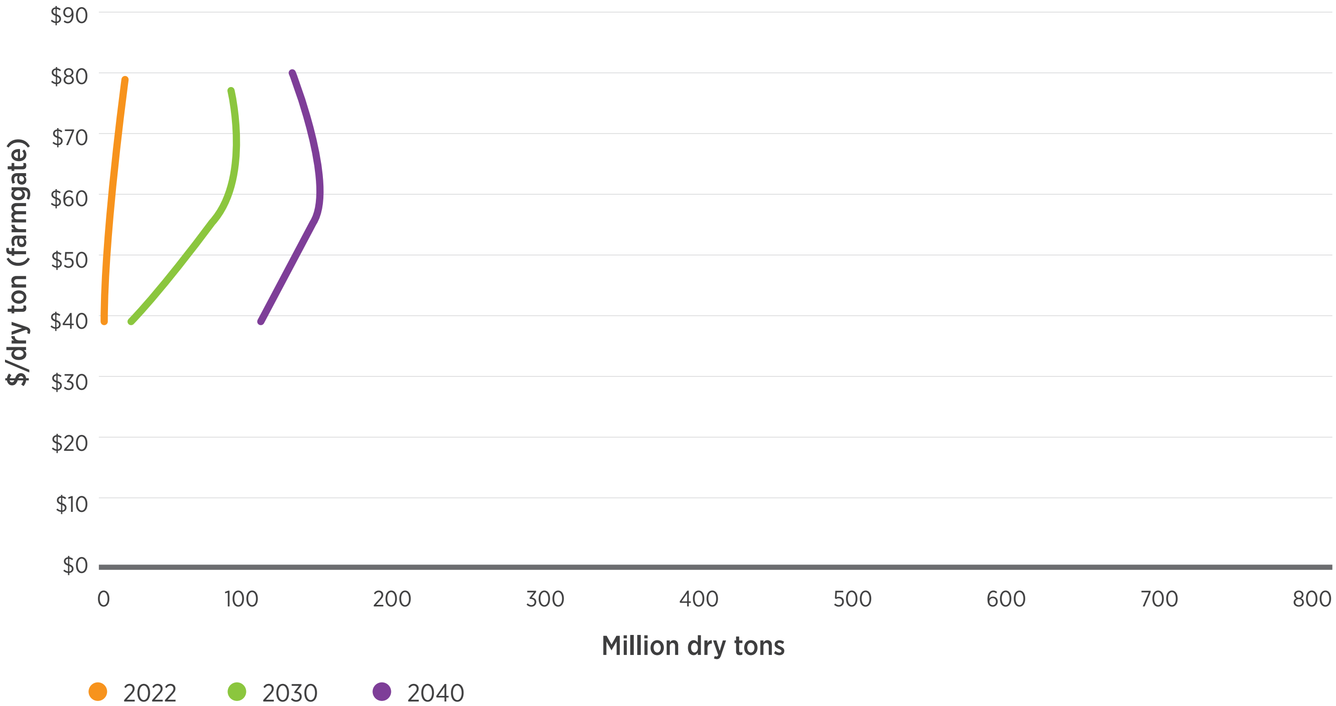


Figure 4.14 | Supply curves of potential woody energy crop production for select years under high-yield (3%) assumptions



Note: Decreasing supplies at higher prices are due to transitions to herbaceous energy crops under these market scenarios.

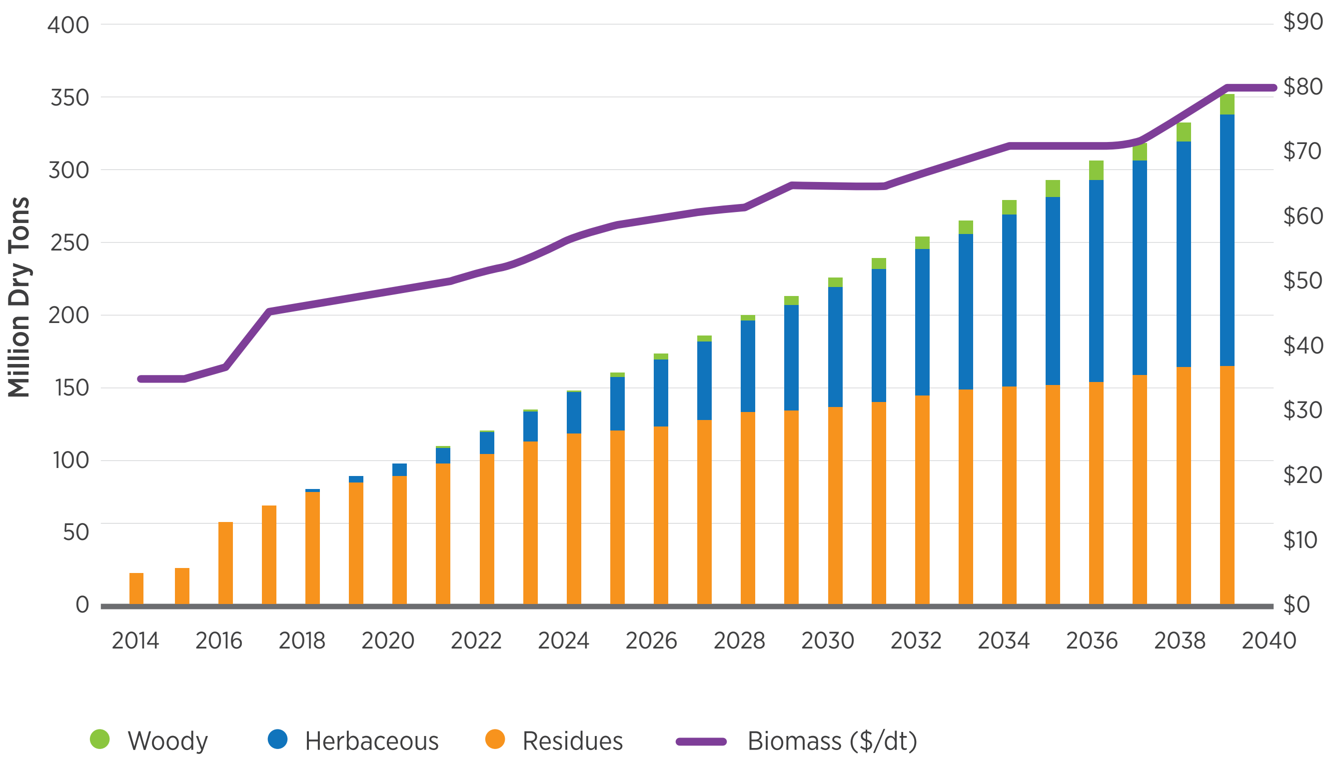
4.6 Prices at Specified Production

In modeling a production-target simulation (demand level 1 scenario[15]) of 250 million tons by 2022, the model solves for a $60 farmgate price in 2022 and is able to achieve 319 million tons of primarily residues (132 million tons) and miscanthus (93 million tons), with switchgrass (64 million ton), coppice woody energy crops (28 million tons), and some energy cane (1.5 million tons) as well. A farmgate price of $60 is again determined to be necessary to meet a national production target of 325 million tons (demand level 2 scenario) by 2022; but this follows several years of prices exceeding $100 that elicit production from miscanthus, which is then sustained for 15 years at lower prices due to rotation assumptions.[16] At that same production target, $83 is necessary for a target year of 2030 (350 million tons achieved). However, the later years of 2035 and 2040 yield slightly lower farmgate prices of $77 (346 million tons) and $80 (351 million tons), respectively. Increasing the production target to 500 million tons by 2040 yields a farmgate price of $79 necessary to achieve this production (606 million tons total, consisting of 176 million tons from residues, 215 million tons from miscanthus, 134 million tons from switchgrass,

[15] The demand-run scenarios simulate a gradual increase in demand and, in turn, feedstock price, over time.

[16] Once an herbaceous energy crop enters production, the entire rotation must be completed. In the case of miscanthus, this is for 15 years. See appendix C.1.

Figure 4.15 | Feedstock supply composition and necessary farmgate price (nominal) under a demand scenario with 325-million-ton national production target by 2040



53 million tons from coppice, 27 million tons from non-coppice woody energy crops, and 0.4 million tons each from biomass sorghum and energy cane). Figure 4.15 shows the increasing farmgate price (to $71) and feedstock supply composition across the three major energy crop types as production steadily increases to meet the target demand of 325 million tons of national production in 2040.

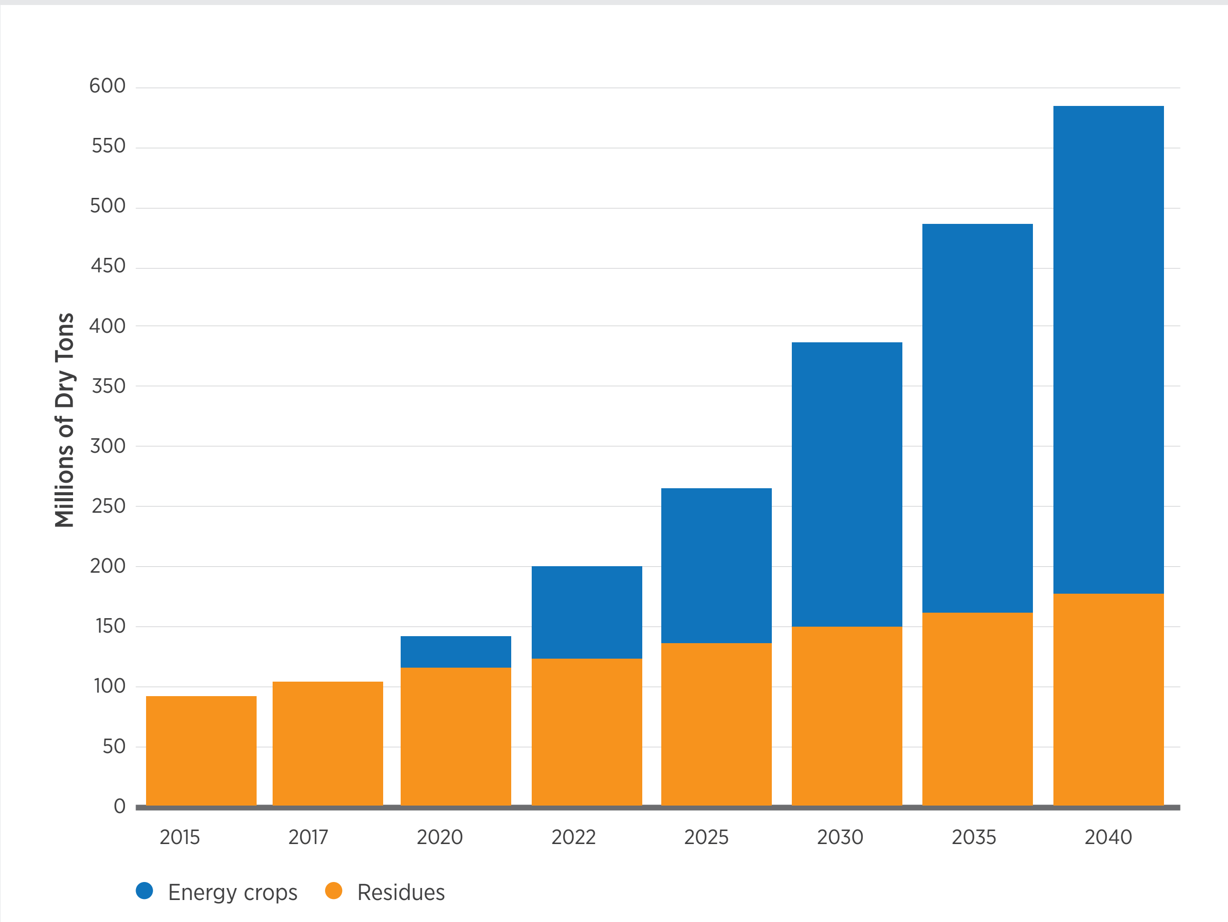
4.7 Discussion

Although model improvements and assumption refinements have been incorporated into this analysis, in general, the results presented for agricultural residues and biomass crops are consistent with the 2011 *BT2* results in feedstock supply composition (e.g., residues dominating in early years, herbaceous in later years). Compared with *BT2* results, this analysis shows a more conservative outlook for all energy crops: residues (e.g., because of new operational efficiency constraints; see appendix C.1), woody energy crops (e.g., due to adjusted costs and model improvements to allow for staggered plantings), and herbaceous energy crops (e.g., due to constraints applied on pasture conversion[17]). Figures 4.16, 4.17, 4.18, and 4.19 show supply curves at selected prices in year 2040 under the base-case and high-yield scenarios for comparison.

[17] Pasture land excluded from POLYSYS land base includes 399.2 million acres out of 446.2 million acres total pasture (see appendix C.1 for more details).

Text Box 4.4 | Realizing Technical Potential With Sustained Market Demand

The biomass resources quantified in this report represent "technically available" potential resources (i.e., tons of resources that could be available at specified prices, if specified markets are provided; see fig. 8.1). Actual market availability of these potential resources is dependent upon future market demands defining the economic viability of their mobilization. While the assumption is that energy crops become "major crops" in 2019 for all scenarios (i.e., they compete with existing eight major crops and hay), it is anticipated that biomass crops continue to develop in local crop markets in the near term. In particular, future energy crops supply, which represents approximately 30%–40% of the potential billion-ton supply by 2040, is entirely dependent upon sustained market demand to incentivize energy crop deployment. For example, the specified price run of ≤$60 per dry ton in the baseline scenario indicates 411 additional million tons of energy crops are potentially available by 2040. This potential 2040 supply is in response to a simulation of a ≤$60 per dry ton price offered in all producing counties in all years between 2019 and 2040, with no limitation of what the market can consume. The response is a nearly linear progression of growth of biomass crops over time.



Potential supply of all energy crops and residues for selected years in the base-case scenario at $60 per dry ton.

Figure 4.16 | Agricultural residues available across four exogenous price scenarios in the year 2035

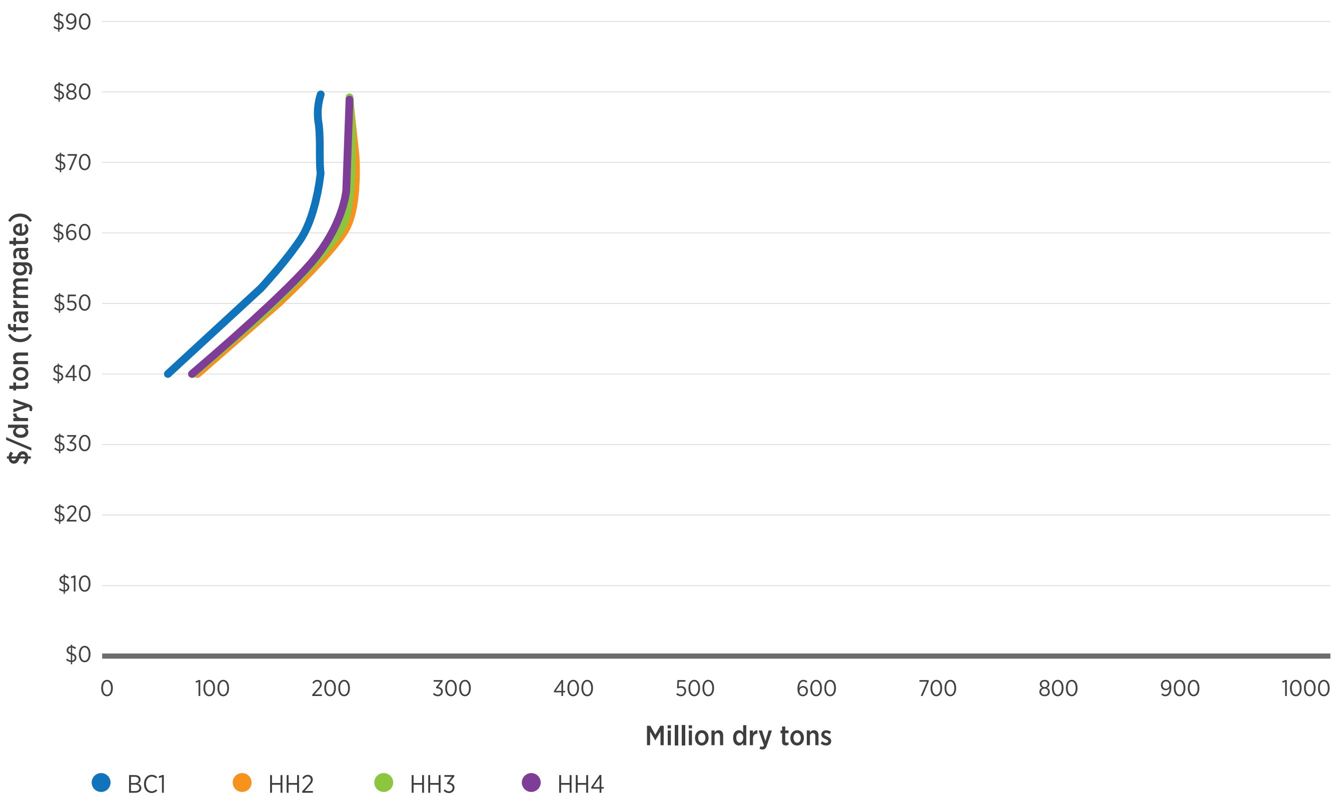


Figure 4.17 | Herbaceous energy crops available across four exogenous price scenarios in the year 2035

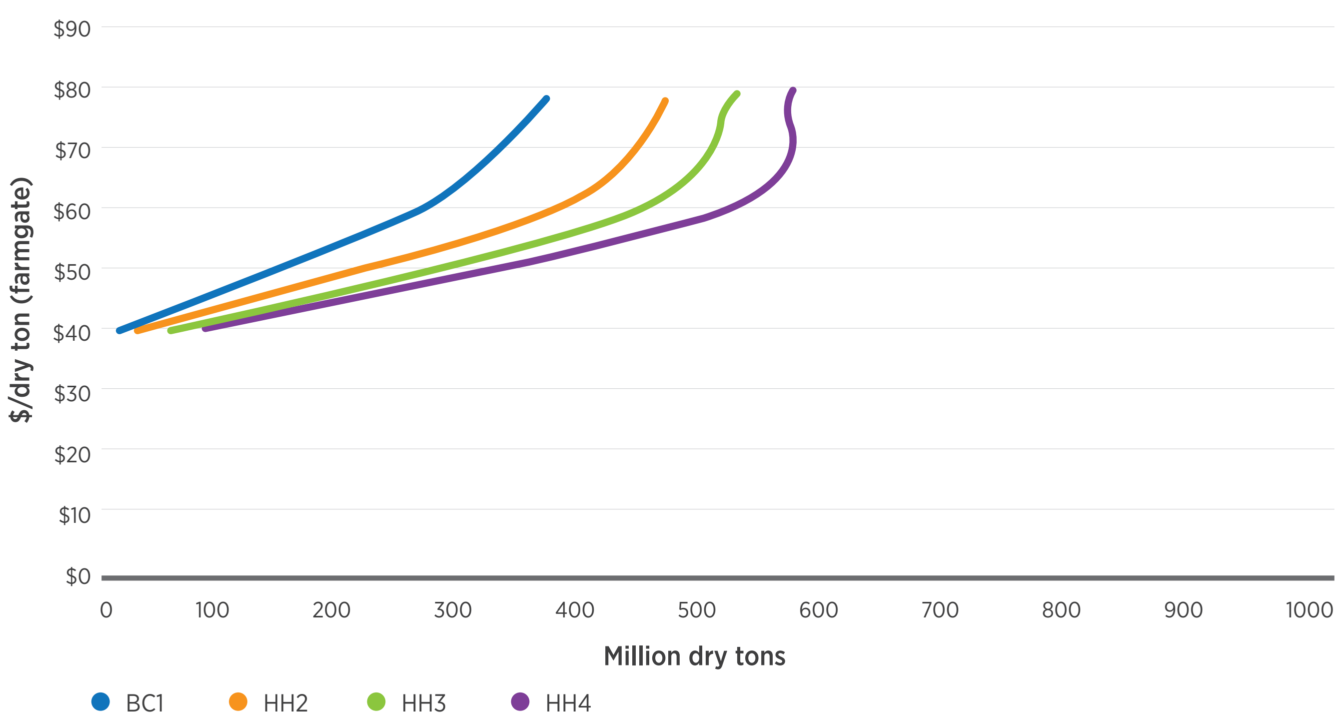


Figure 4.18 | Woody energy crops available across four exogenous price scenarios in the year 2035

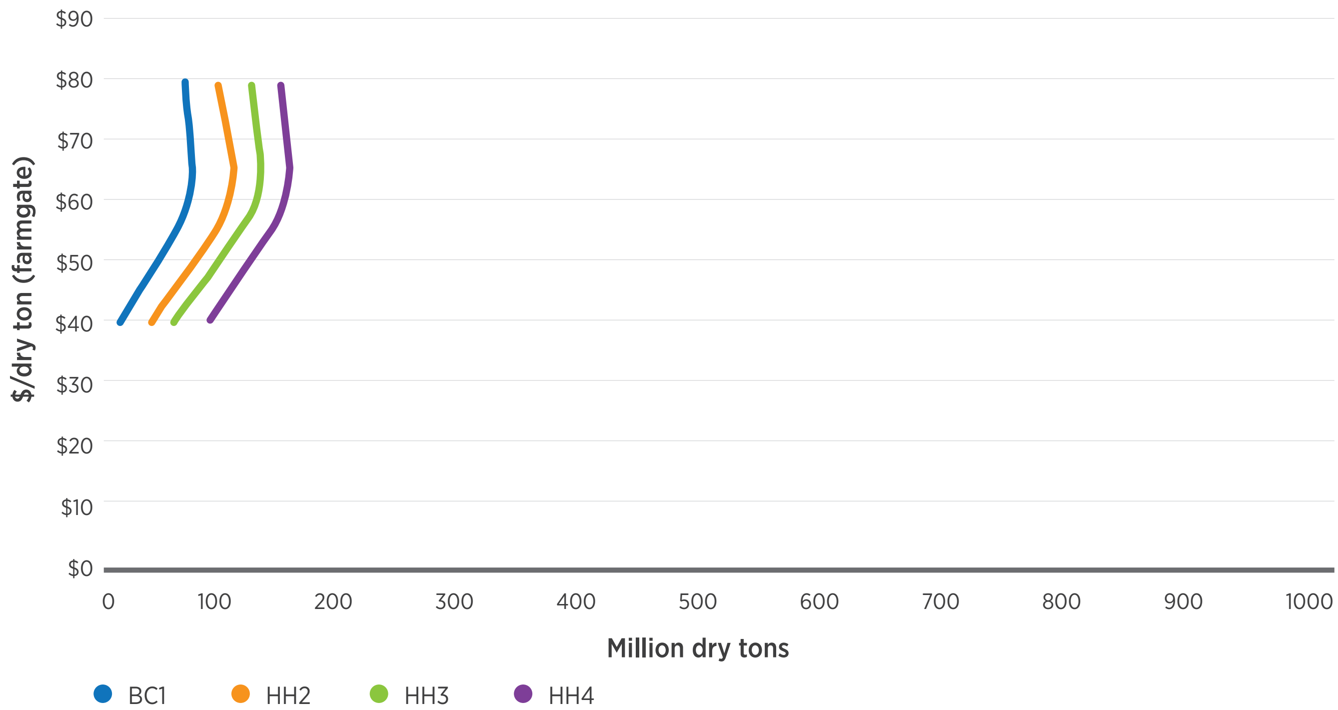
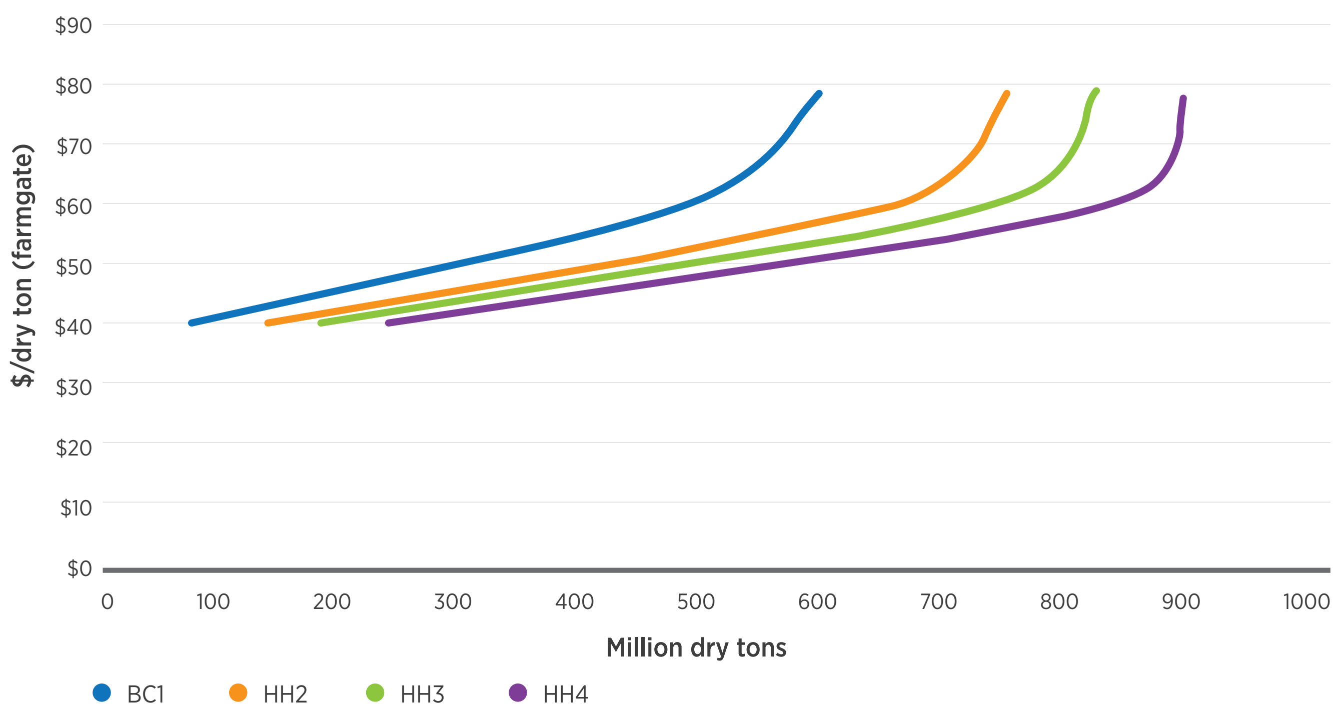
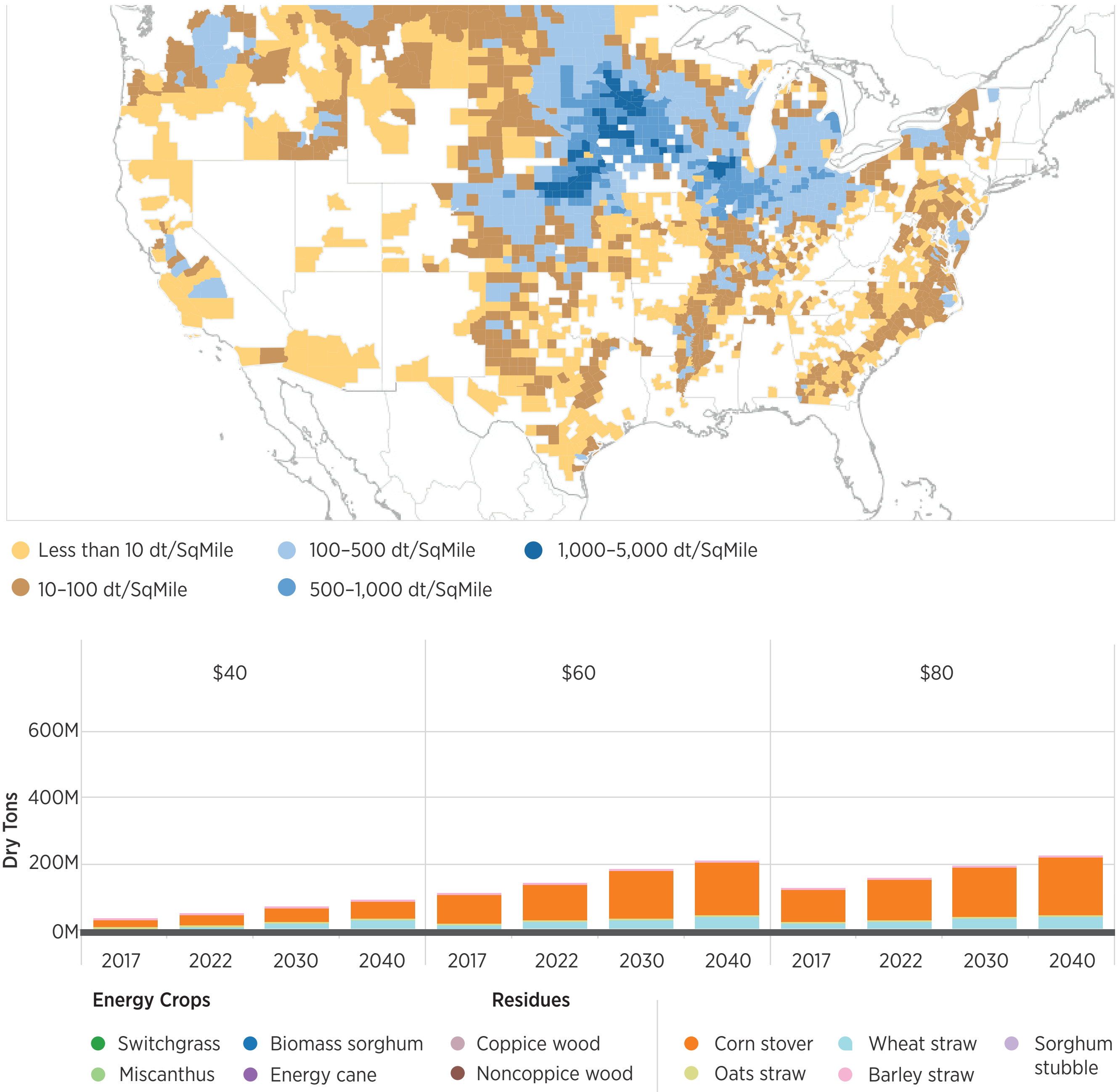


Figure 4.19 | Total biomass resources from agricultural lands available across four exogenous price scenarios in the year 2035



Energy crop production is summarized in the state maps shown in figures 4.20, 4.21, and 4.22.[18] As depicted, the Corn Belt is again the principal area for production of residues. These figures consistently show dominance of the Great Plains in perennial grass. As discussed in the 2011 *BT2*, the dominance of perennial grasses in the Plains is due to the land availability as well as the relatively low profitability of current land uses. Cropland and pasture land are still found to be the two main land-use sources for energy crops.

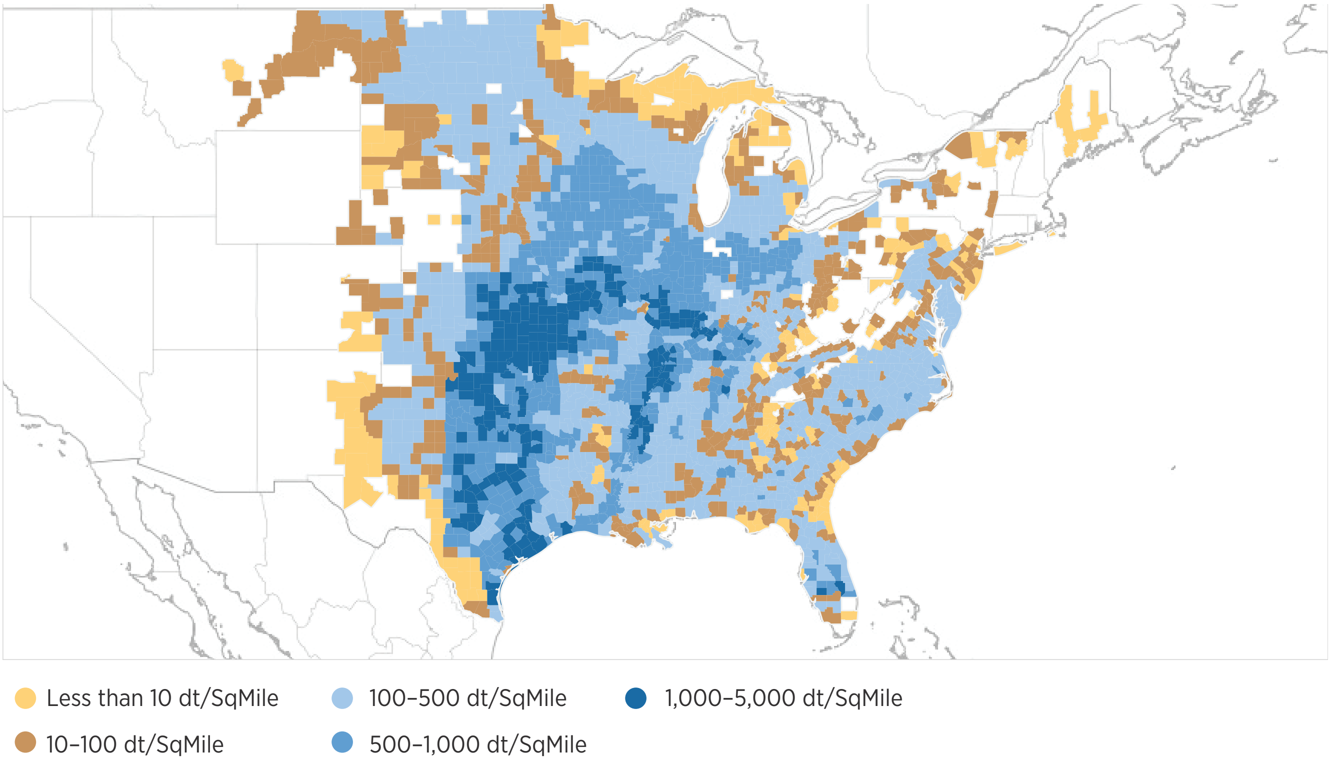
Figure 4.20 | Production from residues at <$60 offered farmgate price under a high-yield (3%) scenario[19]

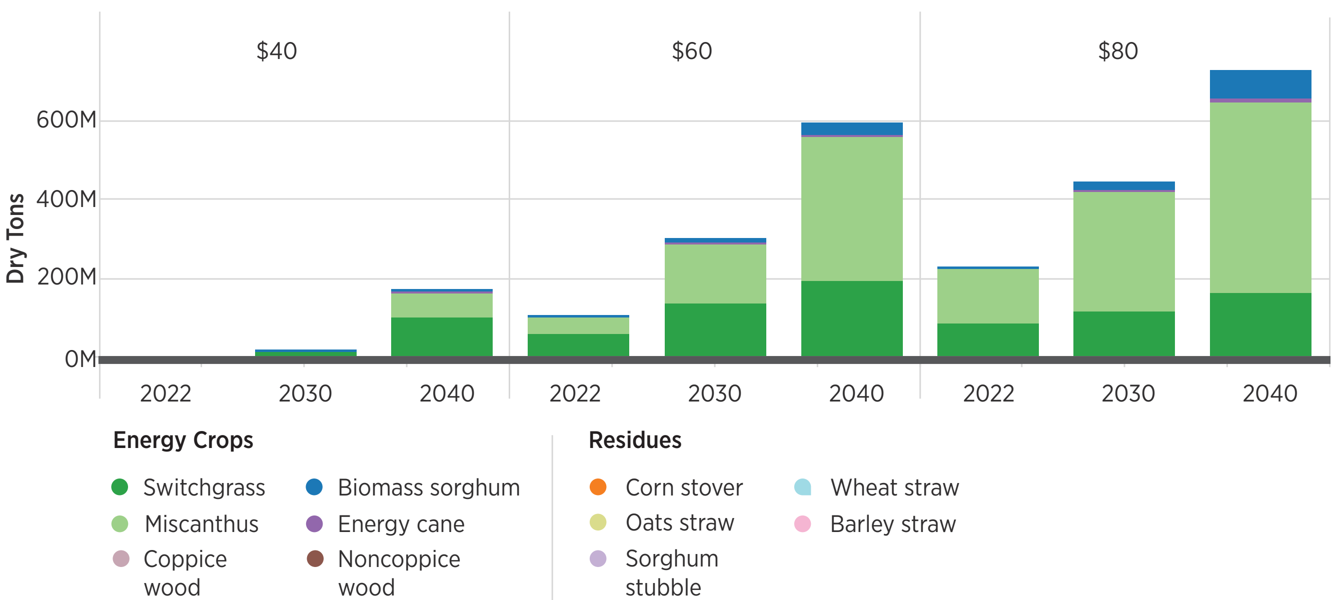


[18] We have highlighted a 3% scenario in these interactive visualizations, although any yield scenario can be selected.

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

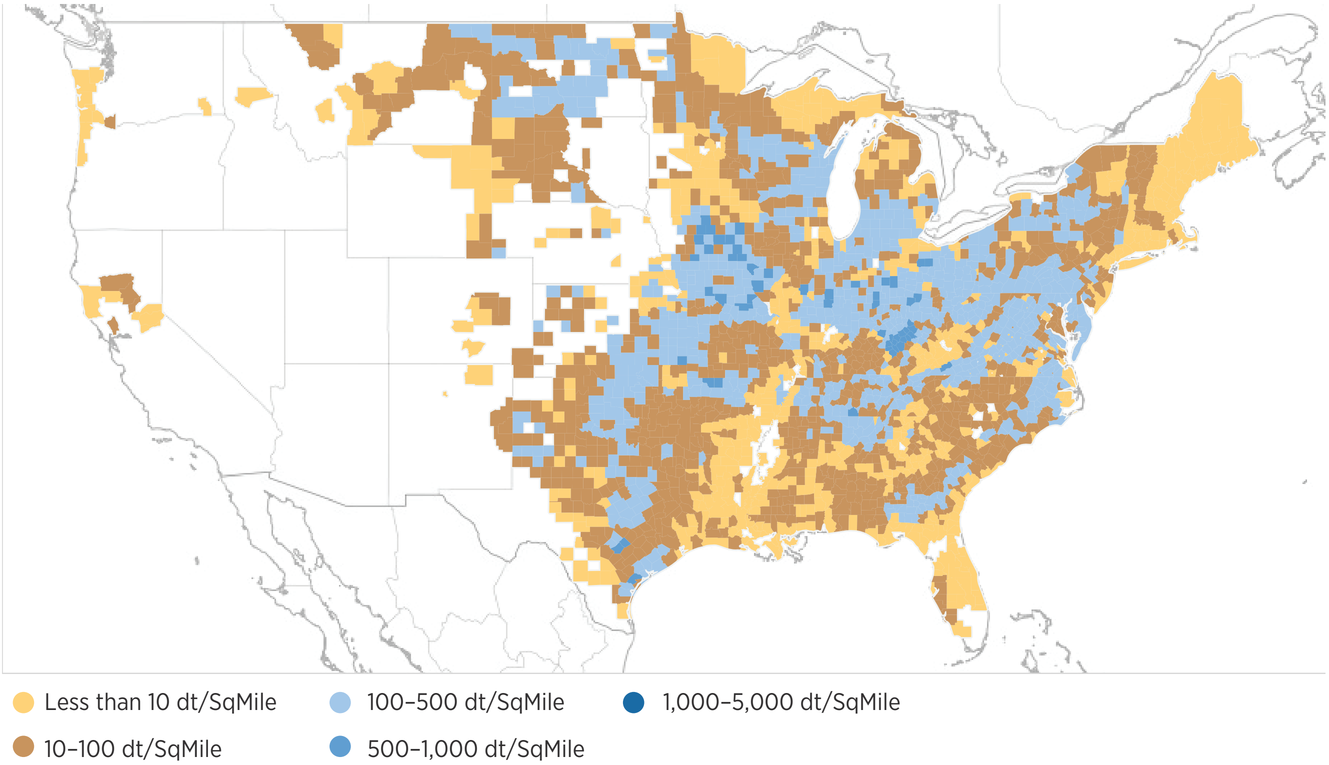
Figure 4.21 | Production from herbaceous energy crops at ≤$60 offered farmgate price under a high-yield (3%) scenario[20]

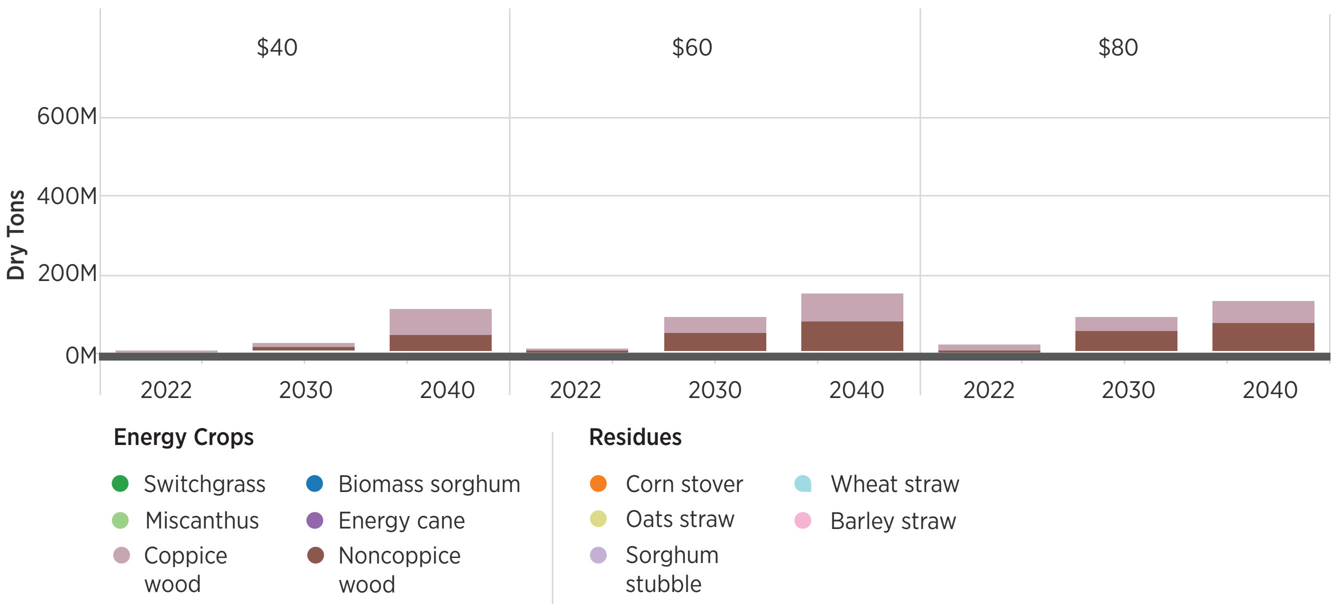




[20] Interactive visualization: https://bioenergykdf.net/billionton2016/4/2/tableau

Figure 4.22 | Production from woody energy crops at ≤$60 offered farmgate price under a high-yield (3%) scenario[21]





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

Table 4.5 | Key Variables and Assumptions

Assumptions	Pessimistic	Reference case	Optimistic
Price scenario (offered farmgate price)	$55	$60	$65
Yield scenario (ton acre[a] annual improvement)	Base-case: 0% High-yield: 2%	Base-case: 1% High-yield: 3%	Base-case: 2% High-yield: 4%
Tillage flexibility (permitted tillage acreage changes by crop)	Base-case: 0 High-yield: 2	Base-case: 1 High-yield: 3	Base-case: 2 High-yield: N/A
Pastureland intensification (MiG land required to replace 1 acre of converted pasture land)	2:1 (i.e., 33% pasture available to convert)	1.5:1 (i.e., 40% pasture available to convert)	1:1 (i.e., 50% pasture available to convert)
Operational efficiency (annual improvement in residue collection efficiency)	50% efficiency in initial year, increasing to 80% efficiency in final year	50% efficiency in initial year, increasing to 90% efficiency in final year	50% efficiency in initial year, increasing to 100% efficiency in final year
Varying input costs (establishment, maintenance, and harvest) for all energy crops	+10%	No change	-10%
Land rental rates (per acre cash rental rates[a] included in crop production costs)	Added	Not added	N/A

[a]For more detail, see section 4.2.3 and appendix C.1.

4.8 Sensitivity Analysis of Key Assumptions

A sensitivity analysis was performed to evaluate the sensitivity of the feedstock supply in 2022, 2030, and 2040, at a simulated offered farmgate price of ≤$60, to the key variables outlined in table 4.5.

4.8.1 Results of Sensitivity Analysis

Figures 4.23, 4.24, 4.25, 4.26, 4.27, and 4.28 illustrate the sensitivity of feedstock supply to key variables in 2022, 2030, and 2040.

4.8.2 Offered Farmgate Price

As expected, the offered farmgate price is found to have the largest effect on total available biomass resources from agricultural lands in the initial years of the simulation (e.g., see year 2022 results in figs. 4.23 and 4.26). In these formative years and at the low prices, such as ≤$60 simulated here, supply is very sensitive to price changes. For example, a $5 drop in offered prices leads to a 38 million ton reduction in total supply in 2022 under a base-case (1%) scenario and a 60 million ton reduction under a high-yield (3%) scenario. Likewise, increasing the offered price by $5 yields 28 million tons more total supply in 2022 under the high-yield scenario and 32 million tons more under the base-case scenario.

Figure 4.23 | Analysis of sensitivity of total supply in 2022 to key variables under a base-case (1%) ≤$60 offered farmgate price scenario

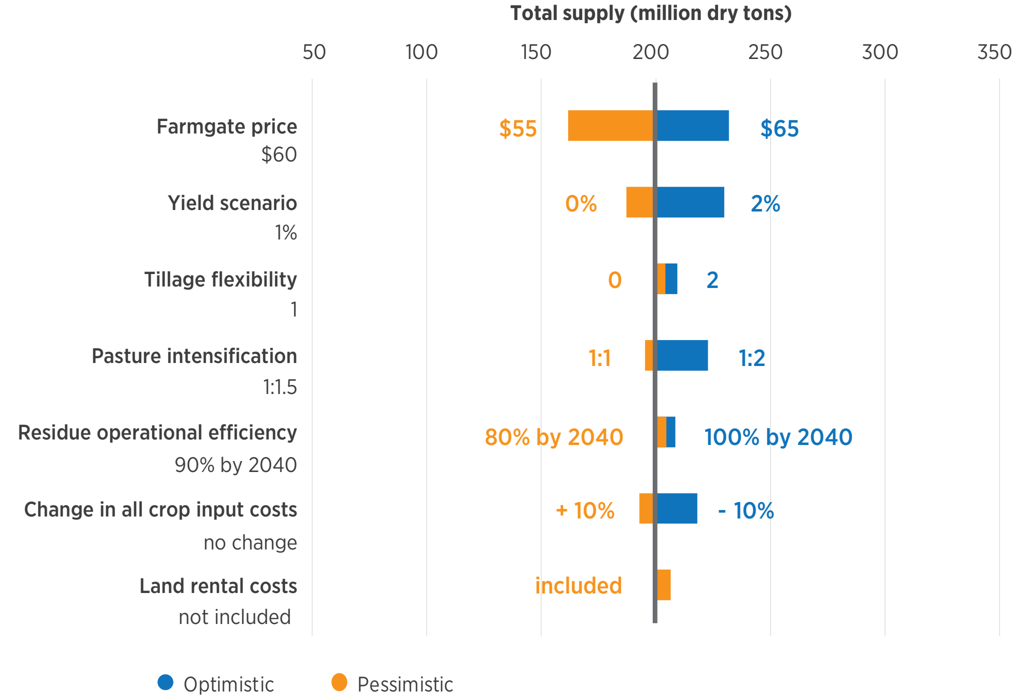


Figure 4.24 | Analysis of sensitivity of total supply in 2030 to key variables under a base-case (1%) ≤$60 offered farmgate price scenario

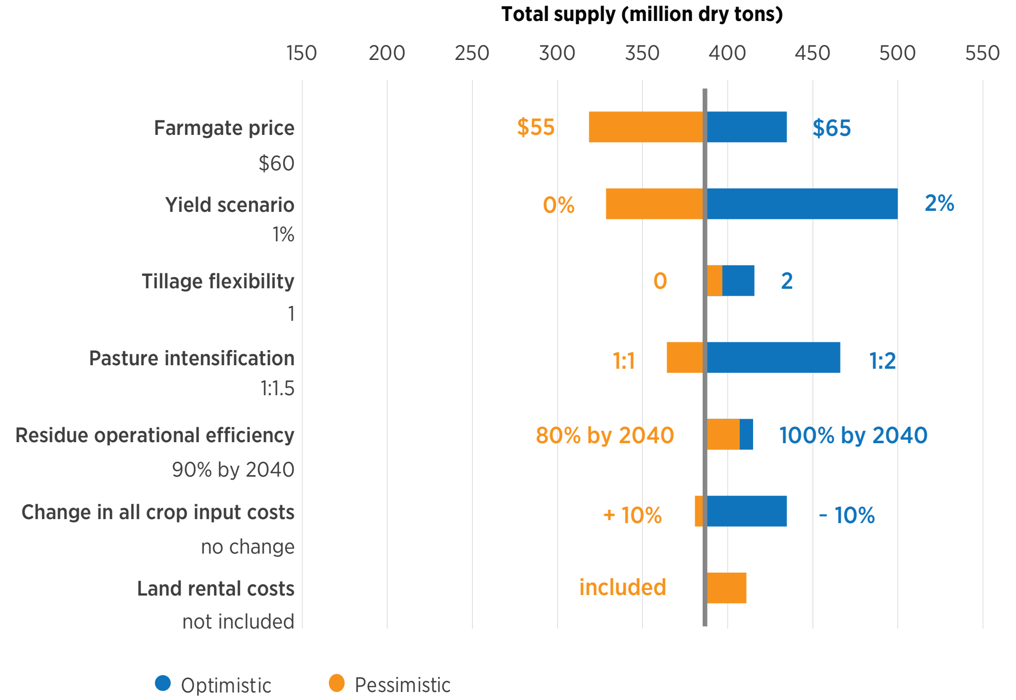


Figure 4.25 | Analysis of sensitivity of total supply in 2040 to key variables under a base-case (1%) ≤$60 offered farmgate price scenario

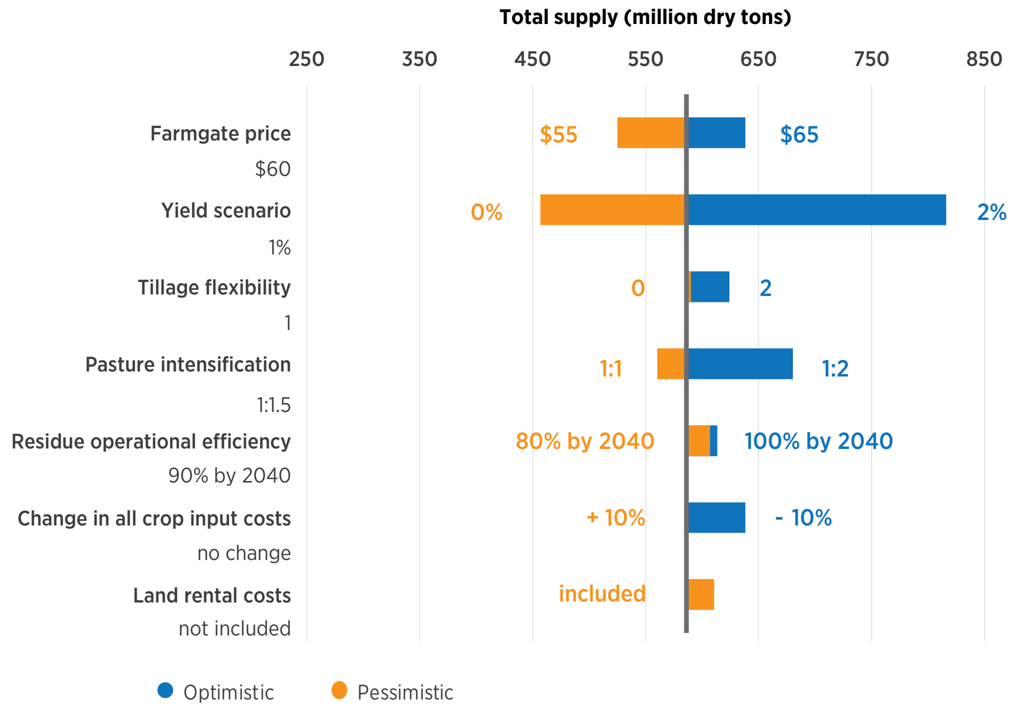


Figure 4.26 | Analysis of sensitivity of total supply in 2022 to key variables under a high-yield (3%) ≤$60 offered farmgate price scenario

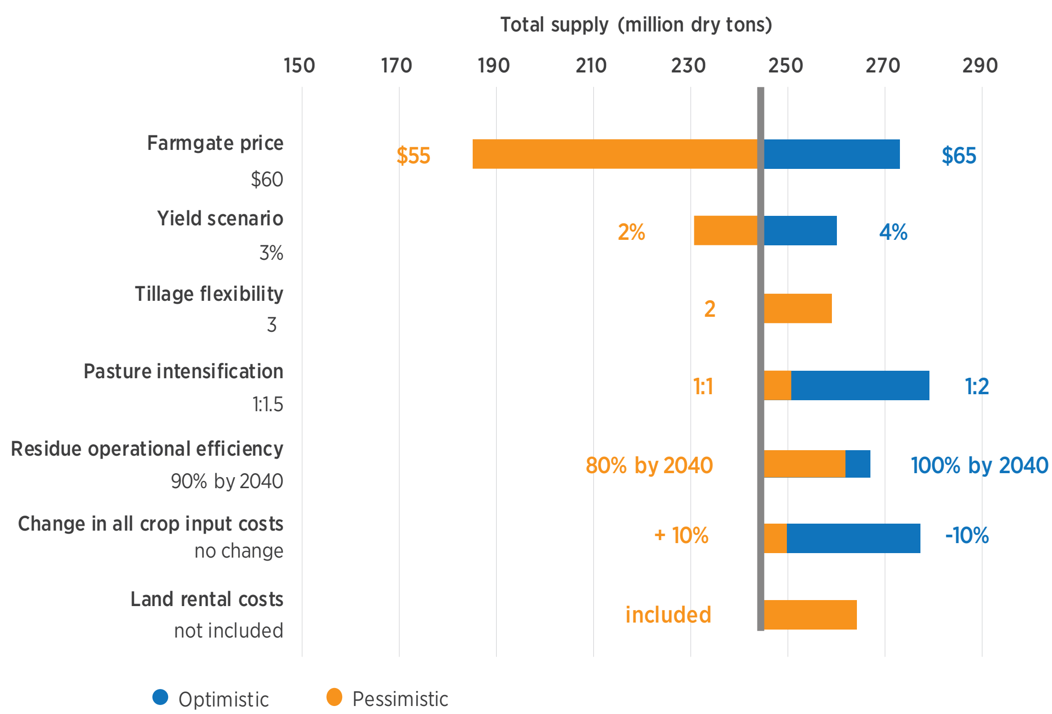


Figure 4.27 | Analysis of sensitivity of total supply in 2030 to key variables under a high-yield (3%) ≤$60 offered farmgate price scenario

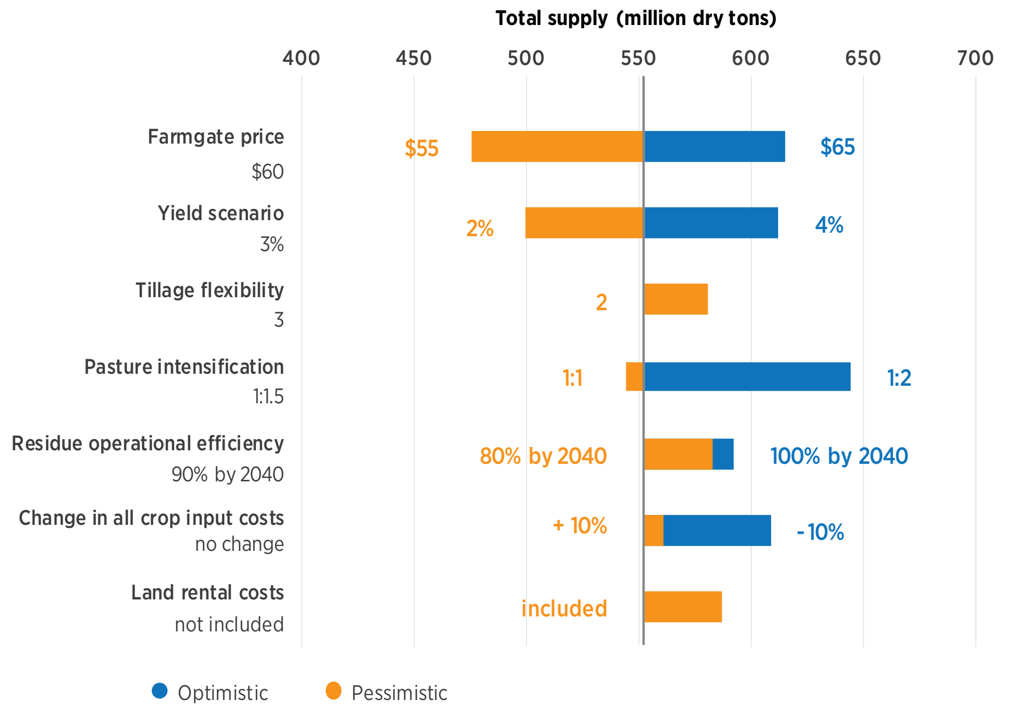
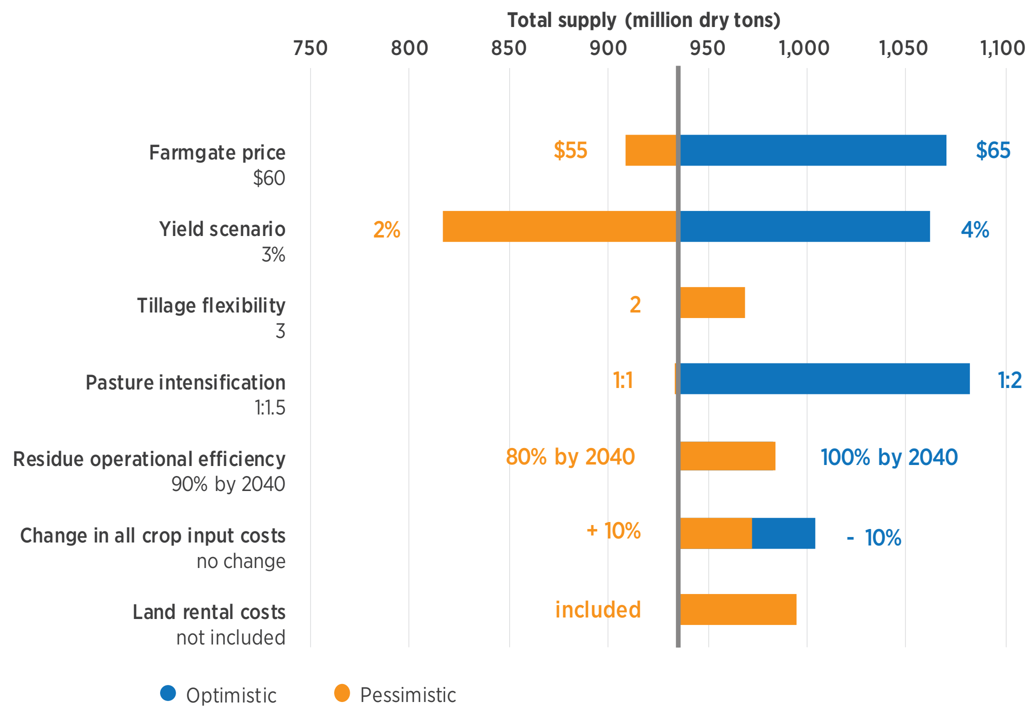


Figure 4.28 | Analysis of sensitivity of total supply in 2040 to key variables under a high-yield (3%) ≤$60 offered farmgate price scenario



At these simulated prices, a decrease in the offered price has a larger effect on total supply under both scenarios in 2022 and 2030, and a larger effect in 2040 under the base-case scenario.

Under both scenarios and in all years, the reduction comes primarily from herbaceous energy crops, which are very sensitive to price changes at these lower price levels because of conversion of marginally profitable land[22] to higher-cost miscanthus. For example, miscanthus loses 32 million tons for the base-case and 50 million tons for the high-yield case under the pessimistic scenario (≤$55) compared with the reference case (≤$60) in 2030. For comparison, miscanthus gains 80 million tons in 2030 under the high-yield optimistic scenario compared with the reference case. Under this scenario, switchgrass is the second most responsive feedstock to the price changes, gaining between 8 and 18 million tons in each year highlighted in figures 4.26, 4.27, and 4.28. Residues—primarily stover, because it has a higher market share than wheat and other minor residues—also respond to the offered prices under the base-case scenario, with -6.5 to + 3.5 million tons in 2022, -6.3 to +4.7 in 2030, and -4.6 to +4.1 in 2040 compared with the reference case. In the high-yield scenario, residues are also heavily affected by price fluctuation, with a loss occurring under both the pessimistic and optimistic scenarios (e.g., -17 to -32 million tons in 2030 compared with the reference case). These reductions in the optimistic scenario are due to substitutions by energy crops (e.g., in 2022,[23] planted acres in corn and wheat are reduced by 4 million acres as miscanthus expands by 4.57 million acres), consistent with scenarios presented in text box 4.5.

4.8.3 Yield Scenario

Varying the yield rate[24] in this sensitivity analysis is also found to have a large effect on total available biomass resources from agricultural lands in 2030 and 2040. The initial year of 2022 did not show as much variability because energy crops are permitted to enter into production only beginning in 2019. In 2040, the range of simulated yield increases introduces a variability from -95 to +94 million tons around the reference case values for herbaceous crops under the high-yield scenarios and from -108 to +159 million tons for the base-case scenario.[25] These increases are attributable to a combination of factors, including greater land availability because less acreage is required to grow the same total biomass, as well as higher yields of dedicated energy crops that allow marginally productive crops to be economically viable. Likewise, under lower-yield scenarios, marginally productive crops are restricted by the economic constraints of the model (as discussed in the farmgate price sensitivity results). For example, the yield reduction between the high-yield (3%) reference case and the pessimistic scenario (2%), a 1% annual change, causes a significant decline in herbaceous crops (primarily miscanthus at a loss of 89 million tons) and woody energy crops (coppice crops primarily, which incur losses of 17 million tons) in

[22] Economic constraints imposed by the model do not allow planting without profitability. Lower-yielding acres under higher-cost crops such as miscanthus are therefore very sensitive to offered prices and yield scenarios, which can push them above or below this constraint.

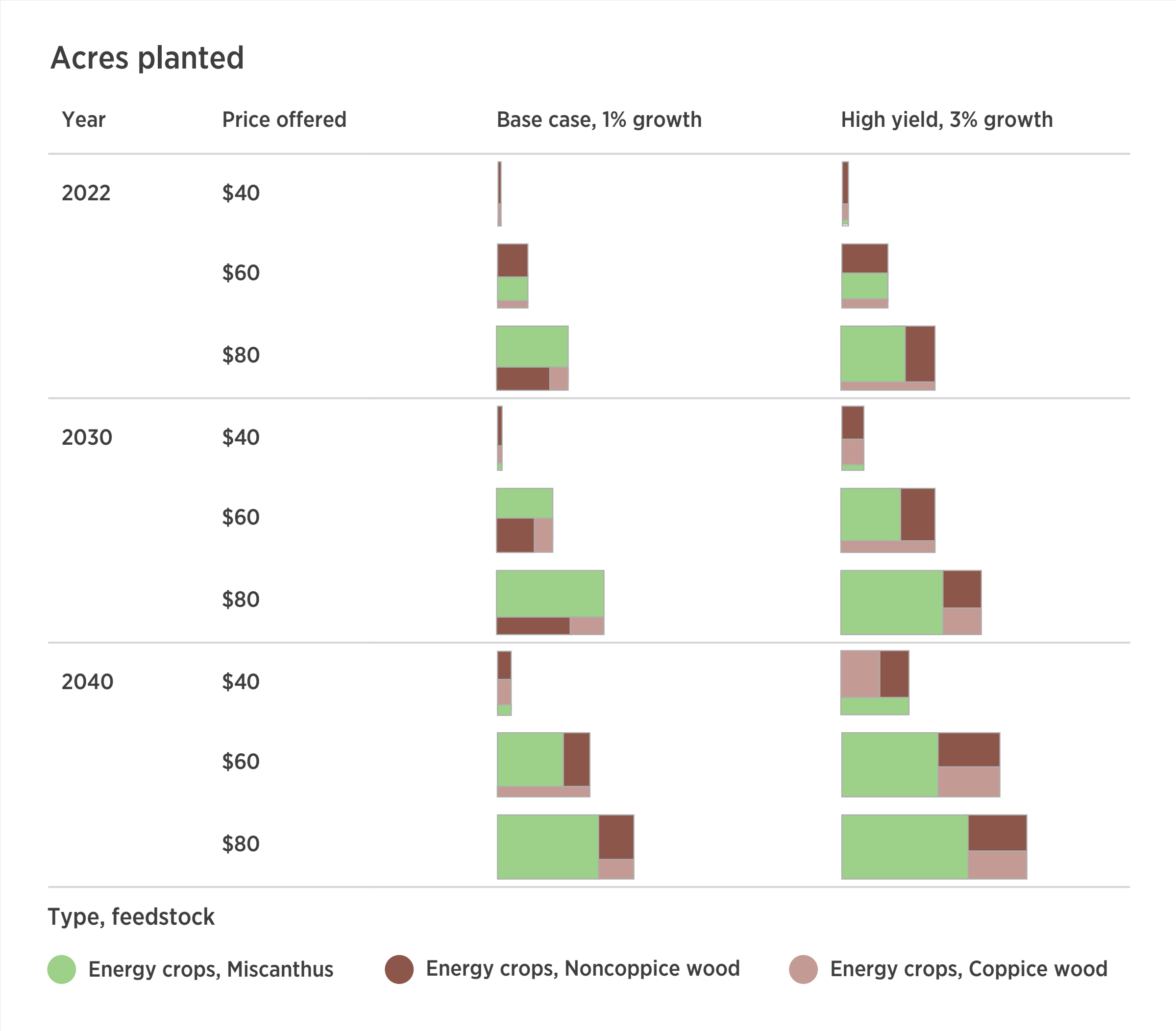
[23] Results by year such as this serve only as a snapshot and do not take into account switching between conventional crops that may occur in subsequent years.

[24] This compounding yield improvement is applied beginning in 2016 and affects energy crops that enter in 2019 by giving them an initial yield boost equal to four times the yield improvement percentage applicable under that scenario (e.g., 4 × 3% = 12% yield improvement in 2019).

[25] The base-case (1%) reference scenario is compared with an optimistic 2% high-yield scenario with a tillage flexibility of 1 for the base-case and 3 for the high-yield. See tillage flexibility discussion in section 4.8.4.

Text Box 4.5 | Independent Model Simulations and Substitutions Among Crops As Prices Increase

Under the high-yield (3%) scenario, the transition from a $60 offered farmgate price to $80 intensifies the surge in higher-price but higher-yielding herbaceous crops such as miscanthus over woody energy crops; the latter actually decrease when production in 2040 is compared under the two simulations. This decrease in production of woody energy crops is shown as a bend in the supply curve under figure 4.14. Displacement of some woody energy crops can be seen in the following visualization of planted acres for the base-case (1%) and high-yield (3%) scenarios.



Tree map showing planted acres for miscanthus, coppice, and non-coppice woody energy crops under the base-case (1%) and high-yield (3%) scenarios across all highlight prices and years.

2040. Likewise, the gains that occur between the optimistic scenario (a 2% high-yield scenario) and the base-case (1%) scenario, a 1% annual change as well, are the result of herbaceous crops (again primarily miscanthus at a gain of 121 million tons) and woody energy crops (again coppice crops with a gain of 24 million tons) becoming more profitable and therefore entering the market to add more total supply.

4.8.4 Tillage Flexibility

The tillage flexibility constraint sets the maximum and minimum of tillage acreage changes for conventional crops. By varying the index levels in this simulation, we are simply controlling the level of intensity for switching between land management types: a higher value (e.g., 3) increases the percentage allowed to transition more rapidly than a lower value (e.g., 1) (see appendix C.1, "Agricultural Residue Modeling Assumptions," for more details). Modifying the constraint to 2 under the pessimistic high-yield (3%) scenario actually allows for a gain in total supply at a given price, as seen in each tornado chart (figs. 4.26, 4.27, and 4.28). The sensitivity analysis demonstrates the interplay between conventional crop acreage and energy crops; as conventional crops are restricted, energy crops can sometimes respond favorably and actually increase supply by taking over some land in conventional crops. For example, when comparing a high-yield (3%) reference case with a tillage flexibility of 3 and a pessimistic scenario with a tillage flexibility of 2, the total change in agricultural lands for corn and wheat is a loss of 1 million acres in 2030. However, in that same year, herbaceous and woody energy crops gain 1 million acres each. Under the base-case reference scenario with a tillage flexibility index of 1, we simulate a ± 1 index: tillage flexibility at 0 in a pessimistic scenario and at 2 in an optimistic scenario. Similar to the high-yield case, the response by herbaceous crops in 2030 (+7.8 million tons) and by woody crops in 2040 (+6.8 million tons) actually causes an increase in total production under the pessimistic tillage flexibility assumption in 2030 and 2040, with a minimal change in production for residues (-5 to +1.8 million tons). In 2030 and 2040, the change between the optimistic (tillage flexibility index of 2) and the base-case reference scenario, however, is more dramatic: a +17.7 to +18.3 million ton change in residues, +10.8 to +15.7 dry ton change in herbaceous energy crops, and -0.2 to +4.7 change in woody energy crops. The total gains in production under both the pessimistic and optimistic base-case (1%) scenarios are shown in figures 4.23, 4.24, and 4.25.

4.8.5 Pastureland Intensification

The third and most important assumption analyzed in this sensitivity analysis is a constraint on the amount of land in MiG that is assumed to be capable of replacing the forage production displaced by one acre of pasture converted to energy crops (see table 4.3, section 4.2.2, and appendix C.2). Similar to the yield scenario analysis, the initial year 2022 does not show as large a variance around the reference scenario as do later years because of the restriction on energy crops that does not release until 2019 and their interaction with pasture land. Results for years 2030 and 2040 show a -22 million ton to +94 million ton variance around the reference case value for the base-case scenario and a -1.4 to +147 million ton variance under the high-yield scenario (3%). These results demonstrate the importance of available pasture acreage to the economic viability of these energy crops. For example, under an optimistic simulation, miscanthus gains 81 million tons of production for a high-yield (3%) scenario and 20 million tons under an optimistic base-case (1%) simulation compared with their respective reference cases in 2040. Switchgrass is also highly responsive, with a gain of 37 million tons in 2040 under an optimistic base-case (1%) scenario. Non-coppice woody crops also respond to the optimistic simulation under the base-case (1%) scenario in 2040 with a gain of 14.6 million tons of production.

4.8.6 Operational Efficiency

As discussed in appendix C, the modeling conducted under this report limits the operationally available residues that can be collected (operational efficiency constraint). Harvestable yield is the lesser of sustainable removable yield and operational efficiency as described in appendix C and figure C.3. In this sensitivity analysis, this constraint is varied to increase linearly to 80% of available residues in 2040 under a low-quantity scenario (pessimistic) and to 100% of available residues in 2040 under a high-quantity scenario (optimistic). This constraint is found to have an effect of between +4.9 and +28.3 million tons compared with the reference scenario in the base-case scenario. Under the high-yield scenario, a change of between +17.2 and +49 million tons occurs under the pessimistic and optimistic scenarios compared with the reference case. There is a loss in residues (e.g., 39 million tons in 2030 under the high-yield scenario) as expected with a pessimistic operational efficiency constraint, but this is offset by gains in other crops (e.g., 97 million tons of woody energy crops in 2030 under the high-yield scenario). This added total production in a pessimistic scenario is depicted in all of the sensitivity analysis figures above.

4.8.7 Varying Energy Crop Input Costs by ±10%

Varying the input costs for all energy crops is shown to have an effect on total supply of between -6 and +70 million tons under the high-yield (3%) scenario and -7 and +52 million tons under the base-case scenario. Miscanthus shows the most sensitivity to optimistic input costs of any crop assessed in this sensitivity analysis in 2022 and 2030 under the high-yield (3%) scenario. For example, reducing the input costs for all crops by 10% allows miscanthus to produce an extra 147 million tons in 2030. The second most responsive crop to optimistic cost changes is switchgrass (e.g., 112 million tons of extra production in 2030 under the high-yield scenario). These two crops contribute to a total gain of 279 million tons of herbaceous energy crops in 2030 under this optimistic high-yield (3%) scenario. Under the base-case (1%) scenario, the effects are more pronounced for non-coppice woody crops (e.g., a loss of 12.3 million tons under a pessimistic scenario in 2030) and for energy sorghum (e.g., a gain of 6.9 million tons in 2030 under an optimistic scenario), although miscanthus remains highly responsive (e.g., a gain of 10 million tons in 2030 under an optimistic scenario). These variations are consistent with the yield scenario and farmgate price sensitivity analyses above and reinforce the importance of the economic constraints applied in POLYSYS to total supply.

4.8.8 Land Rent

A standard approach in agricultural analysis is treatment of fixed and variable costs differently. Fixed costs relate to those invariant to production (also known as sunk costs) and assumed constant across cropping choices. Examples of fixed costs include overhead, taxes, insurance, and rent. Variable costs include those related to specific production practices based upon crop choice, such as seeding rates, diesel use, and labor that vary by management recommendation. The rental rate of cropland is included in these sensitivity scenarios based upon feedback from feedstock supply stakeholders and to provide a scenario that matches the crop costs used for enterprise costing purposes.

In all cases, the inclusion of cropland rent increases the amount of biomass produced in out-years relative to the references case. While the assumption raises crop costs across the board, additional production costs indirectly benefit high-cost/high-yield crops for two reasons: First, because of increased cost of production, low-cost/low-yield crops that would have been first to enter the landscape are now disadvantaged and become unprofitable. Secondly, high-cost/high-yield crops (such as miscanthus) are given preference over all other crops because of positive

Table 4.6 | Summary of Base-Case and High-Yield Scenarios, Energy Crops and Agricultural Residues

Feedstock	≤$40				≤$60				≤$80			
	2017	2022	2030	2040	2017	2022	2030	2040	2017	2022	2030	2040
Base-case scenario (1% annual growth)						Million tons						
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**	**1068**

Note: Totals may differ because of rounding.

net returns when land rent is added. In all cases, the increase of biomass is due to a larger share of miscanthus on the landscape than the reference case.

4.9 Summary and Future Research

4.9.1 Summary

The residues and herbaceous and woody energy crops reported are found to be economically available under imposed constraints. At a farmgate price of ≤$40 – ≤$80, the supply under a specified-price simulation has a range of between 30 million tons and 734 million tons under a baseline scenario and up to 1.068 billion tons under a high-yield scenario of 3% (see tables 4.6, 4.7, and 4.8). Supply potentials vary by year, with a greater supply potential occurring in later years of the simulations as energy crops are established and return higher yields.

Similarly, the production-target simulations of between 250 and 500 million tons yield a range of farmgate prices between $60 and $114, with some peak prices of $150 (maximum allowed under simulation) occurring in years when demand cannot be met because of crop rotations (see appendix C.4, "Energy Crop Feedstock-Specific Assumptions"). Timing for these specified supplies is key: allowing multiple years for a ramp-up of energy crops (establishment and improved yields) keeps prices low in these simulations. A range of available feedstocks are able to meet the specified demand or specified price. These feedstocks vary over time as yield and land uses change. For example, herbaceous energy crops

Table 4.7 | Summary of Base-Case and High-Yield Scenarios, Agricultural Residues

Feedstock	≤$40				≤$60				≤$80			
	2017	2022	2030	2040	2017	2022	2030	2040	2017	2022	2030	2040
Base-case scenario (1% annual growth)						Million tons						
Corn stover	24	30	36	44	89	106	129	154	102	119	142	166
Wheat straw	6	8	9	12	13	16	19	21	15	17	19	20
Sorghum residue	0	0	1	1	1	1	1	1	1	1	1	1
Oat residue	0	0	0	0	0	0	0	0	0	0	0	0
Barley residue	0	0	0	0	0	0	1	1	0	1	1	1
Total	**30**	**37**	**46**	**58**	**104**	**123**	**149**	**176**	**117**	**137**	**163**	**188**
High-yield (3% annual growth)												
Corn stover	23	30	40	52	87	111	141	161	100	122	150	176
Wheat straw	7	12	21	29	17	23	31	37	19	25	32	36
Sorghum residue	0	0	1	1	1	1	1	2	1	1	1	1
Oat residue	0	0	0	0	0	0	0	0	0	0	0	0
Barley residue	0	0	0	0	0	0	0	0	0	1	1	1
Total	**30**	**42**	**63**	**83**	**105**	**135**	**174**	**200**	**121**	**148**	**184**	**214**

Note: Totals may differ because of rounding.

enter into production at lower prices, and increase over time and as prices increase beyond an offered price of $60. Coppice woody energy crops begin to come into production at lower prices as well, with more modest gains as prices increase. Crop residues remain an important feedstock under both the base-case and high-yield scenarios.

4.9.2 Future Research

With regard to biomass resource assessment, future research is needed in a variety of areas:

- Periodic updates are needed to keep pace with advances in agricultural innovation (e.g., crop development and management strategies) and constantly changing agricultural markets (i.e., commodity crop demand changes due to macro-economic variables).
- The international market for bioenergy and bioproducts affects the domestic biofuel industry through competitive forces. Future research should account for demand fluctuations arising from policy shifts domestically and abroad, as

Table 4.8 | Summary of Base-Case and High-Yield Scenarios, Energy Crops

Feedstock	≤$40				≤$60				≤$80			
	2017	2022	2030	2040	2017	2022	2030	2040	2017	2022	2030	2040
Base-case scenario (1% annual growth)					**Million tons**							
Switchgrass	N/A	0	4	27	N/A	46	107	161	N/A	71	100	137
Miscanthus	N/A	0	2	7	N/A	28	79	160	N/A	104	203	293
Biomass sorghum	N/A	0	0	1	N/A	0	4	19	N/A	1	18	58
Energy cane	N/A	0	0	0	N/A	0	0	0	N/A	0	1	2
Non-coppice	N/A	0	4	9	N/A	0	33	45	N/A	0	34	41
Coppice	N/A	1	2	7	N/A	3	17	26	N/A	10	19	15
Total	**N/A**	**1**	**12**	**51**	**N/A**	**78**	**239**	**411**	**N/A**	**186**	**374**	**547**
High-yield (3% annual growth)												
Switchgrass	N/A	1	13	101	N/A	58	133	189	N/A	81	115	163
Miscanthus	N/A	1	5	65	N/A	45	157	370	N/A	146	308	483
Biomass sorghum	N/A	0	0	4	N/A	1	7	31	N/A	2	21	71
Energy cane	N/A	0	0	1	N/A	0	1	5	N/A	1	3	12
Non-coppice	N/A	0	10	41	N/A	0	44	75	N/A	0	48	70
Coppice	N/A	1	12	65	N/A	7	38	67	N/A	16	37	55
Total	**N/A**	**2**	**40**	**276**	**N/A**	**110**	**380**	**736**	**N/A**	**246**	**531**	**853**

Note: Totals may differ because of rounding.

well as price effects arising from changes in imports and exports from international sources.

- Following the introduction of specified-demand scenarios discussed in this analysis, attention should shift from potential biomass availability under hypothetical market simulations to expected biomass availability under expected market conditions. Finally, attention should similarly shift from potential farmgate supplies to potential delivered supplies, as discussed in chapter 6 of this report.

With regard to strategies to improve the economic availability of sustainable biomass, the sensitivity analyses in this chapter indicate key areas of opportunity, primarily market development (i.e., farmgate price) and energy crop yield improvement.

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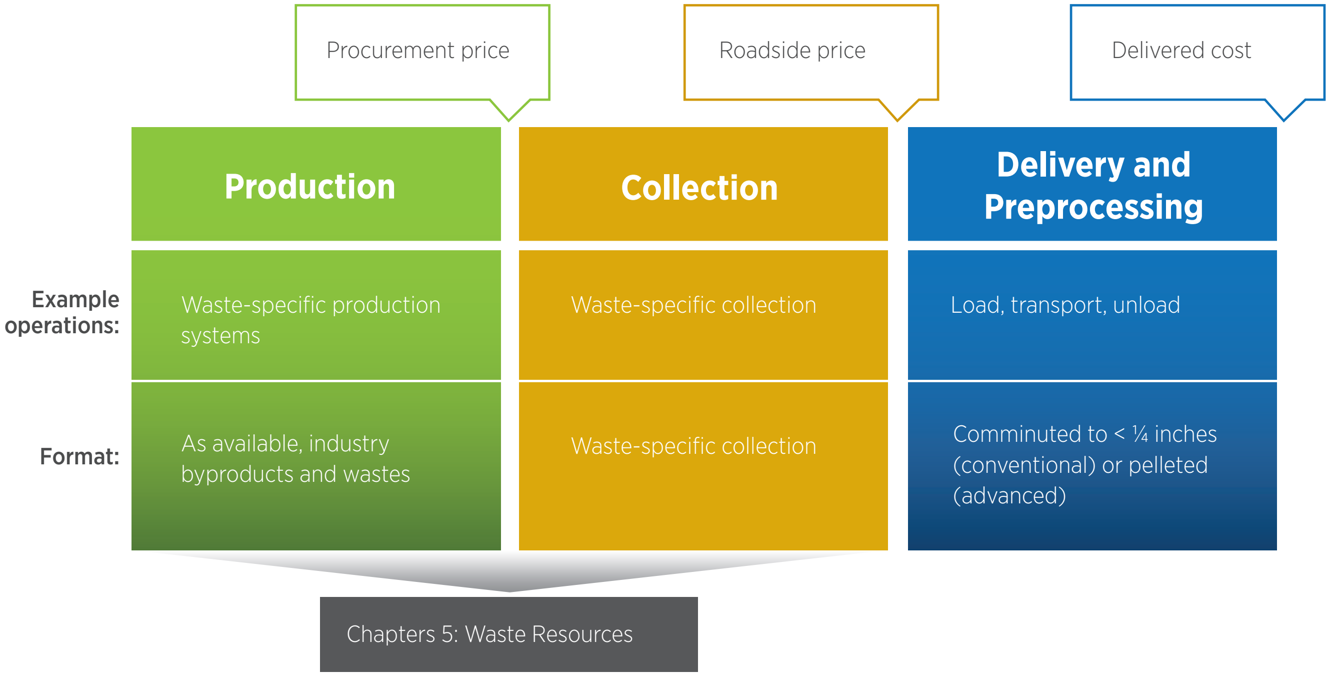
05 | Waste Resources



5.1 Introduction

The use of biomass from waste resources represents low-cost opportunities for bioenergy production without the need for additional agronomic inputs such as land and fertilizer. The economic accessibility of some waste resources has been demonstrated through their successful commercialization; for example, chapter 2 reports that mill residues, landfill gas, and waste grease are "currently used resources" (i.e., resources already being used for bioenergy or co-products). Other waste resources, while they offer a low or negative cost to potential users, may incur logistical and operational costs that challenge commercialization efforts. This chapter reviews a range of additional secondary and waste resources that may be mobilized as part of a bioeconomy strategy. The waste resources evaluated include agricultural secondary wastes, MSW, and forestry and wood wastes. Some resources, such as animal fats and sugarcane bagasse, are already accounted for in chapter 2. These resources are further described in this chapter, but they are not included in the resource totals it estimates. Estimates of the economic availability of these resources are updated from section 4.6 of the 2011 *BT2*, from which much of the descriptive material in this chapter is taken.

5.2 Agricultural Secondary Wastes

Secondary agricultural wastes are quantified in the 2011 *BT2*. The data used to make these estimates, where available, are updated in this report. Primary agricultural residue production is based on the production of corn, barley, oats, sorghum, and wheat, according to the production of the primary grains projected using POLYSYS. These resources are summarized by price in table 5.1.

5.2.1 Sugarcane Residues

Sugarcane is a tall, erect plant with a stalk (which has a high sugar content), leaves, and tops. After the sugar is extracted from the stalk, what remains of the stem is bagasse. The leaves, tops, and any parts of the stalk that remain in the field after harvest are referred to as trash. There are a number of technical coefficients in the literature that relate the amount of bagasse and trash produced per ton of sugarcane.[1] It is assumed that each ton of sugarcane produces 0.14 dry tons of bagasse and 0.075 dry tons of field trash and that one-half of the field trash can be collected.

Sugarcane residues are the product of the sugarcane yield, as reported on a wet basis by USDA (USDA-NASS 2015b), and a technical coefficient—0.14 for bagasse and 0.0375 for trash. Costs for sugarcane trash collection are based on the use of a rake and a large rectangular baler. Estimated supplies of sugarcane bagasse and residues, respectively, total 3.9 to 4.1 million dry tons and 1.1 million dry tons. Farmgate prices for sugarcane field trash are based on the use of a rake, a large rectangular baler, and a bale mover and a grower payment of $21 per dry ton for nutrient value. About 60% of sugar field trash is available at farmgate prices of $40 per dry ton and 100% at $50 per dry ton or less (table 5.2). The bagasse component is currently used for energy at sugarcane mills.

Projections of sugarcane production from the USDA-OCE/WAOB (2015) are used up to 2024. Starting from 2015, the projection shows a very modest increase over time, and it is assumed that after 2024, sugarcane production increases by 0.05 million tons per year. In 2012–2014, bagasse production and trash collected averages 4.36 and 1.13 million dry tons, respectively. In 2040, bagasse production and trash collected are 4.1 and 1.1 million dry tons, respectively (table 5.2). Projected supplies of sugarcane field trash are shown in table 5.1.

5.2.2 Soybean Hulls

Soybean hulls are produced when soybeans are processed to produce soybean meal and soybean oil. The hulls are used as a livestock feed, primarily for cattle. The quantity of soybean hulls produced from crushing soybeans has varied from 3.27 to 3.49 lb per bushel of soybeans over the period 2001 to 2010 and averaged 3.42 lb per bushel (USDA-ERS 2015). Production of soybean hulls over 2013 to 2015 averaged 2.84 million dry tons (assuming a hull moisture content of 9%).

The USDA long-term forecast projects the amount of soybeans crushed over the 2014 to 2024 period. The forecast increases from 1.815 billion bushels in 2014 to 1.975 billion bushels in 2024 (USDA-OCE/WAOB 2015). The extended USDA baseline used for POLYSYS is used for soybean crush for 2025 to 2040. The projected crush volume in 2040 is 1.996 billion bushels. Using 3.42 lb of soybean hulls per 60-lb bushel of soybeans crushed, and a moisture content of 9% for the hulls, current and 2040 soybean hull production are 2.84 and 3.10 million dry tons, respectively (table 5.3).

[1] Assumptions vary in the range of reported moisture, ash, and energy content of bagasse and sugar cane trash. For this report, results from Braunbeck et al. (2005) are adopted. For additional reference, see Deepchand (2005) and Ho (2006).

Table 5.1 | Summary of Agricultural Wastes Potentially Available at $40, $50, and $60 per Dry Ton for Selected Years

Waste type	Current supply[a]	2017			2022			2030			2040		
		$40	$50	$60	$40	$50	$60	$40	$50	$60	$40	$50	$60
	Million dry tons												
Animal manures	17.1	18.0	18.0	18.0	18.5	18.5	18.5	18.6	18.6	18.6	18.4	18.4	18.4
Cotton field residues	3.3	0.0	0.9	1.5	0.0	1.5	2.0	0.0	1.7	2.2	0.0	1.7	3.2
Cotton gin trash	1.7	1.7	1.7	1.7	1.9	1.9	1.9	2.0	2.0	2.0	2.1	2.1	2.1
Grain dust and chaff	5.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Orchard and vineyard prunings	5.5	5.5	5.5	5.5	5.6	5.6	5.6	5.8	5.8	5.8	6.0	6.0	6.0
Rice straw	4.3	0.0	4.9	4.9	0.0	5.2	5.2	0.0	5.4	5.4	0.0	5.6	5.6
Rice hulls	1.2	1.4	1.4	1.4	1.5	1.5	1.5	0.0	1.5	1.5	0.0	1.6	1.6
Soybean hulls	2.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sugarcane field trash	1.1	0.6	1.0	1.0	0.6	1.1	1.1	0.6	1.1	1.1	0.6	1.1	1.1
Total	**34.2**	**27.1**	**33.4**	**34.0**	**28.0**	**35.3**	**35.7**	**27.0**	**36.1**	**36.6**	**27.1**	**36.5**	**37.9**

[a]Current supply without regard to price

Over the period of 2001 to 2010, prices for soybean hulls averaged $91.81 per ton (nominal price), and the price of corn averaged $3.26 per bushel or $116.41 per ton (USDA-ERS 2015). The ratio between the per-ton prices of soybean hulls and corn varied between 0.729 and 1.04 over this period, except in the marketing year 2009 (beginning September 1, 2009, and ending August 31, 2010), when the ratio was 0.479. Excluding this anomalous year (2009), the ratio averaged 0.847. The USDA baseline for 2014 to 2024 projects the average price of corn to be $3.56 per bushel over this period, or $150 per dry ton. Using this projected corn price, then, the price of soybean hulls at a 0.847 ratio would be $128 per dry ton over this period. Supplies are shown in table 5.1, but none are available at prices below $128 per dry ton.

Table 5.2 | Sugarcane and Bagasse Production and Sugarcane Trash Collected 2012 to 2040

Year	Sugarcane	Bagasse	Trash
	Million wet tons	Million dry tons	
2012	32.2	4.51	1.21
2013	30.8	4.31	1.15
2014	30.4	4.26	1.14
2015	31.3	4.38	1.04
2017	27.7	3.88	1.04
2022	28.4	3.98	1.07
2030	28.8	4.03	1.08
2040	29.3	4.10	1.10

Table 5.3 | Soybean Crush and Hull Production 2012 to 2040

Year	Soybean crush	Soybean hulls
	Million bushels	Million dry tons
2012	1,689	2.63
2013	1,734	2.70
2014	1,870	2.91
2015	1,870	2.91
2017	1,850	2.88
2022	1,940	3.02
2030	1,985	3.09
2040	1,996	3.10

5.2.3 Rice Hulls and Field Residues

When rice is milled, its hulls are removed. The hull represents 20% of the mass of rice and generally presents a disposal problem, although rice hulls currently can be used as a filter product or as chicken house bedding (Hirschey 2003). Rice hulls can potentially be used for energy.[2] Rice is produced in six states: Arkansas, California, Louisiana, Mississippi, Missouri, and Texas. Over the years 2013 to 2015, total rice production averaged 200 million hundredweight (cwt, 100 lb)—or 8.6 million dry tons, assuming 13.5% moisture content. Some rice—approximately 30% of total rice production on average—is exported as rough rice (not dehulled). Adjusting for rice that is exported as rough rice, and assuming that rice hulls represent 20% of the rice harvest, 1.2 million dry tons of rice hulls per year are currently produced. The USDA-OCE/WAOB (2015) projects

[2] A facility in Stuttgart, Arkansas, has plans to convert rice hulls into ethanol at a rate of 50 gallons of ethanol per ton and to produce silica sodium oxide at a rate of 440 lb per ton (Bennett 2008).

rice production to 2024. Rice production for 2025 to 2040, as projected in the extended baseline, is 259 million cwt. Rice hull production increases over time, reaching 1.6 million dry tons by 2040 (table 5.4). Prices for rice hulls are based on projected coal prices and supplies on a Btu basis, as shown in table 5.1. (Coal prices are used because as a solid fuel, rice hulls would compete with coal.)

Rice field residues (or straw) remaining on the field usually need to be disposed of. In the past, burning was common, but it is often not allowed now because of air quality concerns. Because the residue has such a high silica content, it is undesirable as a forage supplement. Sometimes it is incorporated into the soil, or it may be removed and used for energy, for example. The harvest index (HI) for rice straw (the ratio of grain to total biomass, or grain plus residue) has been reported in ranges of 0.5 to 0.3 (or straw-to-grain ratios of 1:1 to 2.3:1). Duke (1983) states that rice straw is usually estimated to be two times the grain yield, but for dwarf varieties, a straw-to-grain ratio of 1:1 prevails (HI of 0.5). Sumners et al. (2003) use a straw-to-grain ratio of 1:1. This study uses Sumner et al.'s more conservative HI of 0.5 (straw-to-grain ratio of 1:1) to estimate rice straw residues. Moisture content for grain is assumed to be 13.5%.

The USDA long-term forecast projects the amount of rice produced between 2014 and 2024 (USDA-OCE/WAOB 2015), and the extended USDA baseline used for POLYSYS is used to project rice production from 2025 to 2040. Total straw production is currently estimated at 8.6 million dry tons, increasing to 11.2 million dry tons by 2040. Rice straw is assumed to be harvested like corn stover and cotton residues with a shredding operation followed by raking and baling (a large rectangular baler is assumed for costing purposes). It is assumed that 50% of the rice straw is harvested, with the current resource (2013 to 2015 average) at 4.3 million dry tons and the 2040 resource at 5.6 million dry tons (table 5.4). The rice field straw

Table 5.4 | Rice Hull and Straw Collected 2012 to 2040

Year	Harvested	Yield	Rice production	Rice production	Hulls	Straw harvested
	Million acres	Lb/acre	Million cwt	Million dry tons		
2012	2.7	7,449	200	8.63	1.21	4.31
2013	2.5	7,694	190	8.21	1.15	4.11
2014	2.9	7,572	221	9.56	1.34	4.78
2015	2.9	7,307	188	8.12	1.14	4.06
2017	3.0	7,793	227	9.82	1.38	4.91
2022	3.0	7,981	241	10.41	1.46	5.21
2030	3.1	8,312	251	10.81	1.52	5.43
2040	3.1	8,537	259	11.20	1.57	5.59

price is based on harvesting with a shredder, a large rectangular baler, a bale mover, and a grower payment of $21 per dry ton. Rice straw is available at a farmgate price of $50 per dry ton or less (table 5.1).

5.2.4 Grain Dust and Chaff

Nelson (2010) estimates that wheat passing through an elevator produces approximately 1% of its weight as dust and chaff. Schnake (1981), in a report on the use of grain dust for animal feed, fuel, and fertilizer, considered the composition of wheat, corn, sorghum, and soybeans. We use Nelson's assumption that 1% of grain passing through an elevator (production plus imports) can be captured as dust and chaff. In 2013 to 2015, the average grain supply in the United States (corn, wheat, sorghum, barley, oats, and soybeans) was 507 million dry tons per year. One percent of that is 5.1 million dry tons. In his study, Schnake prices grain dust as an animal feed at 80% of the price of corn. The corn price has averaged $5.22 per bushel (or $221/dry ton) over the 36-month period from July 2012 to June 2015 (USDA-NASS 2014a, 2015a). The June 2015 price was $3.58 per bushel or $151/dry ton. Eighty percent of the 36-month and June 2015 price, respectively, was $176 and $121 per dry ton. The USDA baseline for 2014 to 2024 projects the average price of corn to be $3.56 over this period, or $150/dry ton. We assume the current supply of grain dust is half of the total produced, 1.67 million dry tons at $120 per dry ton.

Over time, the grain supply increases. Until 2024, projections from USDA-OCE/WAOB (2015) are used, and from 2025 to 2040, the extended baseline is used. In 2040, the total grain supply reaches 590 million dry tons, and the total grain dust and chaff that could be collected is 5.9 million dry tons (table 5.5).

Table 5.5 | Grain Supply (production plus imports) and Grain Dust and Chaff Collected 2012 to 2040

	Corn	Sorghum	Barley	Oats	Wheat	Soybeans	Grain produced	Dust collected
Moisture (%)	0.155	0.140	0.145	0.140	0.135	0.100		
Lb/bushel	56	56	48	32	60	60		
Year	Million bushels						Dry tons	
2012	10,915	258	242	154	2,375	3,078	416	4.16
2013	13,865	392	236	162	2,308	3,430	497	4.97
2014	14,246	433	201	177	2,176	4,002	519	5.19
2015	13,585	574	239	185	2,177	3,918	505	5.05
2017	14,130	403	228	158	2,236	3,635	507	5.07
2022	14,785	390	220	161	2,318	3,860	530	5.30
2030	15,735	392	223	163	2,437	3,997	560	5.60
2040	16,754	405	224	164	2,592	4,073	590	5.90

5.2.5 Orchard and Vineyard Prunings

Annual orchard and vineyard prunings are estimated for fruits, citrus fruits, and nuts. The fruits included in this analysis are apples, apricots, avocados, cherries, dates, figs, grapes, kiwi, nectarines, olives, peaches, pears, persimmons, pomegranates, and other non-citrus fruits. The citrus fruits are grapefruit, lemons, limes, oranges, tangerines, and other citrus fruit. The nuts are almonds, pecans, pistachios, walnuts, and other nuts. The estimated biomass available, according to Nelson (2010), totals 5.7 million dry tons. More than 80% of the orchard and vineyard prunings are from five crops: oranges, grapes, almonds, pecans, and apples. About half the resource is in California, 20% is in Florida, and the remainder is located primarily in Washington, Texas, Georgia, New York, Oklahoma, and Michigan. The USDA projections (USDA-OCE/WAOB 2015) forecast a slight increase in the production area of fruits and nuts. Production estimates from the USDA projections are used to index future orchard and vineyard prunings. Census of Agriculture data (USDA-NASS 2014b) from 2012 are indexed to future years using acreage estimates from the USDA projections (USDA-OCE/WAOB 2015), and from 2025 to 2040, acreage is projected to increase by 17,000 acres per year. Per-acre yield data for individual crops from Nelson (2010) are used. Currently available supplies of prunings are 5.5 million dry tons. Total supplies are shown in table 5.6. Half of the orchard and vineyard prunings are assumed to be available at $20 per dry ton, and all are expected to be available at $30 dry ton or less (table 5.6).

Table 5.6 | Orchard and Vineyard Prunings 2007 and 2013 to 2040

Year	Million dry tons
2013	5.47
2014	5.48
2015	5.50
2017	5.53
2022	5.63
2030	5.80
2040	6.02

5.2.6 Animal Fats and Yellow Grease

Animal fats suitable as a secondary agricultural feedstock for biodiesel production include edible and inedible tallow, lard, white grease, and poultry fat. Also included in this discussion is yellow grease. When animals are processed for meats, fats are a byproduct. For beef, these fats are separated into edible and inedible tallow. For hogs, these fats are lard, white grease, and choice white grease. Poultry produces poultry fat. Animal fats generally are a less costly feedstock than vegetable oils; however, animal fats contain high levels of saturated fatty acids, which result in a lesser flow quality than vegetable oil has. Animal fats tend to lose viscosity, causing the formation of crystals that plug fuel filters, especially in colder temperatures. Because biodiesel from animal fat feedstocks has the tendency to solidify in colder temperatures, vegetable oil will likely be the feedstock of choice for biodiesel in northern states during the winter. The supply of animal fats is limited and will not increase as demand for biodiesel increases.

Yellow grease differs from other animal fat feedstocks in that it is the recycled cooking oil from restaurants. It may contain the recycled oils of both vegetables and animals, but the vegetable oil is hydrogenated, so it acts more like animal fat when converted to biodiesel. Yellow grease is the cheapest available feedstock for biodiesel production.

Table 5.7 | Animal Fat Production 2012 to 2014 and Current Prices

Fat	2012	2013	2014	Average	2012	2013	2014	Average
	Million tons				$/ton			
Inedible tallow	1.60	1.59	1.50	1.56	874	805	727	802
Edible tallow	0.90	0.89	0.81	0.87	969	858	785	871
Yellow grease/ used cooking oil	0.97	0.99	1.03	1.00	715	660	555	643
White grease	0.65	0.65	0.64	0.65				
Choice white grease	0.58	0.58	0.57	0.58	840	767	645	751
Poultry fat	0.52	0.53	0.54	0.53	784	719	599	701
Lard	0.07	0.07	0.07	0.07	1,160	981	870	1,004
Total	**5.30**	**5.30**	**5.16**	**5.25**				

Source: Data from EIA (2015b).

Nelson (2010) provides estimates of edible and inedible tallow based on cattle processing at 72 locations in 21 states, and lard and choice white grease based on hog processing at 70 locations in 26 states. Edible and inedible tallow are produced at 95 and 90 lb per cow slaughtered, respectively. Lard and choice white grease are produced at 9 and 10.5 lb per hog slaughtered, respectively. Edible tallow, inedible tallow, lard, and choice white grease are estimated at 1.49, 1.41, 0.43, and 0.51 million tons, respectively, according to Nelson (2010). Nelson does not provide an estimate for poultry fat, but Pearl (2002) estimates poultry fat production at 1.11 million tons.

Swisher (2015) reports that from 2012 to 2014, inedible tallow, edible tallow, yellow grease/used cooking oil, white grease, choice white grease, poultry fat, and lard averaged 1.6, 0.9, 1.0, 0.6, 0.6, 0.5, and 0.1 million tons, respectively, and totaled 5.3 million tons (table 5.7).

Not all of these fats are necessarily available for energy use. Tallow, lard, and choice white grease are potential biodiesel feedstocks, but each also is used in markets such as edible food, soap, lubricants, resins, and plastics. Edible tallow is used for baking or frying fats and margarine, as well as for certain inedible products.

Inedible tallow is most often used as a supplement for animal feed—most of its market share—followed by use in fatty acids, soap, methyl esters (biodiesel), lubricants, and other uses. Poultry fats are used in soaps, pet foods, and a few other consumer products. The feedstock price greatly affects the end price of biodiesel, as feedstock price can account for up to 80% of the total biodiesel cost. Prices for fats (table 5.7) are much higher than prices for cellulosic resources, but fats have different characteristics and uses from cellulosic resources. In past years, prices for fats were lower—in the \$400/ton to \$600/ton range in 2009. It takes about 7.7 lb of fats to make a gallon of biodiesel, whereas cellulosic resources may yield 90 gallons per dry ton (or 22.2 lb per gallon) of ethanol. Assuming 128,000 Btu (higher heating value) per gallon of biodiesel and 84,500 Btu (higher heating value) per gallon of ethanol—considering fats on an equivalent feedstock basis with cellulosic resources—a ton of animal fat at \$700 per ton is equivalent to a dry ton of a cellulosic resource at \$160 per dry ton, ignoring conversion costs.

5.2.7 Cotton Gin Trash and Field Residues

Cotton gin trash is generated from the picking and cleaning processes of cotton harvesting and includes seeds, leaves, and other foreign material, which may include sand and soil. It may have high moisture and nutrient content, and disposal may be costly. Cotton residue refers to the stalks left on the field after the cotton lint has been harvested.

The two main types of cotton harvesters are spindle pickers and strippers (National Cotton Council of America 2009). The stripper is a single-pass system that harvests significantly more of the cotton plant and more foreign material (e.g., sand, soil) than do spindle pickers (0.15 to 0.50 tons per bale for a stripper versus 0.04 to 0.08 tons per bale for spindlers). Strippers are thus suitable for determinate cotton (i.e., produces bolls over a fixed period of time for a single harvest) (Holt et al. 2003; Kim, Park, and Daugherty 2004; Mayfield 2003; Weaver-Missick et al. 2000). Spindle pickers can be used more than once in a growing season to harvest cotton and thus are suitable for indeterminate varieties (i.e., produce bolls over an extended period of time with bolls maturing at different times in the growing season). About 25 to 33% of the U.S. cotton harvest is estimated to be stripper picked, leaving the remaining 67 to 75% to be harvested with spindle pickers (Glade and Johnson 1983–1985).

Cotton gin trash, generated in the cotton mill from cleaning the lint, has been estimated at various levels.[3] On average, cotton gin trash is produced at a rate of 0.16 tons of trash per bale of cotton (480 lb) after foreign material is counted.[4] Future production of cotton gin trash is estimated using state-level harvesting type percentages and applying cotton production forecasts of upland and pima cotton production (USDA-OCE/WAOB 2015). These results are shown in table 5.8. Cotton gin trash prices are based on projected coal prices; the supply is shown in table 5.1.

The USDA-OCE/WAOB (2015) projects upland cotton production up to 2024, forecasting 15.5 million bales from 10.4 million acres, yielding an average of 845 lb per acre of cotton lint in 2024. In 2040, planted upland cotton acreage and yield increase to 10.5 million acres and 893 lb per acre, respectively. Cotton gin trash production based on 2013 to 2015 cotton production is 1.7 million dry tons. This residue

[3] The range of cotton gin trash estimates includes 1.3 million tons (Buser 2001), 2.5 million tons (Comis 2002), and 3.2 million tons (Holt et al. 2003). Parnell, Columbus, and Mayfield (1994) state that in a typical year, gins that handle spindle-picked cotton generate 0.5 to 1.0 million tons of ginning trash, and those that handle stripped cotton generate 1.0 to 1.5 million tons of trash. Their total range of cotton ginning trash produced in a year is 1.5 to 2.5 million tons. Holt et al. (2003) state that in 2001 in the United States, 19.8 million bales of cotton (lint) and 3.2 million tons of cotton gin trash were produced, and in Texas, 4.2 million bales of cotton and 680,400 tons of cotton gin trash were produced.

[4] Holt et al. (2003) state that about 80% of cotton gin trash could be used for fuel pellets. Schacht and LePori (1978) report on six cotton gins in Texas where 11.1% of the cotton gin waste was cotton lint. According to Holt, Knabb, and Wedegaertner (2009), previous research shows that the quantity of recoverable fibers in cotton gin trash is between 10 and 25%. Based on the Texas average of cotton gin trash produced as reported by Holt et al. (2003), 0.1806 tons of trash per bale of cotton lint, applying the 11.1% figure of Schacht and LePori (1978), and assuming that cotton gin trash is 90% dry matter, 40 lb of lint are contained in the trash produced from one bale of cotton lint.

Table 5.8 | Cotton Gin Trash and Field Residues 2013 to 2040

Year	Production	Yield	Planted	Harvested	Cotton gin residue	Cotton field residue
	No. of 480-lb bales (1,000)	Harvest per acre (lb)	Millions of acres		Million dry tons	
2013	12.49	821	10.2	7.3	1.48	2.60
2014	16.94	838	10.8	9.7	2.00	3.53
2015	13.65	789	9.8	8.3	1.61	2.85
2017	14.00	810	9.8	8.3	1.74	3.75
2022	15.10	833	10.2	8.7	1.88	4.16
2030	15.94	863	10.4	8.9	1.98	4.53
2040	16.73	893	10.5	9.0	2.08	4.89

would be available at central sites (cotton gins) and not dispersed in agricultural fields.

Conversely, cotton stalks remain in the field after cotton harvest. The amount in a field will differ according to whether a stripper or spindle harvester is used. The assumptions for calculating cotton gin trash are that spindle and stripper harvesters take around 0.05 and 0.18 tons, respectively, of residue per bale of cotton with them. These amounts must be subtracted from the amount of residue available in the field. To estimate prices of cotton harvest residue, the following operations are assumed: shredding, raking, and bailing with a large rectangular baler. For cotton, shredding is a typical operation performed even if the residue is not harvested. Therefore, shredding operation costs are not included in the cost of harvesting residue. The amount of cotton residue available is estimated at 3.0 million dry tons currently (based on 2013 to 2015 production). Total production is shown in table 5.8. Costs are based on harvesting with a large rectangular baler and bale mover and a grower payment for nutrient content of $21 per dry ton. A shredder is also used, but it is presumed that a shredder would be used even without stalk collection. Cotton field residues supply various prices, as shown in table 5.1.

5.2.8 Animal Manure

Over the past several decades, livestock operations have experienced a trend toward fewer and more concentrated facilities. As a consequence, manure storage issues have arisen. Often, large, confined livestock operations do not have enough cropland or pasture to adequately distribute manure, resulting in excess manure that poses a risk to water quality and human health. Additionally, the land resources within close proximity to concentrated animal production facilities are constrained in their ability to absorb manure nutrients.

There are a number of estimates for the manure production potentially available for utilization. USDA

(2006) estimates 335 million dry tons from all animal feed operations and concentrated feed operations. The American Gas Association estimates usable manure production at between 216 and 721 million wet tons. Assuming 20% dry matter content, this range is 43 to 144 million dry tons (AGF 2011). The National Petroleum Council estimates total animal manure at 156 million dry tons and the practical resource at 24 million dry tons (NPC 2012).

USDA, EPA, and DOE estimate that livestock manure could produce 257 million ft^3 of biogas (USDA/EPA/DOE 2014). EPA (2011) estimates the biogas potential from swine and dairy operations assuming it is feasible to produce biogas from swine and dairy operations with more than 2,000 and 500 head, respectively. EPA (2011, 2015b) estimates that in November 2010 and March 2015, respectively, 160 and 247 manure anaerobic digester biogas systems were in operation. In its 2011 report, EPA estimates that 5,596 swine and 2,645 dairy farms have the potential to produce biogas, and that they produce 74.4 and 79.9 billion ft^3 of methane, respectively. Assuming 7.89 and 3.84 ft^3 of methane per pound of volatile solids for swine and dairy cattle, respectively (EPA 2011), and that volatile solids make up 70% of the manure, this would result in 22 million dry tons of manure.

To estimate manure production down to the county level, we utilized 2012 Census of Agriculture data for swine operations with 1,000 or more head and dairy operations with 500 or more head (USDA-NASS 2014b). Based on information from Penn State Extension (2016), dairy cattle (lactating cows, liquid) produce 13 gallons of manure per animal unit (AU)-day at 5% dry matter; and swine produce, farrow to wean 11 gallons per AU-day at 2.5% dry matter, nursery 14 gallons per AU-day at 1.5% dry matter, wean to finish 5.5 gallons per AU-day at 4% dry matter, and grow to finish 7 gallons per AU-day at 4% dry matter. Lactating cows produce 1 dry ton of manure per AU-year. Averaging over the four swine types results in approximately 0.375 dry tons of manure per AU-year. Each dairy cow is assumed to be 1.4 AU and each swine is 0.4 AU.

Table 5.9 | Manure Production

Year	Million dry tons
Current	17.1
2017	18.0
2022	18.5
2030	18.6
2040	18.4

Based on census data, a conservative estimate of current manure available is 17 million dry tons. Assuming that production changes with animal numbers, using an average of projected animal numbers (hogs, beef cattle, and chickens), production increases to 18 million dry tons in 2040 (table 5.9). Supplies are assumed to be available at a price of $40 per dry ton or less.

5.3 MSW, Garbage Fraction

MSW is a broad term potentially including a variety of industrial and residential waste streams. In this chapter, we limit MSW to garbage—mixed commercial and residential wastes generally destined for landfill or incineration disposal, as well as yard trimmings. Urban wood waste and construction and demolition (C&D) debris are discussed separately in section 5.4.6.

Organic MSW categories potentially available for biofuels include paper and paperboard, plastics, rubber and leather, textiles, food wastes, and yard trimmings. Although the estimates in this chapter represent gross supplies currently landfilled, not all of this supply is economically available because of preprocessing costs. Further, the highest use of MSW remains to be determined, after ongoing efforts toward source reduction and reuse, recycling, composting, and energy recovery.[5]

MSW consists of a variety of items, ranging from organic food scraps to discarded furniture, packaging materials, textiles, batteries, appliances, and other materials. In 2013, 254 million tons of MSW were generated (EPA 2014). About 35% of the total quantity generated (134 million tons) was discarded in municipal landfills. The remainder was either recycled, made into compost, or combusted for energy recovery. Containers and packaging are the single largest component of MSW generated, totaling some 75 million tons, or 30% of the total. Durable goods are the second largest portion, accounting for 20% of total MSW generated. Yard trimmings are the third largest portion and account for about 34 million tons, or 14%, of the total generated.

Estimates were generated by

1. Assuming an MSW landfilled generation rate—after current efforts toward reduction, reuse, recycling, and waste-to-energy—of 2.36 lb per person per day (with moisture), based on EPA (2015a, table 30)
2. Multiplying this rate by county-level 2012 U.S. population data from the U.S. Census Bureau
3. Multiplying these county-level results by MSW category fractions derived from EPA (2015a, table 3).

The resulting 134 million green tons/year landfilled is about half of the 269 million green tons/year estimated in BioCycle's 2010 report *The State of Garbage in America* (van Haaren, Themelis, and Goldstein 2010), and about 42% of Pacific Northwest National Laboratory's unpublished estimate of 305 million green tons/year (Drennan 2014). Shin (2014) estimates total MSW generation in 2011 at 389 million tons. Based on the EPA estimate, about 105 million green tons/year of this supply is organic or composed of organic compounds (including biomass, wood, yard, and food wastes; plastics; and rubber). The EPA data showed lower amounts than other estimates, and so using EPA numbers as a starting point is a more conservative estimate.

In recent years, EPA data show that, from 2005 to 2013, the amount of MSW generated has been relatively flat at around 250 million tons; and from 2009 to 2013, discards to landfills have been relatively flat at around 132 million tons. We assume that discards to landfills remain constant over the projection period, with any increased generation from population growth being offset by increased recycling and composting.

Yard trimmings are estimated to be 13.5% of the MSW generated and 8% of discarded MSW. In 2013 EPA estimated 34.2 million tons (wet basis) of yard trimmings were generated and 14.6 million tons (wet basis) were discarded, either landfilled or used for waste-to-energy. After adjusting for MSW used for waste-to-energy, on a wet weight basis, the amount of yard trimmings potentially available, above what is currently used for energy, is 10.8 million green tons, or 4.3 million dry tons based on 60% moisture. Another estimate, based on McKeever (2004), results in 3.3 million dry tons of wood in yard trimmings that are estimated to be recoverable and available for bioenergy applications after accounting for quantities that are likely to be composted, combusted, recycled, or contaminated and unavailable. The fractions composted, combusted, and contaminated are based on technical coefficients developed by McKeever (2004).

[5] D. Perla, 2014, EPA RICRA Program Office of Research, personal communication to John Jonston of EPA, Southeast U.S. Atlanta Office, and Hope Hillsburry of Office of Resource Conservation and Recovery, March 29, 2014. See http://www.epa.gov/wastes/nonhaz/municipal/hierarchy.htm for more information.

The 4.3 million dry ton estimate is used. To obtain county-level estimates of supply, this total is distributed among counties in proportion to the resident population per county.

The prices of garbage supplies available after sorting are unknown. Price estimates for sorted organic fractions are generated as follows:

- State-level average MSW tipping fees, ranging from $18 per green ton in Idaho to $105 per green ton in Massachusetts, are purchased from Klean Industries Inc.
- For counties with populations of less than 250,000, all material is assumed to be available at the state-level tipping fee (dollars per green ton) plus a $60 per green ton sorting cost.
- For counties with populations greater than or equal to 250,000, 50% of the material is assumed to be available at the state-level tipping fee (dollars per green ton) plus a $40 per green ton sorting cost; the remaining 50% of the material is assumed to be available at the state tipping fee (dollars per green ton) plus a $60 per green ton sorting cost.

Resources with resulting prices of less than $20 per green ton are assumed to be available at $20 per green ton. All supplies and prices are converted to dry tons and to a dollar per dry ton basis assuming the following moisture contents: food wastes 70%, yard trimmings 60%, paper and paperboard 15%, textiles 15%, rubber and leather 10%, and plastics 10%.

It is estimated that 51 to 55 million dry tons per year may be available at prices ranging from $40 to $60 per dry ton (table 5.10) As in the case for terrestrial feedstocks, it is not implied that all of the MSW material is available for biofuels; rather, this is an estimate of supplies and prices that might be available beyond what is currently used for an emerging market or markets. These estimates indicate gross potential and do not capture trends and variability in MSW availability associated with future population growth; innovations in MSW logistics and handling; efforts to reduce, reuse, and recycle; and limitations and opportunities that might be associated with local waste handling contracts. Economic theory suggests that without market intervention, MSW resources would be allocated to the highest-value use, which may or may not be biofuels. MSW garbage supply and price estimates presented here are subject to modification with better information.

In table 5.10, paper and paperboard is estimated at 16–17 million dry tons. This quantity of paper and paperboard is currently disposed of in landfills. Note that in section 932 of the Energy Policy Act of 2005[6] and sections 1201 and 1203 of EISA,[7] paper that is commonly recycled is excluded from the definition of biomass. However, the part of paper and paperboard that is currently landfilled is included as a potential energy resource.

One of the challenges with energy recovery from halogenated plastics is the production of HCl and dioxins/furans. (A halogenated compound contains chlorine, fluorine, bromine, or iodine.) Examples of halogenated plastics include polyvinyl chloride (PVC), chlorinated polyethylene, chloroprene, chlorinated PVC, chlorosulfonated polyethylene, polychloroprene (marketed under the trade name Neoprene) and fluorinated ethylene propylene (NIH 2016).

Estimates of halogenated plastics can be found for PVC. In 2014, the American Chemistry Council (2016) estimated PVC production in the United States at 7.5 million tons and domestic demand at 5.2

[6] Energy Policy Act of 2005, Pub. L. 109-58 Stat. 594, https://www.gpo.gov/fdsys/pkg/PLAW-109publ58.

[7] Energy Independence and Security Act of 2007, Pub. L. 110-140, 121 Stat. 1492, http://www.gpo.gov/fdsys/pkg/BILLS-110hr6enr.

Table 5.10 | Supplies Available from MSW Sources, Excluding Wood and Construction and Demolition Wastes, 2017 to 2040

MSW Sources	$40 per dry ton	$50 per dry ton	$60 per dry ton
	Million Dry Tons		
Paper and paperboard	15.7	17.0	17.1
Plastics	20.0	20.1	20.1
Rubber and leather	4.4	4.4	4.4
Textiles	8.0	8.2	8.2
Other	2.5	2.6	2.7
Food waste	0	0	0
Yard trimmings	0	3.1	3.3
Total	**50.6**	**54.7**	**54.8**

million tons. EPA (2015a) reported that in 2013, total PVC in MSW was 900,000 tons (about 3% of plastics in MSW discards) and that a negligible amount was recovered. In durable goods (which include computer equipment), nondurable goods, and containers and packaging, the amount of PVC in MSW in 2013 was 240,000, 230,000, and 430,000 tons, respectively. If one assumes that the other halogenated plastics are relatively small in quantity, then about 1.0 million tons of halogenated plastics were landfilled.

After extraction of higher-quality fractions for recycling, there remains a mix of plastics contaminated with other compounds (Alston and Arnold 2011). Possible disposal methods for the remaining material include pyrolysis, supercritical fluids, and gasification (Wang and Xu 2014), incineration, and landfilling. Pyrolysis is proposed as a recycling mechanism for plastics from waste electrical and electronic equipment, but steps must be taken so the pyrolysis oil is not contaminated with halogenated compounds (Yang et al. 2013). Hall and Williams (2006) examined fast pyrolysis of halogenated plastics from waste computers. They found conversion of most of the plastics to pyrolysis oil, but the PVC computer cases also produced large quantities of HCl. Incineration and energy recovery of plastic is less prevalent than landfilling primarily because of the perceived risk of hazardous substance release into the atmosphere (e.g., dioxins, other polychlorinated biphenyls, and furans) (Hopewell, Dvorak, and Kosoir 2009). They note that some nations (including Japan, Sweden, and Denmark) use extensive incinerator infrastructure to deal with MSW, including plastics. Although care must be taken to ensure that the energy products are not contaminated with undesirable compounds nor hazardous materials released into the environment, there are options for recovering energy from halogenated plastics. Therefore, we include halogenated plastics in the MSW resources that are potentially available.

5.4 Forestry and Wood Wastes

Forestry and wood wastes are one of the most accessible and, in turn, one of the currently most used biomass resources. Current uses of wood waste total 123 million tons. Some quantity of these currently used wood wastes could shift to bioenergy applications at the right price. However, estimating what amount of these resources could move into bioenergy production is difficult and speculative, as many of these wood wastes not only are used but are also confined or dedicated to a specific process. The following are definitions of the major wood categories that can supply potential biomass resources:

- **Other removal residues:** Unused wood that is cut during the conversion of timberland to non-forest uses and in silvicultural operations such as precommercial thinning (Smith et al. 2009).
- **Thinnings from other forestland:** Wood from removals reducing the number of plants in an area or the quantity of vegetative or reproductive structures on individual plants. Thinning cuts are conducted on other forestland (non-timberland) to improve forest health by removing excess biomass on low-productivity land.
- **Unused primary and secondary mill processing residues:** Bark, mill residues (coarse and fine wood), and pulping liquors generated from the processing of sawlogs, pulpwood, and veneer logs into conventional forest products.
- **Urban wood wastes:** The urban wood waste resource includes a wide variety of woody materials, including discarded furniture; landscaping wood waste; and wood used in the construction, remodeling, and demolition of buildings.

Additional information for each is found in the glossary of this report (see other removals and residues, thinnings, mill processing residues, and urban wood wastes). The following sections discuss the potential additional biomass resources that may be available for each.

5.4.1 Other Removal Residues

The conversion of timberland to non-forest land uses (e.g., cropland, pasture, roads, urban settlements) and precommercial thinning operations generate a relatively significant amount of forest residue biomass. These other removals, especially from land-clearing operations, usually produce various forms of residues that are generally not feasible or economical to recover. It is expected that only half of the residues from other removals can be recovered.

Amounts of other forest removals, by county, are obtained from the TPO database for 2012 (USDA Forest Service 2012). The 2005 *BTS* and the 2011 *BT2* assume that 50% of the TPO residue estimate is recoverable and available. The original estimate is based on discussion with experts concerning the level of difficulty of recovering this feedstock. Specific characteristics of this feedstock—such as small land areas, trees pushed up and piled, and trees cut into small pieces—make it difficult to recover it fully. The assumption that 50% is recoverable is used in this update as well. Few price data are available for these types of feedstocks. Assumptions are made based on the expertise of the contributing authors concerning recovery and transport costs and market prices to derive the stumpage values. Specifically, one-third (4.1 million dry tons) is assumed to be available at $20 per dry ton at roadside and the remainder (~12.2 million dry tons) at $30 or more per dry ton at roadside. Future estimates of other removal residue are based on RPA projections of forest area (Wear 2011). Through 2040, total forest area is projected to decline by 8 to14 million acres, depending on the RPA scenario, which could mean that there could be more “other removals” residues over time through 2040. Table 5.11 shows a slight increase in potential recovery of this biomass over time.

Table 5.11 | Summary of Baseline Potential Forest Biomass and Wood Wastes at Selected Roadside Prices

Feedstock ($ per dry ton)	2017			2022			2030			2040		
	$40	$50	$60	$40	$50	$60	$40	$50	$60	$40	$50	$60
	Million Dry Tons											
Other removal residues	12	12	12	13	13	13	13	13	13	13	13	13
Treatment thinnings, other forestland	0.0	0.0	2.6	0.0	0.0	2.6	0.0	0.0	2.6	0.0	0.0	2.6
Mill residue, unused secondary	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Mill residue, unused primary	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Urban wood waste—construction and demolition (method one[a])	15	23	23	15	23	23	16	25	25	16	25	25
Urban wood waste—MSW (method one[a])	5.1	5.3	6.3	5.1	5.3	6.3	5.1	5.3	6.3	5.1	5.3	6.3
Total	**36**	**45**	**49**	**38**	**47**	**51**	**39**	**49**	**53**	**39**	**49**	**53**

[a]Based on a methodology utilizing McKeever (2004).

5.4.2 Forest Residue Thinnings on Other Forestland

Other forestlands, also known as woodlands, are defined as being incapable of producing at least 20 cubic feet per acre per year of industrial wood under natural conditions because of a variety of adverse site conditions, including poor soils, lack of rainfall, and high elevation. Many of these woodlands (low-stature or sparse forests) are in the western states and are overstocked, especially with stands of pinyon pine and juniper. As with the fuel reduction thinnings on timberland, removal of the excess biomass could greatly reduce catastrophic fire hazards. FIA data (USDA Forest Service 2010) are used to identify overstocked western woodlands. Assumptions similar to those used in the 2005 *BTS* and the 2011 *BT2* are used for this update. The amounts of live biomass on woodland are given in the FIA EVALIDator web application and database (Miles 2015). We assume road access limits the availability to 60% of biomass, which corresponds approximately to the amount of biomass from woodland that is within 1 mile of a road. The biomass would be removed in equal annual amounts over 30 years. In table 5.11, the total residue biomass from thinning other forestlands is estimated at 2.6 million dry tons at a price of $60 per dry ton (none is expected to be available below this price because of the high cost of thinning other forestlands). Above $80 per dry ton, 5.3 million dry tons annually becomes available for all lands. When federal forestlands are removed, 3.1 million dry tons are available above $80 per dry ton, about 40% less. By definition, these lands do not produce commercial-size pulpwood or sawlogs, so the cost of removing the thinnings is borne fully by the biomass harvesting operation. An assumption used in the analysis is that about 50% of the biomass could be removed at a price of $60 per dry ton and the remainder at a price of $70 per dry ton. Again, these assumptions are the best estimates by the contributing authors with knowledge of these types of harvesting systems. The estimates are considered conservative because they represent the high end of thinning costs, as no higher-valued wood is removed with the biomass.

5.4.3 Primary and Secondary Mill Residue

The processing of sawlogs, pulpwood, and veneer logs into conventional forest products generates significant quantities of bark, mill residues (coarse and fine wood), and pulping liquors. Primary mills convert roundwood (tree trunks and logs) into other wood products and include sawmills, pulp mills, and veneer mills. Secondary mills use products from primary mills to produce other products such as furniture and cabinets. With the exception of small quantities of mill residues, these secondary forest product industry residues are currently used in the manufacture of forest products or for heat and power production, and valuable chemicals are recovered from pulping liquors.

Amounts of wood and bark residue from primary product milling operations (by county) are obtained from the TPO database for 2012 (USDA Forest Service 2012). For the baseline case, it is assumed that only unused mill residues are available. Neither the U.S. Forest Service nor any other federal agency systematically collects data on secondary mill residue. One of the few estimates of the amount of secondary mill residue available is provided by Rooney (1998) and subsequently revised by Fehrs and Williston (1999). Fehrs estimates that about 12.5 million dry tons are generated annually, about 40% of which is potentially available and recoverable. The remaining fraction is used to make higher-value products, used onsite to meet some energy needs (such as heat for drying operations), or is not available for other reasons. An estimate of 15.6 million green tons is incorrectly cited from Fehrs as a dry ton amount in the 2011 *BT2*. Milbrandt (2015b) uses Rooney's method and data on number and employee size of secondary wood products establishments for 2012 to estimate residue generation of 8.7 million dry tons for 2012. We estimate 40% of 8.7 million tons, or 3.5 million dry tons, is available.

In 2011, of primary product mill residues, about 26 million tons were used for energy, 33 million tons were used for fiber products and other uses, and 0.5 million tons were unused. Baseline projections estimate primary mill residue consumption in 2040 to be 46 million dry tons (Nepal et al. 2016). Baseline projections of secondary mill residue consumption for energy are very rough and assume that 48% of the current generated amount is used for energy (Rooney 1998). The rate of increase in consumption of secondary mill residues for energy is assumed to be the same as for consumption of primary mill residues. Secondary mill residue consumption for energy is projected to increase from 4 to 6 million dry tons by 2030. It is assumed that the unused mill residues can be purchased at the mill for $20 per dry ton or less, which is comparable to the disposal cost if there are no markets available. Delivered prices could be much higher, especially for secondary mill residues where facilities are small, dispersed, and operate seasonally. There are 0.5 million dry tons of primary mill residues and 3.5 million dry tons of secondary mill residues available annually at $20 per dry ton (table 5.11). It is assumed that any residue associated with increased future demand for primary and secondary wood products is offset by greater mill efficiencies and a continued increase in the use of this material for byproducts.

5.4.4 Fuelwood

All currently used fuelwood (residential and commercial) is estimated to be 34 million dry tons per year. The quantity of fuelwood used for residential and commercial space heating applications, as well as feedstock for dedicated wood-fired facilities and co-firing applications, is projected to decline to 27 million dry tons per year by 2040 (EIA 2015a). This is not an additional supply, as it is already accounted for as currently used supplies in chapter 2.

5.4.5 Pulping Liquors

As is explained in chapter 2, combustible chemical byproducts, such as black liquor from pulping facilities, are currently used for energy production and are not counted as an additional feedstock resource. The available amount is 44 million dry tons, with projections of 37 million dry tons in 2030 (EIA 2015a).

5.4.6 Urban Wood Wastes

The two major sources of urban wood residues are the woody components of MSW and C&D waste wood. The MSW wood component of containers and packaging and durable goods (e.g., lumber scraps and discarded furniture) is 15.8 million tons (EPA 2014). About 15% of this is recycled (EPA 2014). Falk and McKeever (2004) estimate 22% is combusted for energy recovery, leaving 10.0 million tons to be discarded and landfilled. About one-third of this discarded material is unacceptable for recovery because of contamination; commingling with other wastes; or other reasons such as size and distribution of the material (McKeever 2004). The remainder that is potentially available for bioenergy (based on what is refered to here as "method one") totals about 6.6 million dry tons annually. To obtain county-level estimates of supply, this total is distributed among counties in proportion to the resident population per county.

A second method (method two) is used to calculate woody waste from MSW based on coefficients developed by Wiltsee (1998b). For MSW wood, Wiltsee estimates per capita wood generated in MSW as 0.054 tons per person-year either landfilled or incinerated, and 0.03 tons per person-year disposed of by rural dumping. Based on these two categories, 0.057 tons per person-year and assuming 50% moisture content, a total of 9.0 million dry tons of wood was available for use in 2013.

A minimum price of $20 per green ton is assumed. The price is determined by county by subtracting the county tipping fee (based on state tipping fees) from $60 per green ton if the county has a population of less than 250,000. The same calculation is used for half the MSW generated in a county with more than 250,000 people. For the other half of the MSW in a county with a population above 250,000, the tipping fee is subtracted from $40 per green ton, with a minimum MSW price of $20 per green ton.

The other principal source of urban wood residue is C&D debris. C&D wood waste is generated during the construction of new buildings and structures, the repair and remodeling of existing buildings and structures, and the demolition of existing buildings and structures (McKeever 2004). These materials are considered separately from MSW because they come from many different sources. These debris materials are correlated with economic activity (e.g., housing starts), population, demolition activity, and the extent of recycling and reuse programs. The updated estimates of C&D debris wastes total about 23.3 million dry tons. About 10.8 million dry tons are construction debris and 12.5 million dry tons are demolition debris. These estimates are based on technical coefficients developed by McKeever (2004) (method one). To obtain county-level estimates of supply, this total is distributed among counties in proportion to the resident population per county.

A second method (method two) is used to determine the amount of C&D debris available for energy based on Wiltsee (1998b). For C&D debris, Wiltsee estimates that 0.052 tons per person-year are either landfilled or incinerated and 0.002 tons per person-year are disposed of by rural dumping. Based on these two categories (0.054 tons per person-year and assuming 15% moisture), 14.5 million dry tons was generated in 2013. This increases to 14.7 million dry tons in 2015, 14.9 million dry tons in 2017, 15.5 million dry tons in 2022, 16.4 million dry tons in 2030, and 17.4 million dry tons in 2040, with the increase based on projected population growth. The price is determined using the same methodology as described earlier for MSW wood.

Using method one, MSW wood waste, together with C&D debris, sums to 33 million dry tons per year as potential energy feedstocks. As noted by McKeever (1998), many factors affect the availability of urban wood residues, such as size and condition of the material; extent of commingling with other materials; contamination; location and concentration; and costs associated with acquisition, transport, and processing.

Chapter 2 estimates the currently used MSW wood at 15 million dry tons annually and projects that it increases to 16 million dry tons per year by 2040 (EIA 2015a). In this chapter, the unused MSW wood and yard trimming wastes total 10 million dry tons, and the unused C&D debris wood could provide an additional 23.3 million dry tons. Future quantities of unused urban wood wastes (from MSW and C&D sources) will no doubt rise as population increases; however, the increase will likely be less because of ongoing waste recovery efforts and higher landfill disposal costs. For construction waste, it is likely that higher fractions will be recycled and reused; and there will be greater use of engineered lumber, which will reduce dimensional lumber use and also make less waste available.

For C&D wastes, prices were estimated in the same way as MSW wood wastes. After the analysis was completed, data were received on prices for C&D wastes from Ecostrat (2016). The Ecostrat data had prices for 37 states. Prices for C&D wastes from the Ecostrat data ranged from $6.25 to $80 per dry ton. The prices used in the *BT16* analysis range from $24 to $49 per dry ton.

5.5 Other Supplies

5.5.1 Biosolids

Biosolids come from sewage treatment facilities, and about 7 to 8 million dry tons are estimated to be available (Bastian 2013; Beecher et al. 2007). Approximately 55% of biosolids are land-applied for agricultural, forestry, or land restoration purposes (Beecher et al. 2007). We assume that the remaining 45% is potentially available for energy purposes. Beecher et al. (2007) estimate total biosolids production at 7.2 million dry tons in 2004. We assume this increases with population, so in 2015 and 2040, respectively, biosolids production would be 7.9 and 9.3 million dry tons, 45% of which is 3.6 and 4.2 million dry tons. We assume this is available at $40 per dry ton (table 5.12).

5.5.2 Used Cooking Oils

Used cooking oils are generally collected and used for livestock feed, biodiesel, or other products. Subcategories of used cooking oil are yellow grease—which has a free fatty acid content of less than 15%—and brown grease, which is used cooking oil with a free fatty acid content of greater than 15% (Van Gerpen 2015). Yellow grease is accounted for in EIA data on current uses, as is brown grease, which is included under other recycled feedstocks (EIA 2015b).

5.5.3 Brown and Trap Greases

Brown grease can encompass many feedstocks, including used cooking oil with greater than 15% free

Table 5.12 | Biosolids; Trap Grease; Food Processing Wastes from Industrial, Institutional, and Commercial Sources; Utility Tree Trimmings; and Additional Supplies of Landfill Gas

Feedstock ($ per dry ton)	Current	2017			2022			2030			2040		
		$40	$50	$60	$40	$50	$60	$40	$50	$60	$40	$50	$60
Million dry tons													
Biosolids	3.6	3.6	3.6	3.6	3.8	3.8	3.8	4.0	4.0	4.0	4.2	4.2	4.2
Trap grease	1.0	1.1	1.1	1.1	1.1	1.1	1.1	1.2	1.2	1.2	1.2	1.2	1.2
Food processing wastes—industrial, institutional, commercial	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Total biosolids, trap grease, and food processing wastes	8.6	8.7	8.7	8.7	8.9	8.9	8.9	9.2	9.2	9.2	9.4	9.4	9.4
Utility tree trimmings	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Billion ft^3 (no price estimated)													
Landfill gas—additional supplies		45			229			229			229		

fatty acids, trap grease (i.e., kitchen waste), sewage grease, and black grease (Tyson 2002). Trap grease is generally disposed of at wastewater treatment facilities and landfills. Wiltsee (1998a) estimates that 13 pounds of trap grease were generated per person per year in the United States, or about 2.1 million tons total (table 5.12).

5.5.4 Industrial, Institutional, and Commercial Food Processing Wastes

Food wastes, such as those from industrial sources, are not included in EPA MSW data. It is not clear whether food wastes from institutional and commercial sources are included in the EPA MSW data. Matteson and Jenkins (2007) estimate that in California, food processing wastes total 229,000 dry tons. The California Biomass Collaborative estimates that 3.8 million dry tons of food processing wastes are generated in California.[8] The National Renewable Energy Laboratory (NREL) has estimated that 20.6 million wet tons of food waste were generated in 2012 (Milbrandt 2015a). We assume that 65% of this wet weight (Matteson and Jenkins 2007), with a moisture content of 70%, or 4.0 million dry tons, is available at a price of $40/dry ton.

5.5.5 Landfill Gas

EPA (2016) estimates that as of February 2016 there were

- 119 landfills with energy projects that flare landfill gas at 45.3 billion ft^3 per year
- 26 landfills with energy projects either under construction or in the planning phase flaring 22.3 billion ft^3 per year
- 400 candidate landfills that could produce 161 billion ft^3 per year of landfill gas.

In total there is a potential for 229 billion ft^3 per year of additional landfill gas in addition to what is currently being captured and utilized. Currently utilized landfill gas is discussed in chapter 2. EPA defines a candidate landfill as a landfill that is currently accepting wastes or has been closed less than 5 years; that has at least one million tons of waste; that has no operational, under construction, or planned project; or that can be designated as a candidate landfill based on actual interest by the site. For 2017 the estimate of additional supplies is the flared gas at landfills with existing energy projects. For later years it is 229 billion ft^3 per year of additional landfill gas.

5.5.6 Utility Tree Trimmings

NREL estimates that, in 2012, utility tree trimmings were 913,000 dry tons (Milbrandt 2016; NREL 2016). We assume that 50% of these are available (479,000 dry tons) at a price of less than $40 per dry ton, and that supplies are roughly 500,000 tons per year out to 2040 (table 5.12).

5.6 Summary

Biomass from waste resources represents low-cost opportunities for bioenergy without the need for significant additional inputs. A diverse set of agricultural, woody, and MSW resources are covered in this chapter. Some resources are currently used, such as mill residues, sugar cane bagasse, and animal fats, and are included in quantities reported in chapter 2. From 2017 to 2040, at prices ranging from $40 to $60 per dry ton, additional agricultural wastes; MSW wastes, excluding wood and C&D waste; forestry residues; and other waste resources are available in amounts ranging from 27–38 million dry tons (table 5.1), 51–55 million dry tons (table 5.10), 36–53 million dry tons (table 5.11), and 9 million dry tons, respectively (table 5.12). Total biomass waste supplies from sources currently not used total 123 to 155 million dry tons (table 5.13).

[8] N. Parker, 2015, personal communication to A. Turhollow, December 9, 2015.

Table 5.13 | Summary of Baseline Potential of All Biomass and Wood Wastes at Selected Roadside Prices

Feedstock ($ per dry ton)	2017			2022			2030			2040		
	$40	$50	$60	$40	$50	$60	$40	$50	$60	$40	$50	$60
Agricultural	27	33	34	28	35	36	27	36	37	27	36	38
MSW[a]	51	55	55	51	55	55	51	55	55	51	55	55
Forestry	36	45	49	38	47	51	39	49	53	39	49	53
Other	8.7	8.7	8.7	8.9	8.9	8.9	9.2	9.2	9.2	9.4	9.4	9.4
Total	**123**	**142**	**147**	**126**	**146**	**151**	**126**	**149**	**154**	**126**	**149**	**155**

[a]Excluding wood and C&D wastes and about 230 billion ft^3 per year of potential biogas from landfills as shown in table 5.12.

5.7 References

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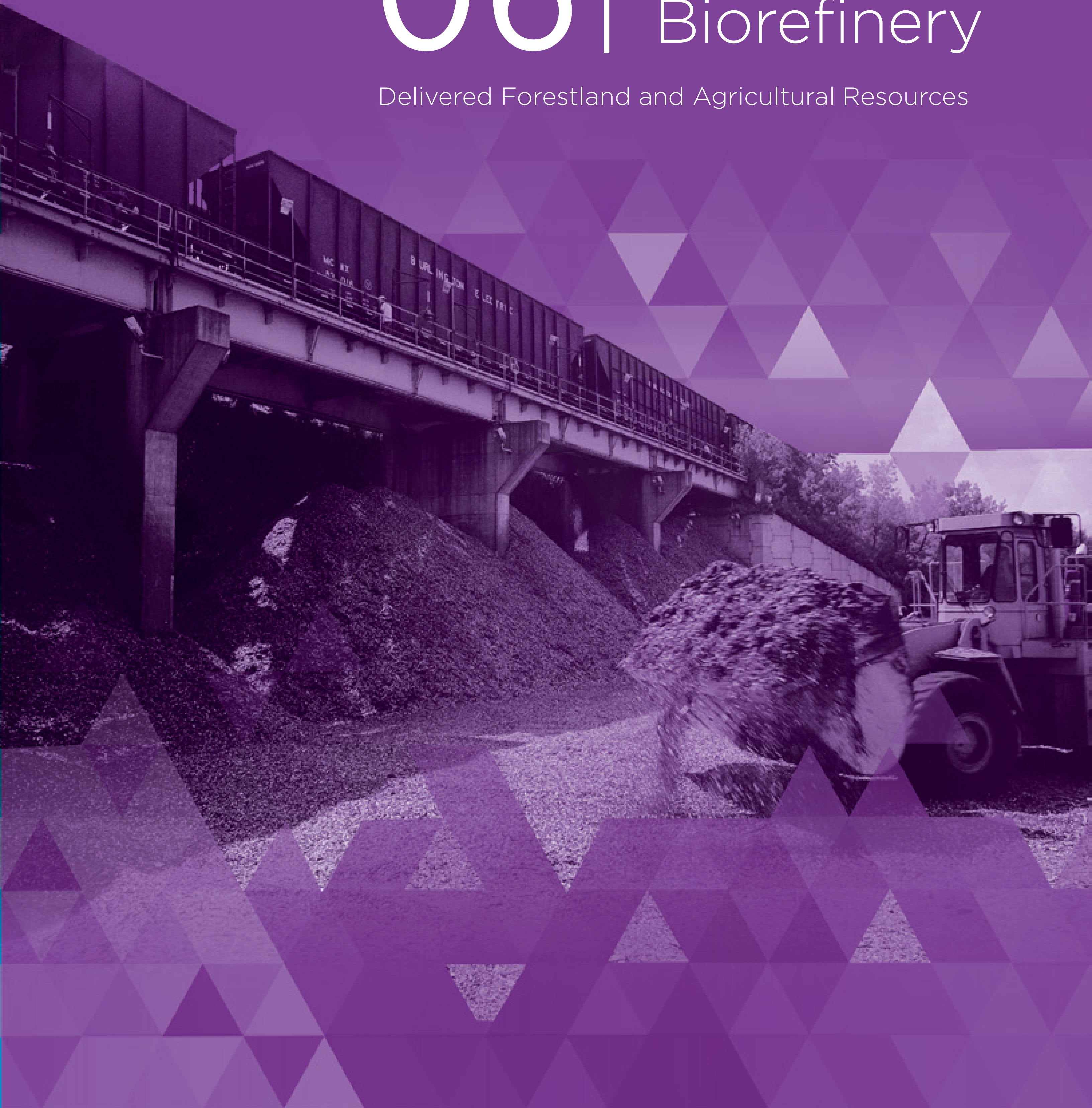
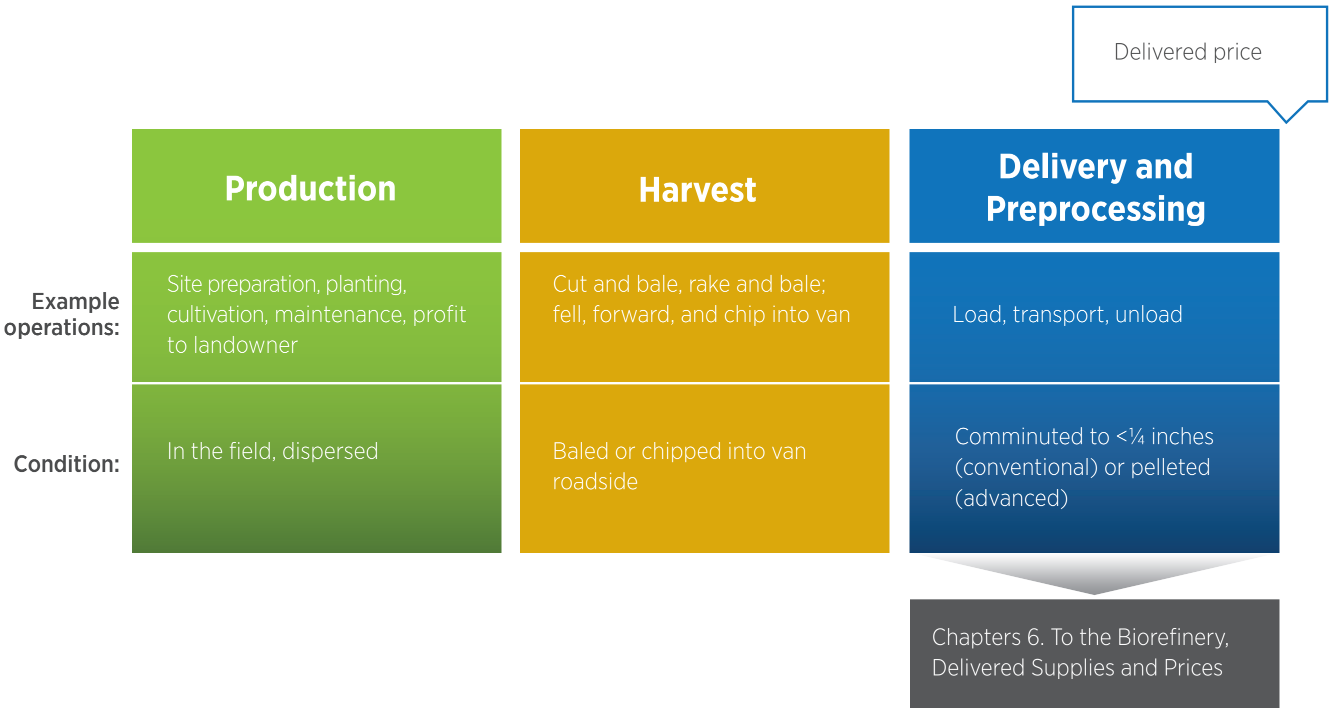
06 | To the Biorefinery

Delivered Forestland and Agricultural Resources





Building a commercial-scale industry capable of achieving DOE cost and production targets for biofuels will require consideration of how feedstock supply systems impact the cost, quantity, and quality of feedstocks delivered to the biorefinery. This chapter adds transportation and logistics costs to the county-level feedstocks estimated in chapters 3, 4, and 5 to characterize the cost and quantity of feedstocks that could be available to biorefineries. The 2011 *BT2* was explicitly limited to analysis of feedstock costs at the farmgate and forest landing. Recognizing that commercialization of biomass-based industries requires a broader, systematic evaluation of feedstock supplies that accounts for the challenges of delivering feedstocks to the biorefinery, this scenario analysis has been added to illustrate how select feedstocks could be delivered from the roadside to the reactor throat.

6.1 Designing Commercial Feedstock Supply Systems

Mobilizing one billion tons of biomass to fully achieve a large-scale bioeconomy will require innovations along the feedstock supply chain. Much has been achieved in recent years to improve efficiency, reduce losses, and preserve quality. Further advances in biomass preprocessing to transform raw biomass into engineered feedstocks could revolutionize the industry and enable commercialization and expansion.

Biomass is a challenging feedstock on which to build industrial processes. Like all agricultural and forestry systems for production of food, feed, and fiber, supply systems designed to provide biomass for energy and other products must contend with material variability (both spatially and temporally), yield reductions caused by weather and pests, and degradation in storage. As supply systems for commodities and products, such as corn grain, produce, milk, livestock, and feed, have matured over time to preserve quality while reducing cost in the face of these external pressures, so, too, must cellulosic feedstock supply systems evolve by increasing efficiency, reducing material losses, and standardizing quality.

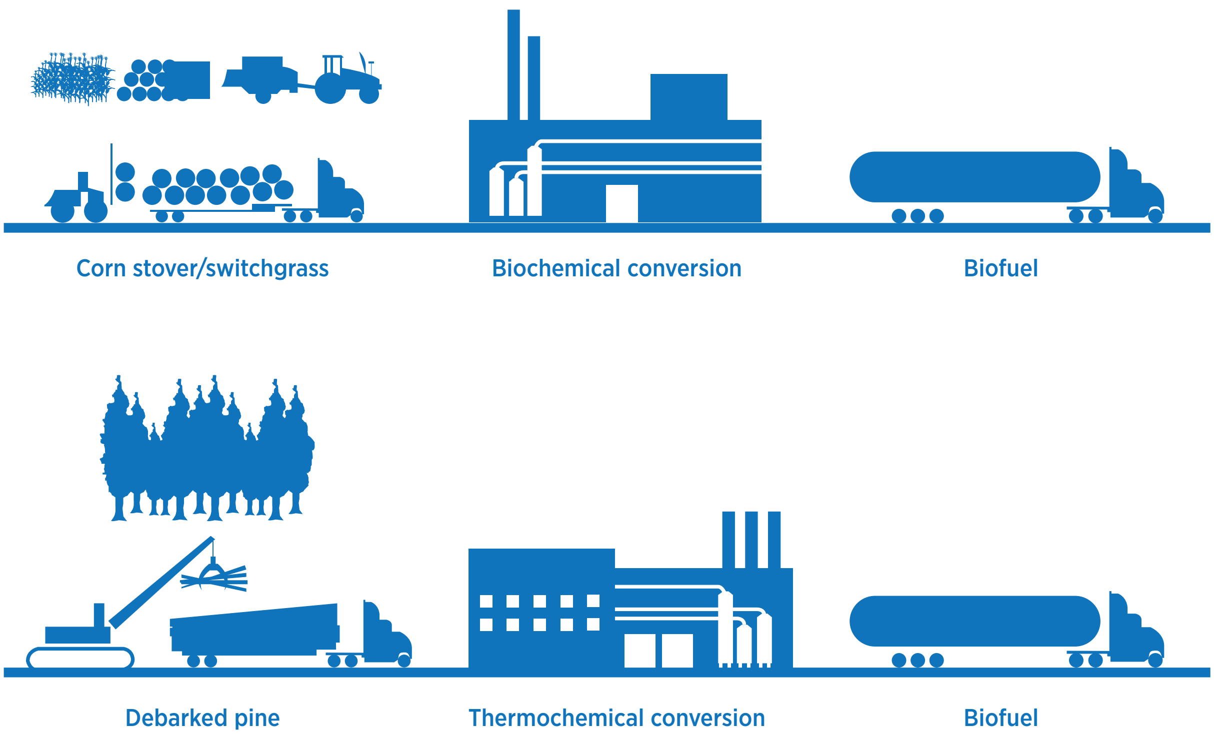
The following barriers to commercialization of feedstock supply systems were outlined by the Feedstock Logistics Interagency Working Group in its 2010 report (Biomass Research and Development Board 2010):

- Low mass and energy density with current harvest and collection equipment
- High biomass moisture content at the time of harvest, leading to degradation and decreased system efficiency
- Insufficient capacity and efficiency of currently available equipment for harvesting and preprocessing biomass
- Variable, inconsistent biomass quality upon arrival at the biorefinery
- Costly transportation options that can strain transportation networks.

The development of supply systems to overcome these challenges will enable mobilization of the more than one billion tons of biomass that was shown in chapters 3, 4, and 5 to be potentially available from agriculture, forestry, and waste resources.

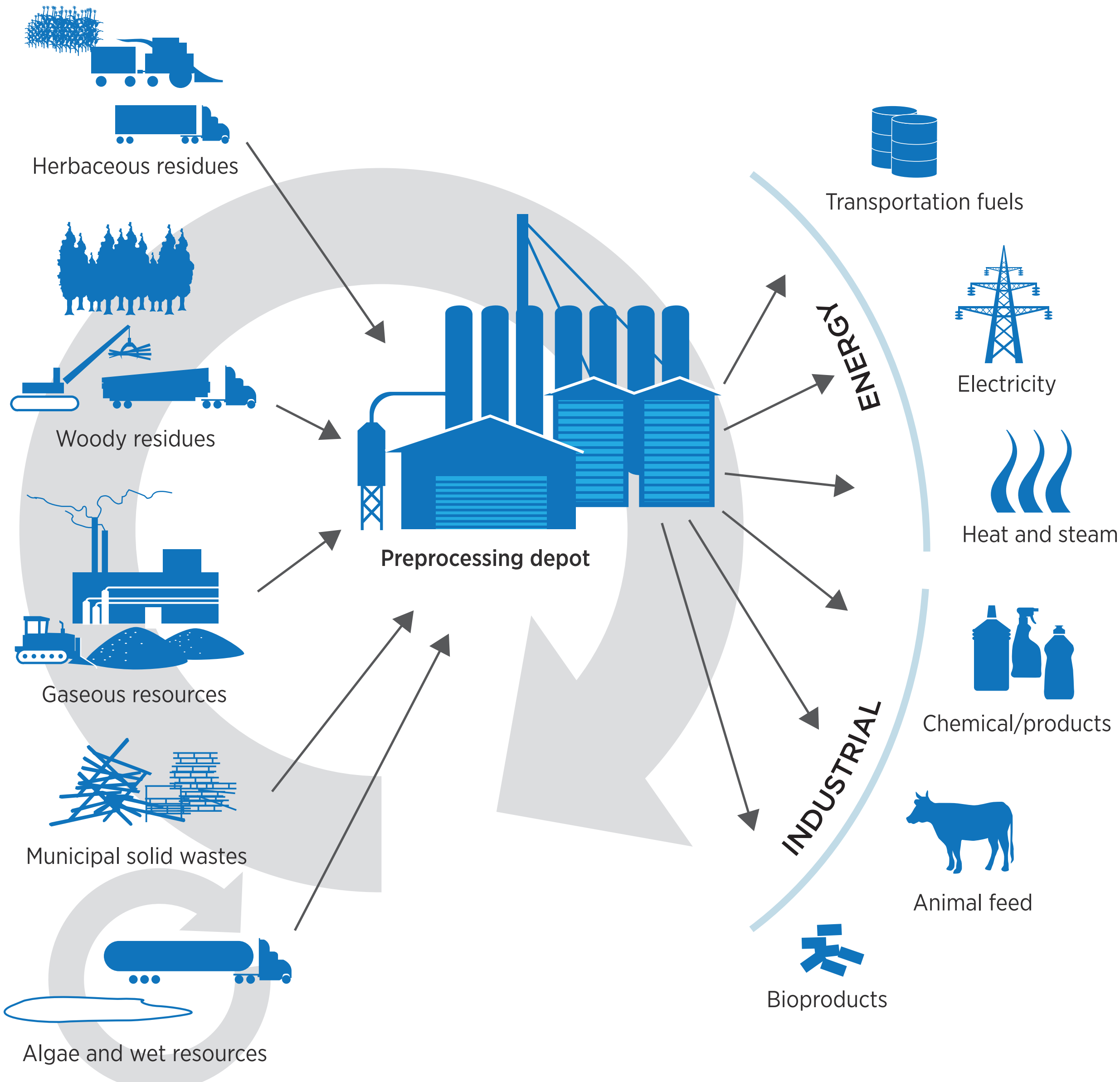
In the near term, design of conventional feedstock supply systems will continue to focus on supplying specified feedstock quantities at the lowest cost. Here, conventional supply systems use equipment that is designed for traditional agricultural and forestry systems. These passive systems have few to no active quality control strategies (an exception is debarking in some whole tree harvest systems). They rely on truck transport within a regional supply shed around the biorefinery. In conventional feedstock supply systems, as shown in figure 6.1, biorefineries accept only one feedstock type, either herbaceous bales (e.g., switchgrass or corn stover) or wood chips.

Figure 6.1 | Current feedstock supply systems are designed to deliver a single feedstock type (e.g., corn stover or switchgrass bales, or wood chips) to the biorefinery using technologies designed for traditional agricultural and forestry industries



(Image courtesy of Idaho National Laboratory)

Figure 6.2 | Proposed future feedstock supply system for transforming raw biomass into stable, tradeable commodities suitable for long-distance transport and handling in existing infrastructure



(Image courtesy of Idaho National Laboratory)

Success of the nascent cellulosic biofuel industry requires high-quality and consistent feedstock supplies to be competitive with more established biofuel and fossil fuel industries. Proposed advanced feedstock supply systems (example shown in fig. 6.2) are designed to meet those demands by transforming raw feedstocks that are aerobically unstable and highly variable into a high-density, flowable format that can be traded as a commodity. These commoditized feedstocks will be suitable for long-distance transportation by rail or barge, can be blended to meet custom requirements and handled in existing grain infrastructure, and have long-term stability in storage.

6.1.1 Improving Efficiency, Capacity, and Reliability

The first challenge to building a commercial-scale bioenergy feedstock supply industry is to develop supply systems capable of cost-effectively delivering increasing quantities of biomass as new biorefineries are constructed. Over the past decade, many modifications have been made to improve the efficiency and capacities of machines for feedstock supply systems, particularly in harvest, collection, preprocessing (including size reduction), handling, and transport. As the biofuel industry begins to expand, work continues to improve these machines—especially their reliability and productivity.

Harvesting biomass for energy is similar to harvesting other crops and resources, such as hay for animal feed, or saw logs. However, a few key differences make using conventional equipment to harvest, preprocess, and handle bioenergy feedstocks difficult and more expensive. Mowing and baling (packaging) high-yielding energy crops such as switchgrass or miscanthus—or corn stover, which has thick, stiff stalks and leaves—with machinery designed for traditional forage crops leads to high maintenance costs, increased downtime from plugging (Womac et al. 2012), shorter useful lifetimes, and expensive repairs. Machine capacities can also be limiting. Larger, faster machines with higher capacity, especially for operations such as collecting and hauling bales in the field or small-diameter trees in the forest, could reduce costs significantly.

Biomass, in both baled and ground form, is difficult to handle with conventional equipment. Picking up bales and placing them on a trailer individually is highly time-intensive and costly, particularly if the bale density is low. Conveying ground biomass has proved to be a significant challenge to biomass facilities. Moving raw biomass in ground or chopped form is difficult with conventional equipment and often results in significant maintenance costs and downtime.

Designing a cost-effective transportation system is also complicated, as suitable land on which biomass can be economically produced may not be concentrated near a utilization facility. Rather, many feedstocks are geographically dispersed, making transport to a biorefinery problematic and costly. Furthermore, the low-bulk density of cellulosic feedstocks exacerbates the transportation challenge, as trucks that are not fully loaded (by weight) travel long distances to deliver bioenergy feedstocks.

In recent years, manufacturers of forage and hay equipment have partnered with researchers from government and academia to modify balers, in-field bale-collection equipment, and trailers to better handle biomass, which can have significantly higher yields than conventional forage crops. Particularly notable improvements are increased bale density—which can significantly reduce transport, handling, and storage costs—and more efficient bale collection and loading. New technologies such as single-pass baling systems reduce machine and labor costs by eliminating operations and reducing the number of passes on the field during harvest. Similarly, forestry equipment manufacturers are responding to a need for equipment to better cut and remove small-diameter trees in thinning operations and to harvest trees purposely grown in plantations for energy.

High-Tonnage Logistics Demonstration Projects

In 2009, the DOE Biomass Program (now the Bioenergy Technologies Office) issued an announcement to fund five projects to develop and demonstrate supply systems for delivering high-tonnage biomass feedstocks (capable of supplying at least 100 million dry metric tons per year) for cellulosic ethanol production (see table 6.1). The primary goal of these projects was to reduce the logistics costs of bioenergy feedstocks delivered to the biorefinery. Projects were required to demonstrate feedstock harvest, collection, preprocessing, handling, transport, and storage and show the impact of these improvements on costs associated with logistics operations costs relative to a benchmark conventional system. These projects are just a sampling of how government-industry-academic partnerships are working together to reduce

Table 6.1 | Examples of How Recent Investments by the Bioenergy Technologies Office in Logistics Demonstration Projects Led to Significant Advances in Feedstock Supply Systems

Lead organization	Year awarded	Crop	Key technologies developed and demonstrated
AGCO Corp.	2010	Corn stover	• Single-pass harvesting • High-density baling • Trailer with automatic load securing
Auburn University	2009	Southern pine	• Tree-length harvesting • In-woods chipping • Transpirational drying • Tracked feller buncher with EPA-compliant engine • Skidder with extra-large grapple • Optimized chip trailer to maximize load weight
FDC Enterprises, Inc.	2010	Corn stover, switchgrass, miscanthus	• Self-propelled baler • High-density baling • Self-propelled bale pick-up truck • Self-loading/unloading trailer
TennEra, LLC	2010	Switchgrass	• Field chopping • Bulk handling • Bulk storage • Bulk compaction
State University of New York College of Environmental Science and Forestry	2010	Willow, poplar	• Single-pass cut-and-chip harvester • Chip handling • Rapid quality assessment methods

Table 6.1 *(continued)*

Lead organization	Year awarded	Crop	Key technologies developed and demonstrated
FDC Enterprises, Inc.	2013	Corn stover	• High-capacity bale movers • Improved harvest data collection and management • Rapid in-field quality assessment • High-density round balers • Horizontal grinder
University of Tennessee	2016	Southern pine, switchgrass	• Whole tree harvesting and delivery strategy • Merchandizing depot for trees • Online quality assessment • Feedstock blending to achieve quality specs
State University of New York (SUNY) College of Environmental Science and Forestry	2016	Willow, poplar	• Improved harvest and collection equipment utilization • Rapid quality assessment

feedstock logistics costs. There are many other efforts under way in companies, universities, and national laboratories across the United States with goals to improve feedstock logistics operations.

Teams led by AGCO and FDC Enterprises developed improved harvesting techniques for corn stover by increasing bale density, developing single-pass and self-propelled baling technologies, and developing advanced bale-collection and loading/unloading systems (see figs. 6.3 and 6.4). The AGCO and FDCE projects were successful in reducing the cost of baled corn stover by increasing the amount of biomass within each bale, reducing the number of operations required during harvest, and increasing the efficiency of loading bales onto trucks for transport out of the field and over the road. Implementing these new technologies is projected to reduce the delivered cost of corn stover by nearly 20%. AGCO project partners included Iowa State University, Stinger, Inc., Midwest Research Institute, Texas AgriLife Research, Oklahoma State University, Noble Foundation, and Idaho National Laboratory. Organizations working with FDC Enterprises included Antares Group, Inc., Kelderman Manufacturing, Inc., Allied Systems Company, MacDon, Inc., Abengoa Bioenergy New Technologies, Rotochopper, and Idaho National Laboratory.

A TennEra LLC-led team, including the University of Tennessee, Laidig Systems, and Marathon Equipment, developed an innovative system for harvesting, handling, transporting, and compacting forager harvester-chopped switchgrass. Bulk compaction, using equipment systems typically used for municipal and construction waste handling, achieved much improved bulk densities, and yet maintained the advantages of automated bulk flow. Although the cost of equipment to handle and store chopped switchgrass at the depot was significantly higher than the costs

Figure 6.3 | The single-pass corn stover baling system demonstrated by an AGCO-led team reduces baling costs by consolidating harvest operations, and reduces ash content by avoiding contact between the ground and the stover.

(Photo courtesy of Maynard Herron, AGCO)

Figure 6.4 | Advanced self-propelled baling technologies (top) coupled with new prototype bale-collection (middle) and loading/unloading equipment (bottom) developed by the FDC Enterprises team were successfully shown to improve baling and handling efficiency and reduce overall logistics costs.

(Photos courtesy of Kevin Comer, Antares Group, Inc.)

Figure 6.5 | In a project led by TennEra LLC, innovative technologies for (top) handling and (bottom) compacting forage harvester-chopped biomass increased bulk flow rates compared with tub-ground bales, resulting in reduced downstream processing and handling costs.

(Photos courtesy of Al Womac, University of Tennessee)

Figure 6.6 | A SUNY-led team developed a modified New Holland forage harvester and innovative wood chip field transport strategies to improve efficiency and reliability in harvesting willow and hybrid poplar.

(Photo courtesy of Tim Volk, SUNY College of Environmental Science and Forestry)

Figure 6.7 | An Auburn-led team developed improved equipment for felling (top), skidding (middle), chipping (bottom), and transporting wood chips from pine plantations

(Photos courtesy of Steve Taylor, Auburn University)

of on-farm bale storage, these costs were somewhat offset by increases in bulk flow rates and decreased investments and costs at the biorefinery (see fig. 6.5). The project provided a basis to further advance and optimally design dedicated equipment systems for economically supplying consistent-quality biomass feedstock to biorefineries.

Improving the reliability, capacity, and efficiency of harvesting and collecting wood chips from willow and hybrid poplar was the focus of a project led by the SUNY College of Environmental Science and Forestry working with Case New Holland, Green-Wood Resources, and Mesa Reduction Engineering and Processing, Inc. The SUNY team modified equipment conventionally used for harvesting agricultural crops to efficiently deliver willow and poplar chips as bioenergy feedstocks (see fig. 6.6) and developed and demonstrated a short-rotation woody crop header for a commercially available forage harvester.

A team composed of Auburn University, the USDA Forest Service, Tigercat, and Corley Land Services, improved forestry equipment to reduce the costs of harvesting biomass from pine plantations by increasing the productivity of the feller buncher, skidder, and chipper, and increasing biomass transport efficiency (see fig. 6.7).

6.1.2 Preserving Feedstock Quality

As the feedstock supply industry expands and matures, biorefineries are expected to evolve from merely securing adequate quantities of feedstock as cheaply as possible to procuring feedstocks that meet quality specifications, so as to optimize feedstock handling and conversion performance. Feedstock quality is key to biorefineries' success, especially in the early years of their development, because meeting quality specifications consistently ensures high rates of conversion from biomass to biofuel, making refineries competitive with other biofuel producers (and even with fossil-fuel producers). Although cost and quantity will remain top priorities, it is expected that, like other agricultural and forestry-based industries, biorefineries will be willing to, within reason, pay more for feedstocks that are easier and less expensive to handle and convert.

Most analyses of bioenergy feedstock supply systems to date have focused on reducing delivered cost, with less emphasis on feedstock quality and consistency. This oversight has interfered with acquiring and handling adequate quantities of feedstock during system startup. As the priority of the bioenergy industries shifts from process development to deployment, attention will increasingly focus on meeting biomass quality specifications for such parameters as ash, carbohydrate, lignin, and moisture content and particle morphology (Kenney et al. 2013).

A guiding principle in the development of the proposed future feedstock supply system designs (DOE 2015) is incorporation of active quality-management technologies that transform raw, highly variable feedstocks into a tradeable commodity. Strategies for minimizing moisture and ash while preserving carbohydrates will be added along the supply chain, as will densification or conversion to liquids to produce intermediates that can be handled in existing storage, conveyance, and transportation infrastructure. The concept calls for the development of regional depots, typically 5 to 10 miles from production sites, where baled herbaceous biomass and/or wood chips would be converted to an intermediate commodity. Depots would be strategically located, with access to major highways, rail, or barges, to minimize long-distance transport to biorefineries or other appropriate markets. The commodities can then be transported to a biorefinery or other utilization facility. The improved handling characteristics of these intermediates make them suitable for blending with other feedstocks to produce custom recipes. Increased bulk density and handling characteristics make long-distance transport via rail or barge a more suitable option.

Bioenergy feedstock quality considerations are somewhat different from those of conventional uses of similar crops. Some biofuel conversion processes are highly sensitive to high ash content. Harvest techniques whereby biomass remains on the ground, as is the case in field drying, result in contamination by dirt, a significant source of ash in biomass. Harvest technique and soil type have a significant impact on the amount of ash (introduced as dirt) or other contaminants. For example, Bonner et al. (2014) observed that mean ash content of corn stover harvested from the same region varied from 11.5% to 28.2%. More aggressive collection techniques collect more of the available biomass, but cause greater soil disturbance. Thus, the benefits of increasing biomass throughput versus the effects of increasing the concentration of non-biological ash resulting from the entrainment of more soil and rocks must be considered when selecting harvest equipment and determining operational parameters.

Biomass moisture management during harvest and storage has significant impact on delivered biomass quality and dry-matter loss. Some bioenergy crops, such as energy sorghum, do not dry well in the field, so harvest, storage, and handling strategies in high-moisture environments are needed. In many regions, ambient weather conditions during harvest inhibit field drying. Field drying is not an option for new single-pass harvest technologies designed to reduce ash content and increase harvest efficiency.

Aerobic respiration during storage, which increases as available water increases, results in the loss of desired chemical components. Storage configurations that allow drying and prevent the entry of additional moisture reduce dry-matter losses. For example, in an untarped dry stack, moisture from precipitation is allowed to accumulate on the top bale. Over extended periods, this moisture accumulation results in high levels of biological activity, which causes loss of feedstock from degradation and bale instability. Dry matter loss also tends to destabilize bale stacks, causing them to topple.

Feedstock quality varies by genetics, location, year, weather, harvesting technology, anatomical fraction, and agronomic treatments. Optimizing the design of a particular feedstock supply system requires a detailed understanding of feedstock variability at a local level to assess the viability of specific feedstock resources for specified conversion processes. Such changing conditions as water availability, local production practices, and weather conditions further complicate matters and can have significant effects on quality.

6.1.3 Reducing Risk along the Feedstock Supply System

Risk is another increasingly important consideration for biorefineries. Risk associated with feedstock supply, financing availability, fire, and safety increases the likelihood of operational disruptions and exposes a biorefinery to higher insurance premiums and, in the case of fire and safety, potential litigation. Designing and operating feedstock supply systems to minimize risk will enable industry expansion. Neglecting risks will discourage investment in new facility construction and drive up costs by increasing operational disruptions and liability.

Feedstock supply uncertainty may limit financing options for a biorefinery, as this will be perceived as a major risk by investors (DOE 2015). Higher interest rates may be imposed, which could significantly increase biorefinery capital investment costs, resulting in higher biofuel production costs. Supply systems must be designed to contend with a number of risk factors associated with feedstock availability, including drought or other inclement weather events, pest damage, lack of producer participation, and competing demands. A pioneer biorefinery near a highly concentrated feedstock is particularly susceptible to feedstock availability risk, as its entire feedstock supply area would be affected by the same external risk factors.

Current options for addressing these risks include overcontracting to secure more feedstock than the biorefinery requires (which will help avoid outages) or downscaling production during feedstock shortages. Both options, although sometimes necessary in the mid-term, are cost-prohibitive for industry expansion. In the long term, advanced supply systems to develop a stable, tradeable commodity that can be transported long distances will alleviate many of these risks, as biorefineries will have more cost-effective options for purchasing feedstocks from beyond their immediate supply sheds (Hansen and Searcy 2015).

Fire is another risk facing bioenergy feedstock supplies; it may not only cause feedstock shortages, but, more importantly, can inflict harm on people and property at the biorefinery or in the surrounding community. The current strategies for minimizing fire risk include spacing biomass stacks and piles far from other structures to reduce the likelihood of fire spread, and securing the area to minimize arson, a leading cause of biomass fires. Research to better understand fire behavior in biomass storage stacks will lead to advanced storage systems—such as high-moisture storage—and biomass formats that reduce the risk of fire spread and minimize the threat of harm to people and property. The threat of fire can never be fully eliminated; rather, efforts to improve storage and handling design should concentrate on minimizing fire spread. Feedstock shortages due to fire can be reduced in the same manner as are other feedstock shortages—by improving access to feedstocks from a broader supply area.

6.2 Approach to Quantifying the Delivered Costs of Biomass Resources

To estimate the costs of biomass resources delivered to the biorefinery reactor throat, the Supply Characterization Model (SCM), a geographically based modeling system for allocating feedstock supplies to potential utilization facilities and calculating the delivered price and quantity of the supplies, was used to simulate feedstock transport from source to destination facility (Webb et al. 2014). Costs of unit operations (storage, size reduction, and handling) and dockage (additional charges incurred for disposal of feedstocks that do not meet quality specifications) were derived from previous studies (Cafferty et al. 2014; Kenney et al. 2014). Locations of utilization facilities are based on minimizing the average total feedstock cost. Facility locations are selected iteratively, in order of increasing total delivered cost, until all of the available supply is used.

For each feedstock, SCM requires five logistics cost estimates—(1) production costs, (2) other logistics costs (storage, handling, and preprocessing), (3) time transportation cost, (4) distance transportation cost loaded, and (5) distance transportation cost empty. Production costs include operations on the farm (corn stover and perennial grass), at the landing (pulpwood and woody residues), or at the sorting facility (construction, demolition, and yard waste), along with the grower payment (herbaceous feedstocks) or stumpage price (woody feedstocks). Transportation cost is divided into time- and distance-based components. Here, the distance component of transportation cost, namely fuel, varies by the distance traveled. The time cost accounts for the capital cost of the truck and labor cost. Fuel economy is known to change with payload, so distance transportation costs are estimated for fully loaded trucks going to the facility and for empty trucks on the backhaul. The other logistics cost parameter includes the costs of all other operations along the supply chain, such as storage, handling, and preprocessing.

The quantities of available feedstock for the SCM analyses presented here are the county-level biomass production estimates (dry tons/county for each feedstock) discussed in chapters 3, 4, and 5, for a near-term scenario (using the 2022 resource base) and a long-term scenario (2040 resource base). The production estimates for agricultural resources represent materials available at an offered farmgate price of $60 per ton. Production estimates for forestry resources are materials available with stumpage plus harvest costs of $60 per ton (or less) selected from the ForSEAM simulation results that had the highest demand level in all years of the simulation (see chapter 3). Associated with each production level was a roadside cost that includes production, harvest, and transport to the landing or field edge. An estimated profit (10% of production and harvest costs) was included for the agricultural resources.

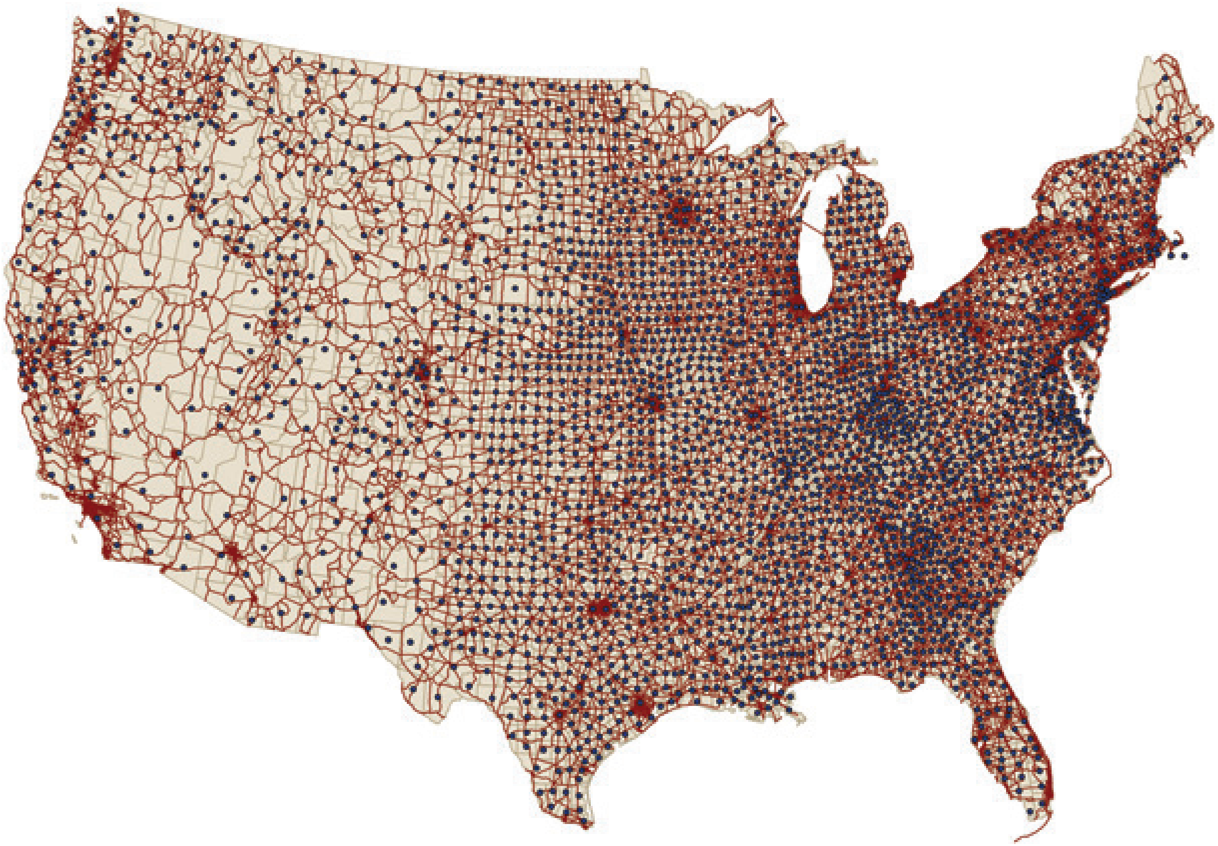
The road transportation network used for these analyses was version 11.09 of the 2013 National Highway Planning Network, a 1:100,000 scale geospatial database representing approximately 450,000 miles of principal arterial and rural minor arterial roads in the United States. Road speeds were assigned to each segment of the road network as described in Webb et al. (2014).

The county feedstock estimates used in the near-term and the stage 1 long-term scenarios (farm or forest to depot) were assigned to their county centroids. Potential facilities (depots and refineries) were restricted to points in a 50-mile spaced grid superimposed on the 2013 National Highway Planning Network road network. The corresponding grid points were then linked to the nearest node in the road network (as shown in fig. 6.8).

6.2.1 Near-Term Feedstock Supply System Modeling Assumptions

In this analysis, near-term or conventional feedstock supply systems use commercially available equipment. The primary goal is to supply the specified quantities at minimal cost. These systems do not include active quality-management strategies; rather, the challenges of dealing with feedstocks that do not meet quality specifications are accounted for in dockage fees applied to the total delivered cost to account for disposal of off-specification material. The model is designed to secure additional feedstock to compensate for off-specification biomass and to fully meet the biorefinery demand.

Figure 6.8 | Potential biorefinery and depot locations for these analyses derived by restricting utilization facilities to a 50-mile grid snapped to nearest highway network intersections



The SCM simulates the near-term scenario by modeling transport of baled herbaceous biomass or wood chips from the county centroid to a biorefinery by truck. For this analysis, the annual biorefinery demand is assumed to be 800,000 tons per year, based on analysis by Argo et al. (2013) and Muth et al. (2014), to optimize the cost per gallon of fuel by considering the tradeoffs between feedstock transport distance and biorefinery economy of scale. Logistics costs for storage, preprocessing, and handling are adapted from 2013 state of technology estimates by Kenney et al. (2014) and Cafferty et al. (2014). It should be noted that harvest and in-field transportation costs were accounted for in roadside cost estimates developed in chapters 3, 4, and 5.

It is assumed that biorefineries with no active quality control can accept only one feedstock type. Dockage fees are applied to delivered costs to represent the costs of disposing of feedstocks that do not meet quality specifications for moisture and ash. Tables 6.2 and 6.3 show estimated dockage fees by feedstock. The ash-dockage fee was calculated based on Bonner et al. (2014) and Bonner and Kenney (2013); moisture dockage fees for herbaceous feedstocks were derived from Kenney et al. (2014). Moisture dockage fees were not applied to woody feedstocks, because it was assumed that they would not be stored long term.

Table 6.2 | Estimating Dockage Fees for Herbaceous Feedstocks

	Corn stover	Switchgrass	Miscanthus	Sorghum	Yard trimmings
Initial ash (%)	7%	6%	4%	7%	10%
Ash dockage fee ($/dry ton)	$2.71	$2.33	$1.55	$2.71	$3.88
Moisture at harvest (%)	20%	15%	15%	40%	20%
Moisture dockage fee ($/dry ton)	$3.36	$3.36	$3.36	$6.72	$3.36

Table 6.3 | Estimating Ash Dockage Fees for Woody Feedstocks

	Whole tree chips	Logging residues	Urban wood waste	Woody energy crops	Construction and demolition waste
Initial ash (%)	1%	4%	4%	2%	1%
Ash disposal cost ($/dry ton)	$0.23	$1.55	$1.55	$0.78	$0.39

Costs for the near-term feedstock supply scenario are described below by operation for corn stover, switchgrass, miscanthus, and energy sorghum, and in tables 6.4 and 6.5.

- **Corn stover:** Following harvest, large, rectangular bales of corn stover are collected from the field and stacked along the farm edge, covered with tarps, and stored until needed by the biorefinery. It is assumed that stover is allowed to field dry to less than 20% moisture content before baling. In reality, weather conditions in some regions during corn harvest are not suitable for field drying, and high-moisture storage systems or mechanical dyers are needed. Future resource-assessment analyses will account for the regional impacts of moisture on the selection of stover harvest strategies. When stover bales are needed by the biorefinery, bales are removed from storage stacks, placed on flatbed trailers, and transported to the biorefinery. Bales are stored temporarily at the biorefinery (≤5 days) and passed through a grinder before entering the conversion process.
- **Switchgrass:** The switchgrass supply chain is much like that for stover, in that the large, rectangular bales of switchgrass are stacked, covered with tarps, and stored on the farm edge until called for by the biorefinery. Bales are transported by trucks with flatbed trailers to the biorefinery, where they are stored temporarily before being ground. It is assumed that the moisture content of switchgrass is 10% to15%, as harvest occurs after the first killing frost, when moisture content declines rapidly.

Table 6.4 | Logistics and Transportation Cost Assumptions for Herbaceous Feedstocks Supplied to a Biorefinery in the Near-Term Scenario

Corn stover		Switchgrass	
Logistics costs ($/dry ton)			
Storage on farm	$3.92	Storage on farm	$3.92
Loading/unloading truck	$3.24	Loading/unloading truck	$3.24
Storage at biorefinery	$1.57	Storage at biorefinery	$1.57
Grinding	$14.00	Grinding	$14.00
Dockage, moisture	$3.36	Dockage, moisture	$3.36
Dockage, ash	$2.71	Dockage, ash	$2.33
Total	**$28.80**	**Total**	**$28.41**
Transportation costs ($/dry ton)			
Time cost ($/dry ton/hour)			$3.90
Distance cost, loaded ($/dry ton/mile)			$0.038
Distance cost, empty ($/dry ton/mile)			$0.027
Biomass sorghum		**Miscanthus**	
Logistics costs			
Module building	$8.29	Storage on farm	$3.92
Storage	$3.92	Loading/unloading truck	$3.24
Loading/unloading truck	$7.17	Storage at biorefinery	$1.57
Storage at biorefinery	$1.57	Grinding	$14.00
Grinding	$8.29	Dockage, moisture	$3.36
Dockage, moisture	$6.72	Dockage, ash	$1.38
Dockage, ash	$2.71	**Total**	**$27.47**
Total	**$38.67**		

Table 6.4 *(continued)*

Corn stover		Switchgrass	
Transportation costs			
Time cost ($/dry ton/hour)	$3.20	Time cost ($/dry ton/hour)	$3.90
Distance cost, loaded ($/dry ton/mile)	$0.033	Distance cost, loaded ($/dry ton/mile)	$0.038
Distance cost, empty ($/dry ton/mile)	$0.022	Distance cost, empty ($/dry ton/mile)	$0.027

Table 6.5 | Logistics and Transportation Cost Assumptions for Woody Feedstocks Supplied to a Biorefinery in the Near-Term Scenario

Whole tree chips		Logging residues	
Logistics costs ($/dry ton)			
Hammer mill (second-stage grind)	$19.14	Hammer mill (second-stage grind)	$19.14
Dockage, ash	$1.38	Dockage, ash	$1.55
Total	**$20.53**	**Total**	**$20.69**
Woody crops—coppice		**Woody crops—non-coppice**	
Hammer mill (second-stage grind)	$19.14	Hammer mill (second-stage grind)	$19.14
Handling	$3.25	Dockage, ash	$0.78
Dockage, ash	$0.78	**Total**	**$19.92**
Total	**$23.16**		
Urban wood waste		**Construction and demolition waste**	
Logistics costs ($/dry ton)			
Hammer mill (second-stage grind)	$19.14	Chipper	$6.83
Dockage, ash	$1.55	Hammer mill (second-stage grind)	$15.65
Total	**$20.69**	Dockage, ash	$0.39
		Total	**$22.87**

Table 6.5 *(continued)*

Transportation costs	
Time cost ($/dry ton/hour)	$4.24
Distance cost, loaded ($/dry ton/mile)	$0.046
Distance cost, empty ($/dry ton/mile)	$0.028

Note: Costs for chipping woody biomass at the source or landing are included in roadside costs estimates (see chapters 3, 4, and 5).

- **Miscanthus:** Supply systems for miscanthus bales (also large, rectangular bales) from storage to delivery at the conversion reactor are the same as for switchgrass and corn stover bales. The delivered costs, however, are lower than for stover and switchgrass, as the average miscanthus ash content is assumed to be 3.5%, which is lower than the 5% biorefinery specification.
- **Energy sorghum:** Unlike stover, switchgrass, and miscanthus, energy sorghum is not easily field-dried, making it a challenge to bale conventionally. This analysis assumed a promising system investigated by An and Searcy (2012) and Searcy, Hartley, and Thomasson (2014) for assembling field-chopped sorghum into large modules (similar to cotton modules) for storage and transport. The large, plastic-wrapped modules are stored along the field edge. When they are needed, a specialized module hauler loads two modules onto a flatbed trailer for transport to the biorefinery. The sorghum has been harvested by a field chopper; ergo, no grinding operation is needed at the biorefinery.
- **Woody resources:** Woody biomass is transported as wood chips from the landing or plantation edge to the biorefinery via chip truck.

A widely recognized weakness of current feedstock supply systems is their inability to deal with risk to feedstock availability (DOE 2015). Such risks include low crop yield due to drought or pests, crop losses during such extreme weather events as floods or hurricanes, fire, and competition for other uses. To address this risk, it is assumed here that biorefineries will secure contracts for a feedstock supply greater than their operational demand to minimize the likelihood of process downtime. This approach is supported by analysis by Golecha and Gan (2016), who demonstrated that biorefineries can mitigate the impacts of year-to-year variations in available stover by maintaining a supply region that is larger than exactly what is needed to feed the biorefinery under average yield conditions. Using U.S. corn yield data since 1975, Golecha and Gan determined that the optimal structure using current supply chain technologies is a supply region where, on average, only 63% of collectable stover is used to supply the biorefinery. The remaining supply area is available each year in case of reduced feedstock availability. A supply buffer of 25% was applied to herbaceous feedstocks supplied via a near-term supply chain in the SCM. This buffer was based on the study by Golecha and Gan (2016), along with the additional assumption that annual variability in perennial energy crop yields is less than that of stover (Langholtz et al. 2014).

It also took into consideration that in most years, a portion of the stover will be available for carryover to the following year. The 25% supply buffer means that no more than 75% of the available supply is used to feed the biorefinery. A supply buffer of 10% was applied to woody feedstocks, based on current estimates of the amount of feedstock that pulp and paper mills keep on hand to avoid supply disruptions.[1]

6.2.2 Long-Term Feedstock Supply Chain Modeling Assumptions

The long-term scenario considered for 2040 assumes that all feedstocks are delivered via advanced feedstock supply systems with regional depots that convert raw feedstocks into pellets. Although in reality long-term supply chain designs will vary depending on feedstock availability, regional conditions, and biorefinery design, a single future supply chain design was selected for simulation here. The model assumes that baled herbaceous feedstocks (stover, switchgrass, miscanthus, and sorghum) are baled and transported by flatbed trailer to a regional depot for drying and densification. Wood chips are similarly transported from the landing or plantation to the depot by chip truck. At the depot, feedstocks are dried and processed into pellets by a high-moisture pelletization process described by Lamers et al. (2015). While this pelletization technology is not yet viable at commercial scale, it provides a reasonable estimate of the costs of future depot-processing technologies. For the purposes of this analysis, pellets are transported by truck from depots to large biorefineries.

For this analysis, the SCM is used twice for each long-term supply chain: once for simulating the transport of raw feedstocks from the county centroid to the depot (with demand of 80,000 dry tons/year), and again for the transport of pelleted feedstocks from the depot to the biorefinery (with a feedstock demand of 800,000 dry tons/year); see tables 6.6, 6.7, and 6.8. Logistics costs for storage, preprocessing, and handling are adapted from the 2017 cost targets developed by Kenney et al. (2014) and Cafferty et al. (2014). Note that harvest and in-field transportation costs were accounted for in roadside cost estimates from chapters 3, 4, and 5.

The long-term feedstock supply systems include improvements over the near-term supply systems, described in section 6.2.1, to better address risk to feedstock availability and deal with biomass that does not meet quality specifications. A primary goal of the future feedstock supply chain presented here is to create commoditized feedstocks—with standard quality characteristics—that can be transported farther and traded in the same manner as commodities such as corn grain. Although advanced preprocessing operations at depots will require additional energy and add cost, active quality controls—such as drying and blending—will significantly reduce or eliminate dockage fees. This system should also eliminate the need for the supply buffer added in the SCM simulations of near-term systems to account for the additional feedstock contracts that biorefineries must secure to reduce the risk of feedstock supply shortages.

In the SCM analysis of long-term feedstock supply systems, biorefineries are designed to accept any pelleted feedstock. Recognizing that the chemical natures of some feedstocks are better suited for particular conversion processes, this analysis allows herbaceous feedstocks (stover, switchgrass, miscanthus, and sorghum) to be blended together for biorefineries with biochemical conversion processes, and woody feedstocks to be blended for thermochemical biorefineries. This is oversimplified, as some feedstocks, such as miscanthus, are suitable for both biochemical and thermochemical conversion processes, and there may be conversion designs that call for blend-

[1] Steve Kelley, 2015, personal communication to Erin Webb, Oak Ridge National Laboratory. December 9, 2015.

Table 6.6 | Logistics and Transportation Cost Assumptions for Herbaceous Feedstocks Supplied to a Local Preprocessing Depot

Corn stover		Switchgrass	
Logistics costs ($/dry ton)			
Storage on farm	$3.92	Storage on farm	$3.92
Loading/unloading truck	$3.24	Loading/unloading truck	$3.24
Dockage, moisture	$3.36	Dockage, moisture	$3.36
Total	**$10.52**	**Total**	**$10.52**
Biomass sorghum		**Miscanthus**	
Logistics costs ($/dry ton)			
Module building	$8.29	Storage on farm	$3.92
Storage	$3.92	Loading/unloading truck	$3.24
Loading/unloading truck	$7.17	Dockage, moisture	$3.36
Dockage, moisture	$6.72	**Total**	**$10.52**
Total	**$26.10**		
Transportation costs			
Time cost ($/dry ton/hour)			$3.83
Distance cost, loaded ($/dry ton/mile)			$0.037
Distance cost, empty ($/dry ton/mile)			$0.027

Table 6.7 | Logistics and Transportation Cost Assumptions for Woody Feedstocks Supplied to a Local Preprocessing Depot

Short-rotation woody crops	
Logistics costs ($/dry ton)	
Handling	$3.25
Transportation costs	
Time cost ($/dry ton/hour)	$4.24
Distance cost, loaded ($/dry ton/mile)	$0.046
Distance cost, empty ($/dry ton/mile)	$0.028

Table 6.8 | Logistics and Transportation Cost Assumptions for Densifying Feedstocks at a Depot and Delivering to a Biorefinery

Corn stover/switchgrass/miscanthus		Biomass sorghum	
Logistics costs ($/dry ton)			
Grinding	$14.00	Grinding	$8.29
Drying	$6.27	Drying	$6.27
Densifying	$4.93	Densifying	$4.93
Handling	$2.13	Handling	$2.13
Storage at biorefinery	$0.47	Storage at biorefinery	$0.47
Total	**$27.80**	**Total**	**$22.09**
Whole tree chips/logging residues/ non-coppice/energy crops/waste		**Coppice woody energy crops**	
Logistics costs ($/dry ton)			
Hammer mill (second-stage grind)	$19.14	Drying	$6.27
Drying	$6.27	Densifying	$4.93
Densifying	$4.93	Handling	$2.13
Handling	$2.13	Storage at biorefinery	$0.47
Storage at biorefinery	$0.47	**Total**	**$13.80**
Total	**$32.94**		
Transportation costs			
Time cost ($/dry ton/hour)			$3.35
Distance cost, loaded ($/dry ton/mile)			$0.032
Distance cost, empty ($/dry ton/mile)			$0.022

ing herbaceous and woody feedstocks. Here, these groupings of herbaceous and woody feedstocks are based primarily on minimizing the cost of receiving equipment to handle either baled or chipped biomass at the depot.

6.3 Results and Discussion

A scenario analysis was conducted using the SCM to estimate the delivered costs of herbaceous feedstocks (biomass sorghum, corn stover, miscanthus, switchgrass, and yard trimmings) for a biochemical conversion refinery and woody feedstocks (whole tree chips, logging residues, short-rotation woody crops, urban wood waste, and construction and demolition waste) for a thermochemical conversion refinery using primarily conventional systems in the near term and primarily advanced systems in the long term. In the near-term scenario, bales and wood chips are delivered directly to the biorefinery with no active quality management along the supply chain. Each biorefinery is limited in the types of feedstocks it can accept; a dockage fee is applied to feedstocks that do not meet specifications for ash and for losses due to higher-than-desired moisture content. The long-term scenario includes regional depots for transforming baled biomass and wood chips into a stable, tradeable commodity suitable for long-distance transport.

Table 6.9 and figure 6.9 show the marginal delivered costs and annual quantities of select herbaceous and woody bioenergy feedstocks using the available resources (from chapters 3, 4, and 5) for the base case (1% annual yield increase for agricultural and woody energy crop resources) and a high-yield (3% annual yield increase) scenario. For the purposes here of a scenario analysis to approximate delivered costs, logistics costs are based on 2013 feedstock supply system state-of-technology assessments for near-term systems and 2017 targets for future, advanced systems.

This analysis projects that with the base-case yield scenario, near-term systems could deliver approximately 139 million tons at a marginal cost below the DOE $84 per ton cost target (2014$) while long-term systems supply 249 million tons. Here, marginal cost is defined as the additional cost of incorporating feedstock from an additional county. Including delivered costs up to $100 per ton, still considered to be economically feasible given the uncertainty in simulation results and the potential for reducing logistics costs with technology improvements, brings the quantity up to 194 (near term) and 465 (long term) million tons. Adding the biomass resources of chapters 2, 3, 4, and 5 not considered in this logistics analysis, the total quantity of available feedstock increases to 710 and 981 million tons in the near and long term, respectively. Achieving the higher-yield scenario increases future availability to 742 million tons coming in below $100 per ton.

It may also be helpful to consider not only the marginal delivered costs, but also the quantity weighted running average as shown in figure 6.10 and table 6.10. The quantity weighted average provides an estimate of feedstock costs across all regions. Considering the quantity weighted average cost, 217 and 467 million tons are available at the DOE programmatic target of $84 per ton in the base-case scenario in 2022 and 2040, respectively. In the long-term high-yield scenario, total feedstock quantities less than $84 per ton increase to 825 million tons.

Figures 6.11, 6.12, and 6.13 summarize the quantities of feedstocks delivered to the reactor throat at less than $84 per ton, quantities delivered at between $84 and $100 per ton, and the portion available at the roadside that is unused. Unused portions are those that would be delivered at a cost greater than $100 per ton, are lost along the supply system because of biological degradation or mechanical losses, or are part of the overcontracting buffer included in near-term systems to mitigate supply variability. These diagrams also show the portions of each feedstock type considered that fall in these three delivered categories. In the near-term scenario (fig. 6.11), corn stover and forest resources are the only feedstocks that meet delivered cost targets. This is to be expected considering that dedicated energy crops (e.g., switchgrass, miscanthus, willow) are not planted in this analysis until 2019. Given the single-feedstock constraint imposed on near-term supply systems in this analysis, spatial density of dedicated energy crops in the near term leads to longer transport distances. In reality, energy crop plantings will be strategically clustered to reduce transport distance, a factor not accounted for here. In time, as production of these feedstocks expands, so does their contribution to the feedstocks that meet delivered cost targets, as shown in figure 6.12 for 2040. Their impact increases even more if higher yields can be achieved (fig. 6.13).

Table 6.9 | Feedstocks Available at Marginal Roadside Cost and Delivered Costs of $84 and $100 per Ton

	Herbaceous[a]		Woody[b]		Total	
	Near term	Long term	Near term	Long term	Near term	Long term
Base-case yield scenario (million tons)						
Roadside at <u><</u>$60	184	497	126	182	310	679
Delivered <u><</u>$84	51	198	88	52	139	249
Delivered <u><</u>$100	99	367	95	98	194	465
Unused[c]	85	130	31	84	116	214
High-yield scenario (million tons)[d]						
Roadside at <u><</u>$60	N/A	754	N/A	232	N/A	985
Delivered <u><</u>$84		419		109		528
Delivered <u><</u>$100		588		154		742
Unused[c]		166		77		243

Note: Including resources not accounted for in this delivered cost analysis brings the total available annual feedstock supply to more than one billion tons.

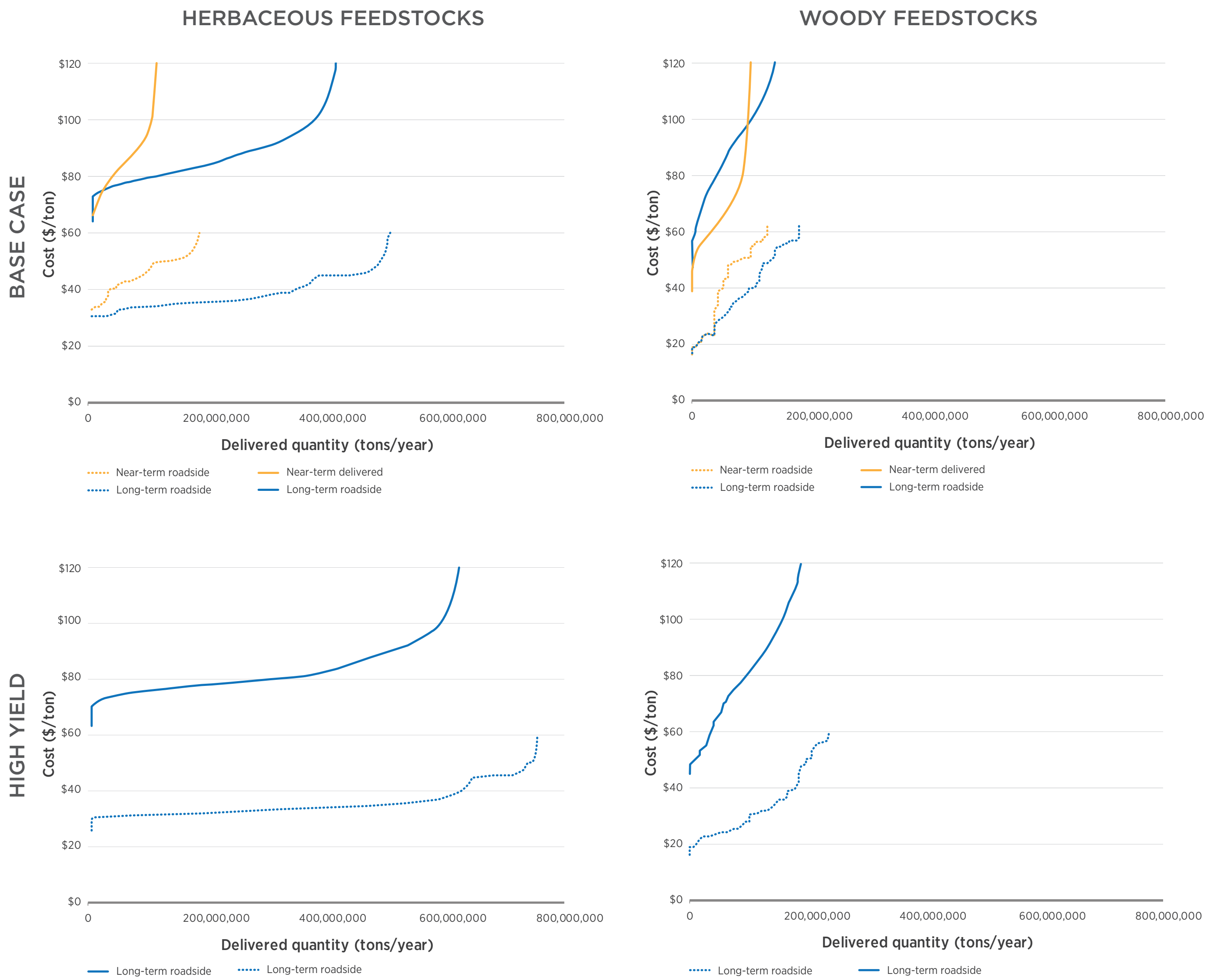
[a]Biomass sorghum, corn stover, miscanthus, switchgrass, and yard trimmings.

[b]Whole trees, logging residues, woody portions of C&D and MSW, and woody energy crops.

[c]Unused resources are those delivered at greater than $100 per ton, lost along the supply chain, or part of the overcontracting buffer included in the near-term systems to mitigate supply risk.

[d]A high-yield scenario was not considered for near-term resources, as there would be only minimal impact within such a short time frame.

Figure 6.9 | Marginal costs ($/dry ton) of select herbaceous (biomass sorghum, corn stover, miscanthus, switchgrass, and yard trimmings) and woody (whole trees, logging residues, woody portions of C&D and MSW, and woody energy crops) feedstocks at the roadside and delivered to the reactor throat



Note: Currently used resources from agriculture and forestry (chapter 2) and agricultural wastes (chapter 5) totaling 516 million tons for the base yield case (567 for high yield) are not included in this analysis.

Figure 6.10 | Marginal and weighted average costs ($/dry ton) of select herbaceous and woody feedstocks at the roadside and delivered to the reactor throat in the near and long term for a base yield scenario

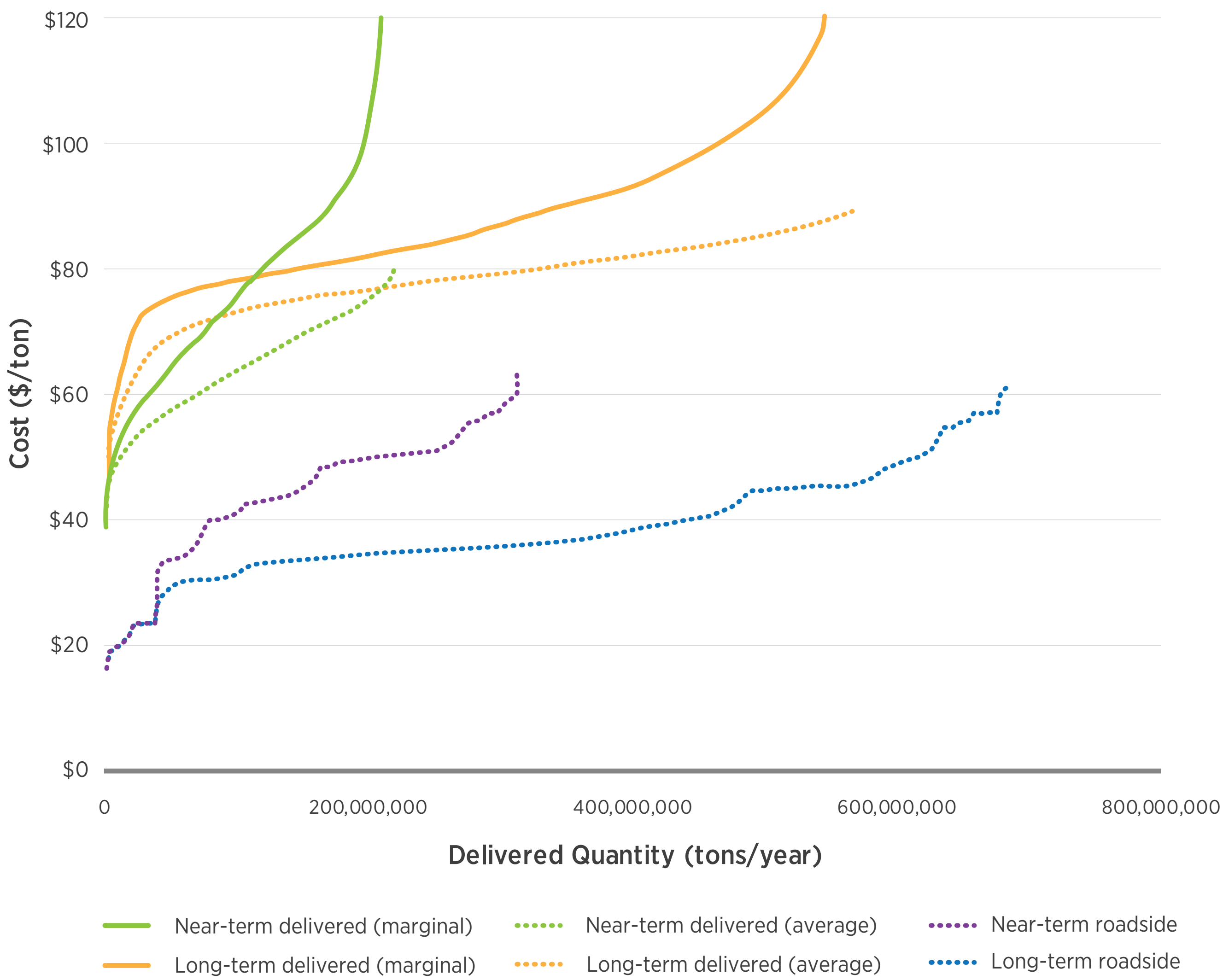
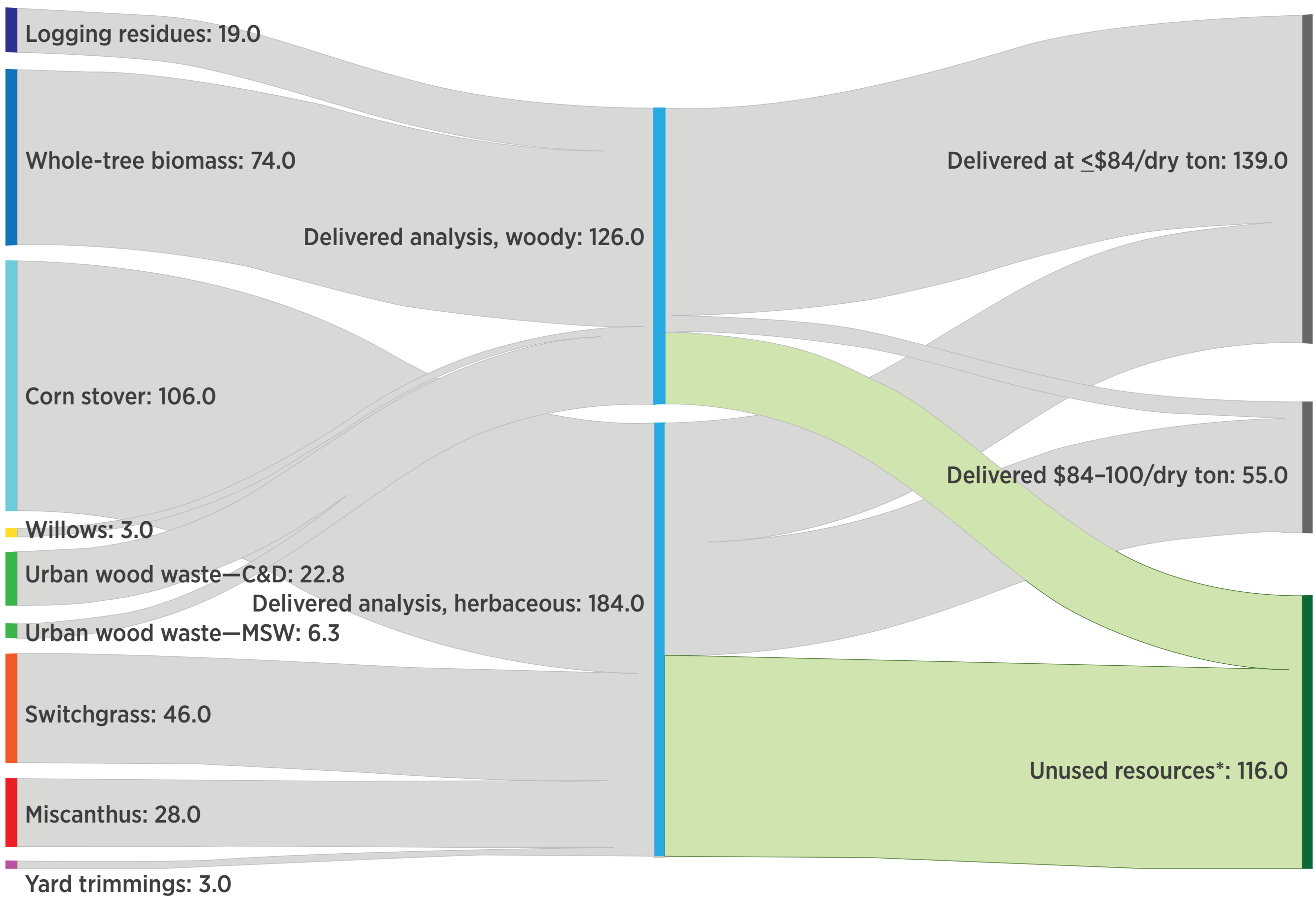


Table 6.10 | Total Feedstocks Available at Average Roadside Cost and Delivered Costs of $84 and $100 per Ton

	Near term	Long term
Base-case yield scenario (million tons)		
Roadside at ≤$60	310	679
Delivered ≤$84	217[a]	467
Delivered ≤$100	217	564
Unused	93	114
High-yield scenario (million tons)		
Roadside at ≤$60	N/A	985
Delivered ≤$84		825
Delivered ≤$100		825
Unused		160

[a]Near-term availability of feedstocks delivered at less than $84/ton diverges from DOE targets as (1) previous analyses were based on *BT2* roadside availability assessments and (2) this analysis does not include all biomass sources.

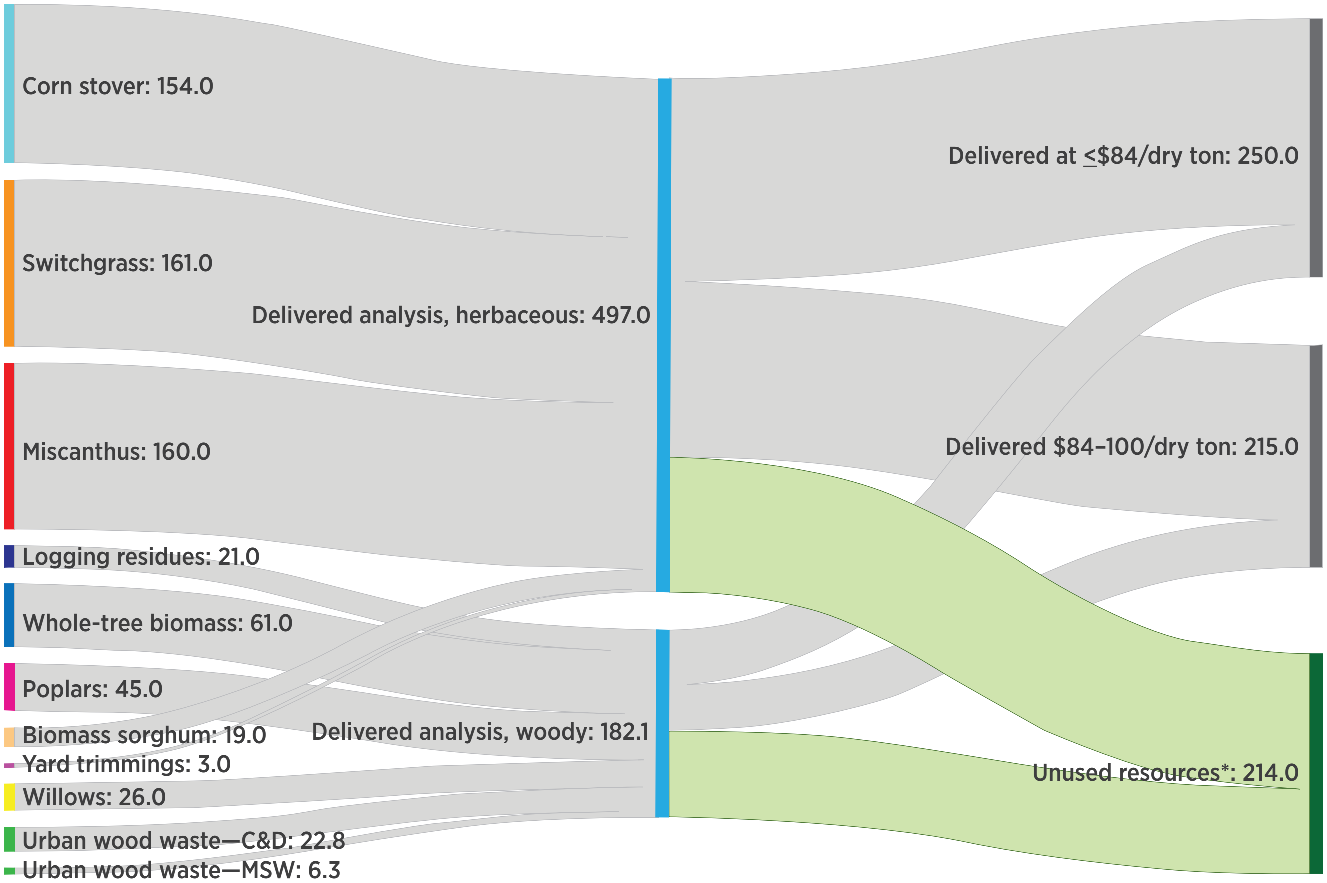
Figure 6.11 | Quantities (million tons) of select herbaceous and woody feedstocks delivered at less than $84 per ton, less than $100 per ton, and unused in a near-term scenario[2]



Note: Unused resources are those that are delivered at greater than $100 per ton, lost along the supply chain, or part of the over-contracting buffer included in the near-term systems to mitigate supply risk.

[2] Interactive visualization: https://bioenergykdf.net/billionton2016/6/3/bc-2022/sankey

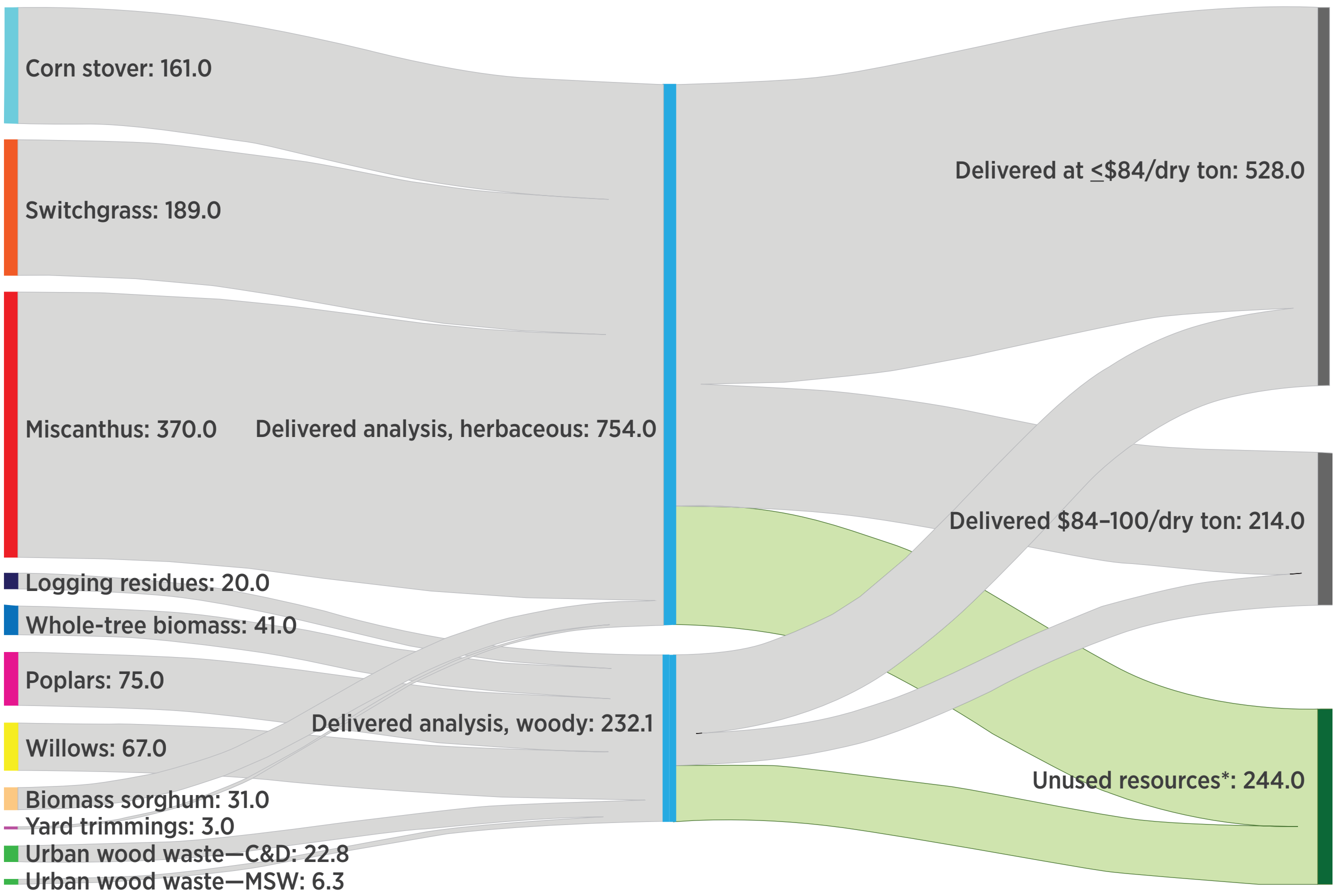
Figure 6.12 | Quantities (million tons) of select herbaceous and woody feedstocks delivered at less than $84 per ton, less than $100 per ton, and unused in the long-term in a base-case yield scenario[3]



Note: Unused resources are those that are delivered at greater than $100 per ton, lost along the supply chain, or part of the over-contracting buffer included in the near-term conventional systems to mitigate supply risk.

[3] Interactive visualizations: https://bioenergykdf.net/billionton2016/6/3/bc-2040/sankey

Figure 6.13 | Quantities (million tons) of select herbaceous and woody feedstocks delivered at less than $84 per ton, less than $100 per ton, and unused in the long term in a high-yield scenario



Note: Unused resources are those that are delivered at greater than $100 per ton, lost along the supply chain, or part of the over-contracting buffer included in the near-term systems to mitigate supply risk.

6.4 Summary and Future Research

Based on previous research and discussions with industry stakeholders, it is assumed that future feedstock supply systems will evolve to include advanced supply systems capable of transforming raw biomass into a tradeable commodity. Building on experiences currently being gained with conventional feedstock supply systems for pioneer biorefineries, further research to incorporate advanced depot-based preprocessing technologies will allow mobilization of more of the projected resource base. Ongoing advances in harvest operations to increase efficiency and capacity, better manage moisture, and minimize ash contamination will continue to reduce costs and provide higher-quality feedstocks. In the proposed system, feedstocks will be delivered to a regional processing facility where they will be transformed to multiple intermediate products for conversion to biofuel, biopower, or bioproducts. While these advanced preprocessing steps do increase cost and energy requirements, it is expected that these costs would be outweighed by the value added in improving quality and reducing risk.

In a near-term supply system scenario considered here, for a $60/ton offered price at the roadside, 217 million tons of biomass could be available at a delivered cost ≤$84/ton. In a long-term scenario, increasing yields, additional feedstocks, and improved supply systems increase this delivered quantity meeting cost targets to 467 and 825 million tons per year under the base-case and high-yield scenarios, respectively. It is worth noting that the delivered costs are simulated costs using an economic-engineering approach; they are not prices expected to be paid by biorefineries, as they do not account for profit beyond the roadside, transaction costs, or other business costs.

Future research to better represent and analyze feedstock supply systems will involve the following:

- Quantifying costs of risk and quality
- Quantifying the economic benefits that may be achieved through improved supply reliability, quality, and handling characteristics of advanced logistics systems
- Accounting for regional variation in moisture content at time of harvest on logistics cost estimates
- Adding rail as a transportation option in the SCM from depot to biorefinery.[4]

Future research to reduce the delivered costs of biomass feedstocks is also planned in the following areas:

- 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
- Further improvements in harvest efficiency and cost to increase the profitability of producers and encourage higher rates of energy crop production.

Expansion of biomass-based industries will be enabled, in part, by successful evolution across all of the feedstock supply system to better address risk and quality challenges. For simplicity, this analysis considered conventional and advanced supply systems independently. However, future analysis should consider industry evolution and how adopting advanced systems can enable industry expansion by creating favorable markets for feedstock production where conditions are unfavorable (e.g., low feedstock density, high risk of feedstock shortages, high feedstock variability).

[4] Interactive tools for exploring the SCM model results are at bioenergykdf.net/billionton2016/6/1/tableau and bioenergykdf.net/billionton2016/6/2/tableau.

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07 | Microalgae

7.1 Introduction

Algae can be single-celled or filamentous bacteria, or they can be single-celled or multicellular eukaryotes. Algae include microalgae, macroalgae (seaweeds), and cyanobacteria (historically known as blue-green algae). They typically live in aquatic environments and are capable of photosynthesis, although this is not always the case. In this chapter, we model only the cultivation of microalgae and define them as photosynthetic organisms that use sunlight and nutrients (CO_2, nitrogen, phosphorus, and other elements) to create biomass. Algal biomass contains lipids, proteins, and carbohydrates that, in turn, can be converted and upgraded to a variety of biogas and biofuel end products. These end products include but are not limited to hydrogen, methane, renewable diesel, jet fuel, and ethanol. Owing to their diverse characteristics, the type and strain of algae cultivated will ultimately affect every step of the algal biofuels supply chain.

Algae are an attractive feedstock for many locations in the United States because of their high biomass yield and lipid content per unit of area per unit of time. Depending on the strain, algae can be grown using fresh, saline, and/or brackish media from a variety of "clean" surface freshwater sources, groundwater, or seawater; additionally, they can grow in water from second-use sources such as treated industrial wastewater; municipal, agricultural, and/or aquaculture wastewater; or produced water generated from oil and gas drilling operations. Microalgae require ammonia and/or nitrates, phosphates, trace metals (i.e., iron, manganese, zinc), and CO_2 as nutrients and have the potential to provide beneficial use of waste streams and provide significant co-benefits to municipalities, industry, and the environment. Research and development on algal biofuels, moving toward commercial applications, is ongoing in states including Hawaii, California, New Mexico, Arizona, Florida, Texas, and Iowa.

Depending on conversion and upgrading pathways, residual biomass can be used for high-value coproducts such as livestock and aquaculture feed, for biofertilizers. or as recycled nutrients that are processed and reintroduced to the cultivation system. Until now, more than 90% of all algae production globally has been used for nutritional products. A rough estimate of total biomass production is 15,000 tons/year, of which about two-thirds is *Spirulina*, one-fourth is *Chlorella*, and the rest is *Duniella* and *Haematococcus* (Benemann 2013; Benemann 2016).

7.1.1 Goals of Analysis

As is the case for terrestrial feedstocks, important resource analysis questions for algae include not only how much of the crop may be available but also what price might be needed to procure that supply. Identifying resource co-location opportunities for algal biofuel facilities has the potential to reduce costs, utilize waste resources, and focus attention on appropriate technologies and locations for commercialization.

This chapter provides an estimate of biomass potential from open-pond production at given minimum selling prices. This is not a projection of actual measured biomass or a simulation of commercial projects. Biomass potential is estimated based on 30 years of hourly local climate and strain-specific biophysical characteristics using the Biomass Assessment Tool (BAT) (Wigmosta et al. 2011), assuming sufficient available nutrients (including CO_2).

The economic availability of biomass resources is influenced by variables including but not limited to biomass market development, land values, rate of adoption, and the profitability of alternative land uses (see text box 7.1). For example, in chapter 5, the economic availability of switchgrass is quantified by assessing the potential profitability of switchgrass production compared with other crop alternatives from the farmer's perspective. Switchgrass is assumed to be economically available if results suggest it is the most profitable crop option. Lacking a comparable framework to evaluate the opportunity cost of land that could be allocated to algae production, we use nutrient co-locating strategies as a proxy to quantify the most likely locations and quantities of algae resource production. These most likely locations may well change in the future, as new technologies determine the least-cost algae production methods.

Exogenous CO_2 is a requirement for viable commercial production of algal biofuels and one of the major costs of production (Campbell, Beer, and Batten 2011, Rogers et al. 2014). As a consequence, a better understanding of the costs associated with transport and delivery of CO_2 is needed (Davis et al. 2014, Quinn et al. 2013).

The goal of this chapter is to estimate the site-specific and national economic availability of algae biomass under co-location scenarios, (i.e., locating algal biomass production with coal-fired electric gener-

Text Box 7.1 | Algae Resource Analysis

A limited number of studies have analyzed the potential supply of algae biomass and biofuel in different geographic regions in the United States.

- Benemann et al. (1982); Vigon et al. (1982); Maxwell, Folger, and Hogg (1985); and Lundquist et al. (2010) provided a foundational basis for later resource assessment works, defining general criteria and offering more detailed analyses for the state of California.
- Wigmosta et al. (2011) investigated the potential national U.S. supply of algal biofuels produced from open-pond facilities while optimizing production on the basis of water use efficiency.
- Biofuel potential from microalgae cultivated in photobioreactors (PBRs) (i.e., closed reactors providing a controlled environment) in regions of the United States was estimated by Quinn et al. (2012) using *Nannochloropsis*. Quinn et al. (2013) also conducted resource sensitivity analyses related to land and CO_2 resource assumptions for the conterminous United States (CONUS) on a state-by-state basis.
- Pate (2013) reviewed current and future resource demand challenges associated with commercial scale-up of algal biofuel production in the United States. ANL, NREL, and PNNL (2012) reconciled assumptions related to algae biomass production from techno-economic analysis and life-cycle analysis models, creating a performance baseline and prioritizing the most favorable group of sites that would support a production target of 5 billion gallons per year of renewable diesel. This work was further evaluated in Davis et al. (2014).
- Bennett, Turn, and Chan (2014) identified priority lands available for open-pond algae production in Hawaii and estimated yields for the state.
- Orfield, Keoleian, and Love (2014) evaluated potential biomass and associated lipid yields in the CONUS, considering co-location with CO_2 flue gas and wastewater sources. Several scenarios dictated by available resource trade-offs were used to estimate biomass and associated fuel production by multiple processing pathways in the CONUS (Venteris, Skaggs et al. 2014a).
- Moody, McGinty, and Quinn (2014) estimated global biofuel potential from microalgae in PBRs on non-arable land. Langholtz et al. (2016) assessed potential land competition between algal and terrestrial feedstocks for pastureland in the United States and found little competition for production sites.

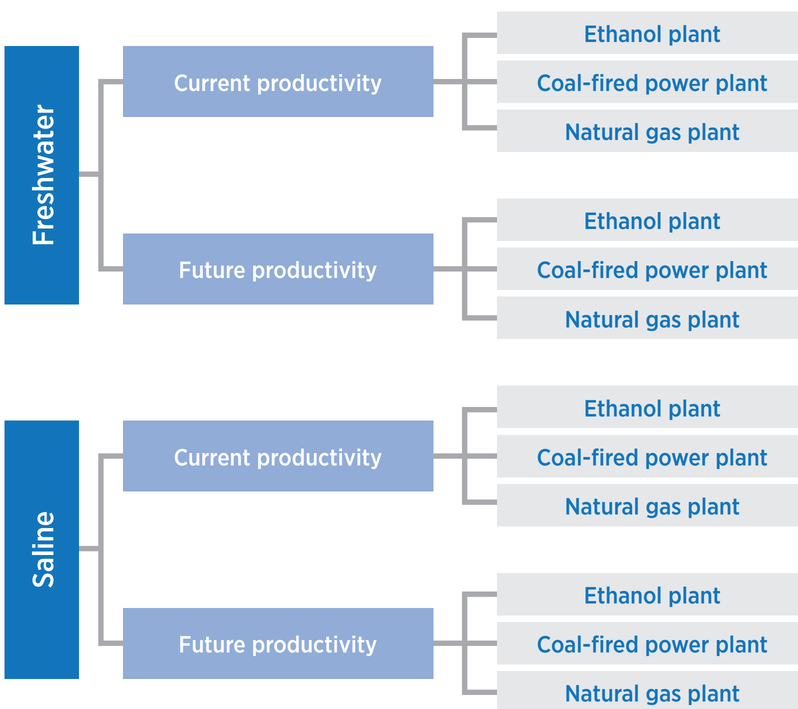
ating units [EGUs], natural gas EGUs, or ethanol production facilities that produce waste CO_2). We evaluate the potential economic benefit of the three CO_2 co-location scenarios with a defined cost limit of $40/ton of CO_2 to avoid exceeding commercial supply costs. In combination with the CO_2 co-location sources, a current productivity rate scenario and a future high-productivity scenario are presented for both freshwater and saline water algae strains. For saline scenarios, both fully lined ponds and minimally lined ponds are considered because of the substantial costs of pond liners and uncertainty as to where they are needed. Key variables in the algae analyses are depicted in figure 7.1.

This chapter provides the first estimate of the national algae biomass supply available for fuel in a billion-ton biomass supply and price report. The analysis of potential supply moves toward DOE's goal of modeling a sustainable supply of 1 million metric tonnes (1.1 million tons) of ash-free dry weight (AFDW) cultivated algal biomass by 2017 and 20 million metric tonnes (22 million tons) by 2022. However, as in the other chapters, the potential biomass reported has not been produced; and even for future projections, a viable market would be needed to achieve the potential.

7.2 Scope of Analysis

The scope of the chapter focuses on microalgae. It does not reflect the full range of algal biomass production systems, but rather, the systems for which we have sufficient engineering and cost data. We consider only the well-established open-pond/raceway production systems in the current analysis, largely because costs of PBRs have not been well quantified in the literature, and there are many different types of PBR systems (e.g., flat plate systems, hanging bags, vertical tubes, horizontal tubes).

Figure 7.1 | Key variables in the algae analyses



Representative freshwater and saline algal strains, *Chlorella sorokiniana* (DOE strain 1412) and *Nannochloropsis salina*, respectively, were selected because these strains offer good growth potential in outdoor ponds under varying environmental conditions, are well studied, and have been parameterized in several different biomass growth models; see for example, NAABB (2010); Bechet et al. (2011); Huesemann et al. (2013); Dong et al. (2014); Orfield, Keoleian, and Love (2014); Venteris, Wigmosta, et al. (2014); and Huesemann et al. (2016). Heterotrophic production pathways are not considered. The analysis incorporates direct consideration of water resource availability for both freshwater—following the DOE algae model harmonization study described in ANL, NREL, and PNNL (2012)—and brackish/saline water within a salinity range of 2–70 practical salinity units (PSU).

Co-location strategies were investigated for the potential use of waste CO_2 from natural gas and coal EGUs and ethanol production plants. The analysis required (1) site-specific spatial routing analysis and biomass production estimates, (2) site-specific techno-economics to estimate the cost of delivering waste CO_2 to the algae facility, (3) aggregation to county-level production and cost estimates, and (4) the comparative cost of algae biomass production without co-located resources. The chapter considers productivity and cost estimates for 2014 and a non-specific future year.

The chapter focuses on fuel pathways that require use of the lipid fraction or whole algae and that can result in a variety of fuels and coproducts; however, non-destructive algae pathways such as ethanol secretion are not currently considered. The biomass endpoint for the resource analysis and supply curves is a 20 wt % solids content that is agnostic to the eventual fuel pathway. With respect to the biofuel supply chain, this endpoint is beyond the production "pondgate" (analogous to the farmgate in previous chapters); it includes dewatering processes and costs and allows an optimum starting concentration for downstream conversion processes such as algal lipid extraction and upgrading or whole algae hydrothermal liquefaction and the production of coproducts. Low-cost drying strategies for stabilizing wet algae for storage and transport are also of interest for further development after initial concentration to 20% solids content. The analysis endpoint is consistent with the recent cultivation design case report that was used to estimate minimum selling prices for algae biomass in the analyses in this chapter (Davis et al. 2016).

The following are some of the questions that are addressed:

- Can waste CO_2 be transported cost-effectively, and under what conditions are the greatest cost savings projected?
- How much suitable land is available near CO_2 sources?
- What are the production potential and associated costs from freshwater and saline water sources?
- What effect does increased future productivity have on potential biomass and minimum selling price estimates?
- Can existing CO_2 waste streams meet future productivity demands?

7.3 Algae Biomass Resource

7.3.1 Differences between Algae and Terrestrial Feedstocks and Biofuel Pathways

Earlier chapters focus on terrestrial bioenergy feedstocks (i.e., vascular plants that grow in soil). This chapter considers the production of biomass from microalgae and elements of the biofuel supply chain, which are well integrated with the production step.

Table 7.1 | Major Differences between Terrestrial and Algal Biomass Production Systems

	Algal biomass	Terrestrial biomass
Growth medium	Aqueous nutrient media	Soil
Water used	Freshwater, brackish, saline, or otherwise non-potable water	Rainwater
Resource requirements	CO_2, nitrogen, phosphorus, and other supplements such as iron, manganese, and zinc	Nitrogen, phosphorus, and other agricultural supplements (e.g., potassium and lime)
Infrastructure and equipment for production and harvesting	Pond liners, photobioreactors, paddlewheels, pumps, and others	Farm equipment
Harvesting	Frequent (i.e., daily, weekly, or monthly)	Annual or less frequently than annual, depending on maturity
Storage duration	Short-term (days) unless dried	Long-term (months)
Dewatering	Low solid concentration in water for some applications	Relatively dry
Location of biorefinery	Onsite (except when biomass is dried) with offsite potential	Usually offsite
Recycling of water and nutrients during production	Yes, potential for ~90% nutrient recycle	No, nutrient losses through erosion and runoff

Some of the important differences between algae and terrestrial feedstocks are described in table 7.1. All of these differences affect estimates of the potential supply, costs, and geography of algal biofuel production.

Algal feedstocks discussed in this chapter are unicellular aquatic species cultivated in engineered open ponds. Hundreds of thousands of different natural algal strains have adapted to local environmental conditions and can flourish across a massive range of diverse conditions. Tens of thousands of these species have been characterized and cultured (see for example ncma.bigelow.org and utex.org). Some species grow in media containing freshwater (e.g., BG-11 medium at a pH of 7.0 containing NO_3 and PO_4) and others grow in brackish or saline- or hypersaline-based media from groundwater resources or seawater (e.g., pH of 7.5 in f/2–Si medium at 35 PSU salinity, and pH of 7.5 containing NO_3 and PO_4) (Crowe et al. 2012, Huesemann et al. 2016). Exogenous CO_2 is required for viable commercial production of algal biofuels. Unlike in terrestrial crop production, water and nutrients can be recycled through the algal cultivation process.

Algae have some distinct advantages compared with terrestrial crops. Because algae are cultivated in engineered systems, they do not require arable lands and thus do not typically compete for land resources with cultivated agriculture. Also, the areal productivities of algae are substantially higher than those for terrestrial crops. The use of non-potable water from wastewater treatment facilities and brackish, saline, or hypersaline water from groundwater or seawater is also an option in some locations (Craggs et al. 2011). Co-location with wastewater resources is not considered.

In most algal biofuel systems, biomass is harvested much more frequently than are terrestrial crops; however, in contrast to long-term storage of terrestrial feedstocks, downstream processing of algae needs to be completed within days to prevent feedstock deterioration. Drying of the algae feedstock can overcome this storage limitation, but strategies need to be developed to reduce the costs associated with thermal drying. Because algae are highly responsive to temperature and light fluctuations, seasonal growth patterns are evident and impact downstream processing and design (Coleman et al. 2014; Huesemann et al. 2016). The combination of the seasonal variability of biomass production and the need for consistent volumes of feedstock supply are challenges for the design of downstream conversion equipment. Consider that most terrestrial biorefineries require a fixed feed rate over a full year to remain economically viable. The challenges can be partly alleviated by microalgae crop rotation, which is not considered here, as well as by feedstock blending.

Because most algal biofuel pathways are in an earlier state of commercialization than most terrestrial biofuel pathways, the production model parameters and results are more uncertain for algae than for terrestrial crops. For many pathways, coproducts may drive the economics of the production system.

7.3.2 Cultivation

Algae cultivation must account for aspects of strains selection, solar radiation, temperature, pond and/or growth medium design, and nutrient and CO_2 availability. Following is a description as applicable to open-pond production.

Photosynthesis and Algal Strains

Photoautotrophic microalgae grow by converting solar energy to chemical storage in the form of biomass via photosynthesis. With adequate nutrients, the growth rate of microalgae is predominantly influenced by the intensity of specific wavelengths of incident solar radiation and the corresponding water temperature of the growth media. In particular, solar radiation in the form of photosynthetically active radiation (which operates at the 0.4–0.7 µm portion of the electromagnetic spectrum) provides available light for photosynthesis; whereas shortwave radiation, operating at 0.285–2.8 µm, has a dominant influence on heating water within the open cultivation ponds and closed PBRs. For any photosynthesizing plant, available light intensity below or above the optimum range causes a decline in biomass productivity (Bechet, Shilton, and Benoit 2013, Rubio et al. 2003, Weyer et al. 2010). Photosynthetically active radiation is limited by normal diurnal and seasonal fluctuations as a function of the sun's changing zenith angle throughout the year. Consequently, algae cultivation sites at lower latitudes experience less change in solar insolation (outside of monsoonal zones) and will generally have a more consistent daily availability of photosynthetically active radiation due to a limited change in solar insolation. Cloud cover and storms have a significant impact on available photosynthetically active radiation; however, photosynthesis still occurs at a reduced rate using available diffuse radiation (Churkina and Running 1998). Although areas within the United States, such as the Southwest, receive high percentages of available and uninhibited photosynthetically active radiation, the lack of cloud cover and low relative humidity can also present issues with thermal energy loss from open ponds at night due to low nighttime temperatures. Thus, from a climate-resource perspective, areas where strain-specific optimal temperature ranges exist, and have limited variability within the diurnal and seasonal air temperature regimes, tend to be more suitable locations for growth.

The water temperature within shallow microalgae cultivation ponds is bounded by the principle of conservation of energy to a fluid volume and is thus influenced by pond water depth; water density (which varies by level of salinity); the specific heat of water; and net surface heat-flux, including net solar short-wave radiation, downward atmospheric longwave radiation, longwave back radiation, and heat flux due to evaporation and conduction. All of these are driven by meteorological variables, including air temperature, wind, and relative humidity. Thus, open-pond systems are subject to dominant control from environmental conditions, barring engineered solutions such as the use of industrial waste heat during cool-temperature months or the introduction of cool makeup water during warm-temperature months. The water temperature in an open pond will be impacted by large diurnal swings in air temperature and the degree of evaporative cooling. Because of the thermal properties of water, the water temperature will respond to air temperatures with varying degrees of latency and dampening.

Optimal media temperatures vary among types and strains of microalgae (Christi 2007, Pate 2013, Sheehan et al. 1998). Many microalgae can tolerate temperatures down to 15°C below their optimal, but exceeding the optimal temperature range by 2°–4°C can cause total culture loss (Mata, Martins, and Caetano 2010). Photosynthetic reactions become limiting outside the optimal temperature range and, if the minimum temperature is not reached or maximum temperature is exceeded, the suboptimal temperatures will more than likely lead to reduced cell viability. Understanding the basic growth characteristics of specific strains of microalgae is fundamental to determining what and where to grow to maximize biomass production potential.

Open-Pond Production System

Production in open ponds, generally taking the form of raceways (fig. 7.2) or circular ponds, is well established and represents the cultivation design of choice for the vast majority of commercial algae biomass production globally. A major incentive for the use of open ponds, and in particular mixed raceway ponds, is that they are less expensive to build, scale up, and operate than their PBR counterparts (Davis, Aden, and Pienkos 2011, Amer, Adhikari, and Pellegrino 2011, Sun et al. 2011). In addition, open ponds have demonstrated commercial success in scale-up, e.g., several hectares for individual ponds. For example, the Hutt Lagoon in western Australia contains ~7,000 acres of food-grade algae, and EarthRise Nutritionals exemplifies sustainable large-scale operation in California's Imperial Valley. However, CO_2 loss is generally higher from algal ponds than from PBRs. It is not uncommon for both research and commercial cultivation systems to include a hybrid system, where single or multiple-scale PBR systems are used for algae culture scale-up and inoculation to the open pond.

Figure 7.2 | Traditional open-pond raceway design used in the current analysis

The selection of algal strains for use in open ponds must be considered carefully to meet location-specific primary environmental conditions (light and temperature) and suitability for survival in the local pond water ecosystem. Local, natural strains have an advantage, as they have adapted to predators and diseases found in the locale. Strains may also be rotated to adapt to seasonal environmental conditions to help ensure the highest possible production performance.

For open ponds, a significant capital cost is pond construction, particularly pond liners, which can comprise 20%–35% of the capital costs (Abodeely et al. 2014, Davis et al. 2012, Coleman et al. 2014). For freshwater systems, eliminating pond liners through construction with clay soil compaction or biological sealants would reduce capital costs and improve profitability, but it would be dependent upon local and state regulations and potential water quality effects (Venteris, McBride, et al. 2014). For some saline water systems, soil plugging approaches without plastic liners may not be permissible under local and state environmental regulations; however, there are existing cases in which saline aquaculture facilities were repurposed for microalgae production and do not have liner requirements.

Resource Requirements

Land and water are the primary resources needed to grow algae. However, to enhance algae productivities over those observed in natural environments, extra quantities of CO_2, nitrogen, and phosphorus are provided. Some nutrients can be recycled, depending on the downstream process method, but "fresh" nutrients also need to be procured. If nutrients were available as a result of co-locating with waste stream resources near the algae facility, the purchase of consumables for biofuel production could be reduced. The cost reduction in biofuel production will largely depend on the nutrient; nutrient source; required processing for utilization; and distance, method, and subsequent expense for transportation.

7.3.3 Logistics

In chapter 6, the quantified potential biomass supply is the amount delivered to the refinery, which is an advance over previous billion-ton reports. The advanced logistics operations for supply of terrestrial feedstocks consist of transporting biomass to intermediate preprocessing centers (depots) where the biomass is modified to meet the biorefinery specifications. At the depot, the biomass may have to be dried to become stable in storage and densified for economical transport and storage.

In the context of this chapter, we define "logistics" as all operations to dewater algae and recover it from its growth media in open ponds. A wide range of methods and equipment have been proposed and tested for collecting and thickening microalgae, with the range of output concentrations and costs depending on the technology. For example, at the beginning of the harvest, the dispersed small particles of microalgae at a concentration of 0.5 g/L (0.05% dry matter content) are removed through sedimentation, filtration, and centrifugation. Then algae are subjected to various additional pathway steps, including possible extraction and conversion processes to make fuel and coproducts (Laurens et al. 2015). Considerations of logistical operations become important, especially when the production of higher-value coproducts like animal feed becomes an integral part of biofuels for algae.

Post-production processes for algae can include harvesting, dewatering, drying, densification (e.g., granulation), storage, and transport, although the exact processes depend on the conversion technology, the location of the biorefinery, and cost (Chen et al. 2009). Drying and densification operations for large-scale volumes of algae biomass have not been developed and costed yet, and conventional heated air-drying methods could make GHG and energy balances more challenging. In this chapter, the endpoint for which we evaluate minimum selling prices is dewatering to 20 wt % solids, which makes the biomass available for potential extraction, conversion, and transport to the biorefinery. Some conversion processes, such as pyrolysis, would require additional dewatering (Bennion et al. 2015).

7.3.4 Conversion to Fuel

Algae can be processed into a variety of fuel products. A strong emphasis has been placed on developing drop-in fuels for major liquid transportation fuel sectors, including diesel (biodiesel or renewable diesel/green diesel[1]) and kerosene (jet fuel/aviation biofuel), although processes have also been developed for the production of ethanol, methane gas, butanol (biobutanol; higher energy density than ethanol), gasoline (biogasoline), hydrogen (biohydrogen), crude oil, and syngas.

Likely conversion options include lipid extraction (in which "algae lipid upgrading" may enable sugars and potentially proteins to be converted to other fuel products), hydrothermal liquefaction, catalytic hydrothermal gasification, and direct ethanol or hydrocarbon secretion. The ultimate conversion process has a significant impact on the production/resource co-location strategy, particularly the sources and demands for nutrients and CO_2 (Venteris, Skaggs, et al. 2014b). For example, if a lipid extraction pathway is the goal, anaerobic digestion or catalytic hydrothermal gasification could be used in the site design to recycle biomass for nutrients and generated methane, thus reducing the overall consumptive resource demands. Alternatively, the remaining biomass could be sold to a coproduct market, and no nutrient recycling would be possible. If hydrothermal liquefaction is the pathway, all of the biomass may be used—or coproduct compounds such as polysaccharides may be separated in a preparatory step (Chakraborty et al. 2012)—and anaerobic digestion is not included. For all pathways, the selected strain(s) is a critical factor to optimize for the intended pathway requirements (i.e., biomass production, lipid content).

One conversion process pertinent to algae that is different from terrestrial processes is the direct secretion of ethanol or other fuel products by live algae (Luo et al. 2010). This process is not currently evaluated in this study because few peer-reviewed publications on the topic exist, and no DOE techno-economic assessments or design case reports detail the process costs and production rate outcomes. Also, the billion-ton reports present biomass quantities, because they are related to the quantity of biofuel that can be produced. In ethanol secretion processes, the quantity of biomass may not be closely related to the amount of fuel: while there is turnover, each algae cell produces ethanol continuously without harvest until it dies. In future analyses, this process will receive more attention.

7.3.5 Coproducts

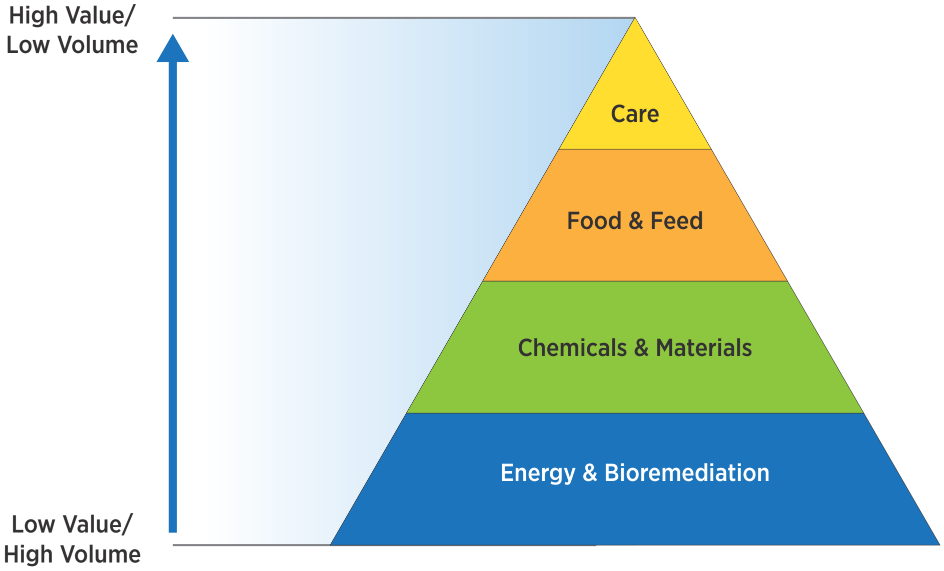
Coproducts are currently required for the commercial viability of most algal biofuel systems (Zhu 2015, NRC 2012). In the past year, some algal biofuel companies in the United States have announced an increasing focus on non-fuel products, with biofuels produced from remaining biomass. In an example from one company, 10% of the biomass drives 80%–90% of the product value, with biomass destined for fuel oils and feed making up the rest (Schultz 2013).

Example coproducts include nutraceuticals; defatted, high-protein livestock (swine and poultry) feed; aquaculture food; polyunsaturated fatty acids; and recombinant products such as astaxanthin (Austic et al. 2013, Brennan and Owende 2010, Kiron et al. 2012, NRC 2012). Except for animal feedstuffs, all of these potential coproducts have small volumes, with market saturation at hundreds to thousands of tons of biomass.

The coproducts with large commercial markets are animal feedstuffs (NRC 2012). In addition, algae biomass remaining after lipid extraction can be anaerobically digested and applied to land as a fertilizer (Frank et al. 2012), a use that may improve the energy balance more than does using it as animal feed (Sills et al. 2012).

[1] Biodiesel is a fuel consisting of mono-alkyl esters of long-chain fatty acids, also referred to as FAME (fatty acid methyl ester). Renewable diesel refers to biomass-derived diesel fuels that are not mono-alkyl esters.

Figure 7.3 | Value and volume pyramid for possible biofuel coproducts from microalgae; "Care" indicates personal care products



Source: Modified from van der Voort et al. (2015).

Figure 7.3 is a qualitative representation of the value and volume of products that can be obtained from algae. The lowest value and largest volume are associated with energy and environmental products. Bioremediation applications for wastewater treatment belong to this group as well. Personal care products, including pharmaceuticals, have the lowest volume but the highest value. Nutraceuticals from microalgae are classed as foods and include ingredients for animal feed. Bioplastics are grouped with chemicals.

7.4 Co-Location

Co-location strategies involve pairing an algae production system (e.g., open pond) with an existing industrial facility (e.g., EGU, ethanol plant, wastewater treatment plant) for the purpose of utilizing available waste products (e.g., CO_2, nutrients, process heat) to provide benefits to either or both co-located operations. Co-location of an algae facility with waste resources provides an opportunity to reduce the cost of those resources and potentially reduce the cost of the disposal or other disposition of the waste materials.

Carbon dioxide is a waste product from many industrial processes, each a potential source for inexpensive CO_2 for algae, especially where federal and state policies have put a policy restriction or price on carbon emissions. Waste CO_2 is also generated by ethanol, cement, and ammonia production, in addition to many refinery and other industrial chemical processes. Other nutrients (nitrogen, phosphorus) are generated in the waste processing from confined animal-feeding operations, dairies, and other farm operations, as well as in municipal wastewater treatment plants. These are potential sources of nutrients for algae that may be co-located with algae cultivation facilities.

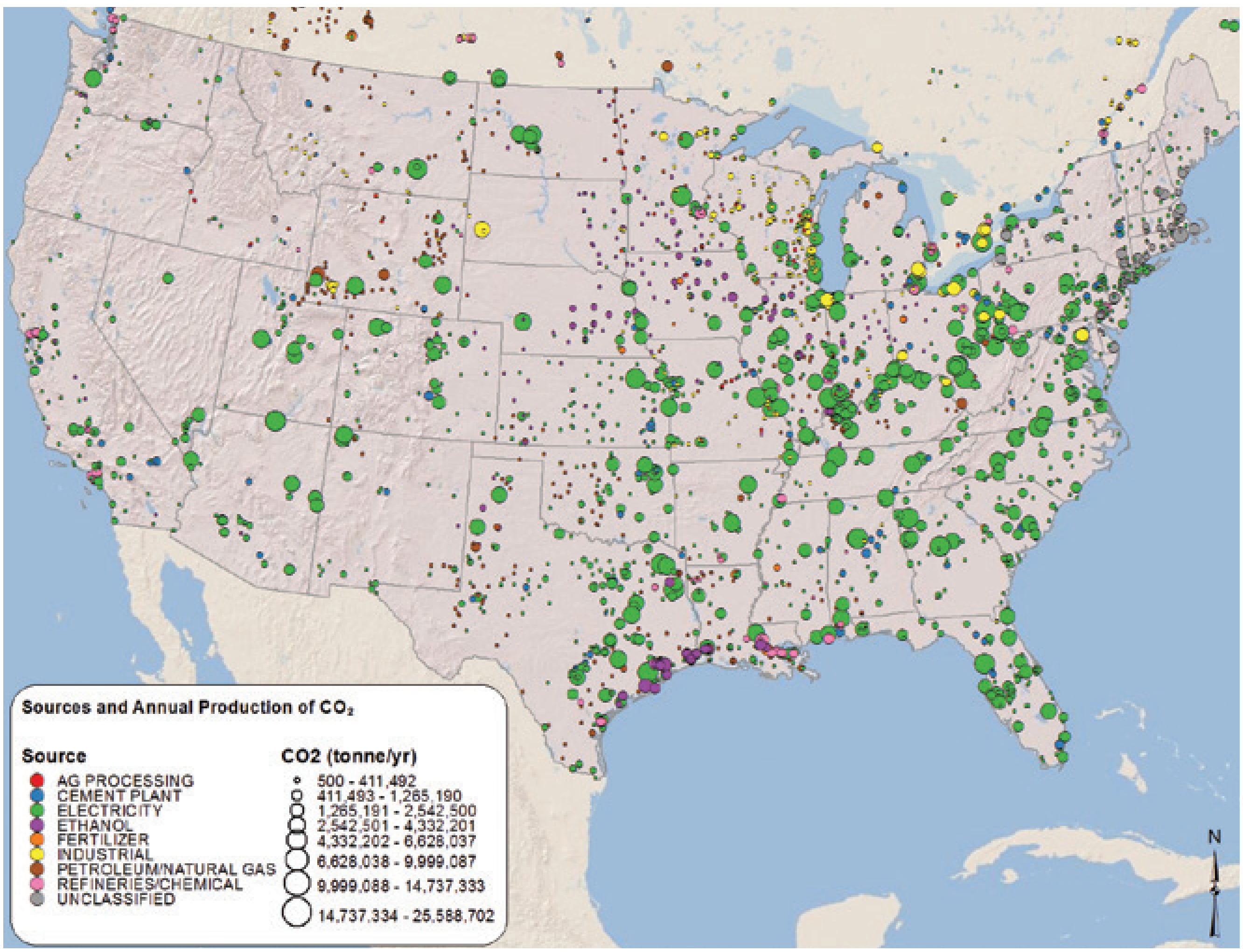
The United States currently emits 6.4 billion tons of CO_2 per year from all sources (point and non-point sources). More than 3.3 billion tons of these emissions are from point sources that can potentially be used for algal biomass production (fig. 7.4) (NATCARB 2015, Middleton et al. 2014). Generally speaking, with the total amount of waste CO_2 that is available, approximately 1.4 billion tons of algal biomass could be produced. However, these numbers are irrespective of the spatial relationships between the CO_2 point sources and the potential cultivation sites identified, and of the economic constraints of transport. In general, for algae cultivation operational expenses, CO_2 supply is a significant cost factor, contributing approximately 20%–25% of the costs. The co-location with point sources of waste CO_2 has been demonstrated in both research and commercial industry environments.

7.4.1 Transport and Purity of CO_2

The biggest constraint in CO_2 co-location is cost-effective delivery, which is limited by the concentration of gases other than CO_2 in the waste stream, which in turn, impacts the distance over which CO_2 can be transported. The purer the CO_2 stream, the less expensive is the transport system.

The most important distinction between sources is those that provide a nearly pure CO_2 stream (>95% CO_2) and those that provide CO_2 mixed with other

Figure 7.4 | General categories of CO_2 point-source emissions and associated total annual output for 2012–2013



Source: Data from NATCARB (2015) and Middleton et al. (2014).

gases (mainly N_2), typically the result of air combustion. When the waste stream is essentially pure CO_2, such as the emissions from ethanol (~99%), ammonia, or hydrogen production plants, delivery to the algae facility is similar to the simple purchase of CO_2 from an industrial supplier (Middleton et al. 2014). Distribution is handled similarly. Ethanol plant flue gas, containing a nearly pure stream of CO_2, is ideal for transport, in terms of volume, capital, and operating expenses.

When flue gas from an EGU is used, the composition of the gas is variable, and the CO_2 fraction may not be high enough to provide the enhanced productivity desired. For example, carbon-rich fuels such as coal produce a waste gas with a concentration of ~14% CO_2 (by volume), whereas natural gas EGUs produce a lower concentration of ~5% CO_2. In a dilute mixture, most of the gas being transported (N_2) is not valuable to the algae, but the pipes and compressors still need to be sized and costed to move the unwanted extra components. These diluents increase not only capital cost but also operating (electricity) costs. While CO_2 flue gas can be used directly (see for example, Wilson et al. (2014)), there are technologies available to strip CO_2 from lower-concentration CO_2 streams (e.g., amine scrubbers), allowing for CO_2 storage and making for more cost-effective transport.

Table 7.2 provides several CO_2 sources, their associated CO_2 concentrations, and total annual reported emissions. Note that under the EPA Greenhouse Gas Reporting Rule (74 FR 56260), only large facilities exceeding emissions of 25 kt of CO_2 or CO_2 equivalents (CO_2e) are reported. For this study, smaller CO_2 sources are also identified and considered for co-location (see section 7.5.4, CO_2 Co-Location Model).

7.4.2 Three Sources of CO_2

Three significant sources of waste CO_2 were selected, representing a range of purities and geographic distributions: natural gas EGUs, coal EGUs, and ethanol production facilities. These three classes of point-source CO_2 represent approximately 86.6% of CO_2 emissions in the CONUS and thus represent the major portion of the U.S. waste CO_2 supply. Table 7.3 provides the three sources of waste CO_2 considered in this study along with the assumed concentration, the

Table 7.2 | Sources of CO_2, Including Percent of CO_2 in Output Stream and Total National Emissions for Large Facilities

CO_2 source	Percent CO_2 in output stream	2013 U.S. CO_2 emissions (million tons)[a]
EGUs	4%–15%, depending on fuel	2,316
Cement plants	~24%	122
Fertilizer/ ammonia plants	~97%	28
Ethanol plants	>99%	19
Hydrogen plants	~99%	46
Refineries, chemical plants	Varies; as high as 99% for steam methane reformers	525

[a]From www.epa.gov/ghgreporting for sites > 25 kt/year CO_2 or CO_2e.

Table 7.3 | Sources of Point-Source CO_2, Concentrations, Total Output, Percentage Contribution, and Number of Individual Sites

CO_2 source	CO_2 concentration	Estimated annual output (million tons)	Total CONUS CO_2 (%)	Number of sites in CONUS
Ethanol	99	140.8	3.8	317
Coal EGU	14	2,677.3	72.2	1,339
Natural gas EGU	5	394.5	10.6	1,774

EGU = electric generating unit.

CONUS = Conterminous United States.

total CONUS annual CO_2 output (including smaller sites with <25 kt CO_2/year not reporting to the EPA Greenhouse Gas Reporting program), the fraction of total emissions, and total number of individual sites (NATCARB 2015; Middleton et al. 2014).

7.5 Approach and Assumptions

The overall approach to quantifying algae biomass supply is (1) developing engineering and cost estimates for co-location scenarios; (2) selecting priority land areas for co-location; (3) generating national, site-specific biophysically based production estimates; (4) developing spatially explicit transport pathways and incorporating available CO_2 supply, demand, and costs; and (5) generating estimates of minimum selling price as a function of supply. We also estimate the cost differential between co-location and a base case. The base case costs are primarily based on a process design case report for the production of algal biomass in open ponds (Davis et al. 2016). Both a current-technology productivity scenario (2014) and a future, high-productivity scenario are considered for algae strains *Chlorella sorokiniana* (freshwater) and *Nannochloropsis salina* (saline water). For saline scenarios, both fully lined ponds and minimally lined ponds are considered (see fig. 7.1).

7.5.1 Engineering Design and Transport Cost Analysis

A major portion of the engineering analysis focused on the cost of transporting co-located resources to identify locations where it was cost-effective to transport waste CO_2. Cost-effective designs were created with specific pipe sizes, parallel piping, compressors, and power requirements. The transportation analysis feeds into the spatial analysis of potential co-location sites.

The transport of gaseous CO_2 is modeled as compressible gas flow, with major component costs in the transport pipeline and compression system. The major factor determining the system design and sizing is the gas flow rate required for the assumed productivity of algae, and this in turn is determined by the fraction of CO_2 in the flue gas stream. The pipe and compressor system are sized for 1.25 times the CO_2 needed to supply algae, to account for much of the summertime peaking. Under the future, high-productivity scenario, a larger system is engineered to meet the increased CO_2 demand, compared with the present productivity scenario. Strain type and seasonal variability of biomass production play a significant role in engineering design and are recognized to have a site-specific response. The engineering assumptions used herein provide a reasonable estimation considering varying growing conditions across the CONUS. We assume that (1) an aboveground pipeline carries the gas from the emission source to the algae production facility; (2) there is no separation of the CO_2 from the flue gas; and (3) the gas flow rate depends on the pipe diameter, pressure drop, and properties of the gas. The equation for the gas flow rate, as well as the assumed pipe configurations, is presented in appendix D.

Many assumptions go into the analysis that determines the engineering design for how to supply the required CO_2 to an algae production facility. The productivity of the algae is one significant variable. The mean annual biomass growth—13.2 g/m^2/day, as reported in ANL, NREL, and PNNL (2012)—is based on output from the BAT model for the Gulf Region as part of the DOE algae model harmonization study for open-pond production systems. It is used as a basis for the engineering design. This value corresponds closely with strain-specific mean annual values of 12.8 g/m^2/day for *Chlorella sorokiniana* and 13.8 g/m^2/day for *Nannochloropsis salina* in the Gulf Region, using common model harmonization sites. For purposes of gas transport engineering design, 1,000 acres of pond area (1,200 acres total with the required infrastructure) is used and is consistent with the DOE harmonization study. The resulting required gas flow rates from the coal-fired and natural gas–fired EGUs are higher than from the ethanol plants because of the lower CO_2 concentration in the former gas streams (table 7.4). Therefore, we assume a series of parallel pipelines from natural gas-fired EGUs and coal-fired EGUs. Electricity costs are estimated for powering transport (blower and pump) equipment.

Ethanol Plant Co-Location

The design of the ethanol plant co-location is defined by a 99% pure CO_2 stream, and systems are broken into two different system designs based on pipeline distance. A high-pressure system (>100 pounds per square inch gauge [psig]) is used for pipelines >10 miles, and a low-pressure system (20 psig) is used for pipelines ≤10 miles (fig. 7.5). For least-expensive system costing, the low-pressure (≤10 miles) and high-pressure (>10 miles) delivery systems were cost-competed. This cost-competition was trivial if

Table 7.4 | Volume Flow Rates for the Gas Transport Systems

CO_2 resource	CO_2 in gas stream (%)	Gas mass flow rate (max) for 1,000 acre, open-pond facility
Coal-fired EGU	14	7,700 scfm
Natural gas–fired EGU	5	22,000 scfm
Ethanol plant	99	1,100 scfm

scfm = standard cubic feet per minute.

all the cultivation sites being fed by a single ethanol CO_2 source were above or below the 10 mile threshold (defining a low- or high-pressure pipeline system). In many cases, however, a single CO_2 source is feeding an enterprise of cultivation sites that have pipeline distances ≤10 miles and >10 miles. In these cases, a "majority rules" approach is used; for example, if 12 cultivation sites have a cost preference for a high-pressure system and 3 cultivation sites have a cost preference for a low-pressure system, all cultivation sites are assigned to use a high-pressure system.

Coal EGU Co-Location

Coal EGU plants are assumed to have a 14% pure CO_2 stream. Under the current production scenario, the transport system is characterized by dual (parallel) low-pressure (20 psig) pipelines with blowers and in-line boosters as required by distance (to prevent pressure drops in the pipeline) (fig. 7.6). Under the future high-productivity scenario, the number of parallel pipelines increases to six. Since there is only one system, there was no requirement for cost-competing systems, as was the case with algae cultivation facilities receiving CO_2 from ethanol production.

Figure 7.5 | Ethanol-based CO_2 co-location using either a high-pressure or low-pressure system

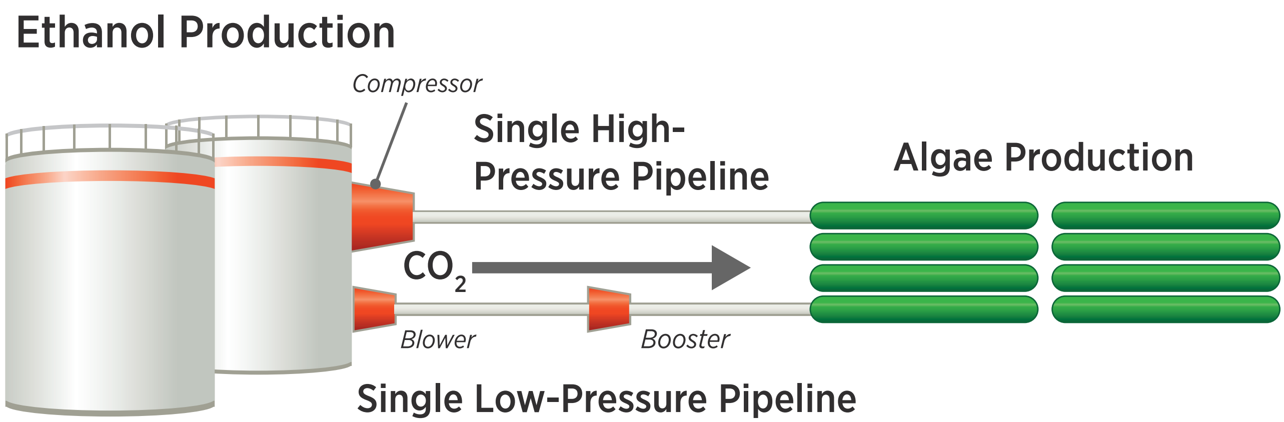
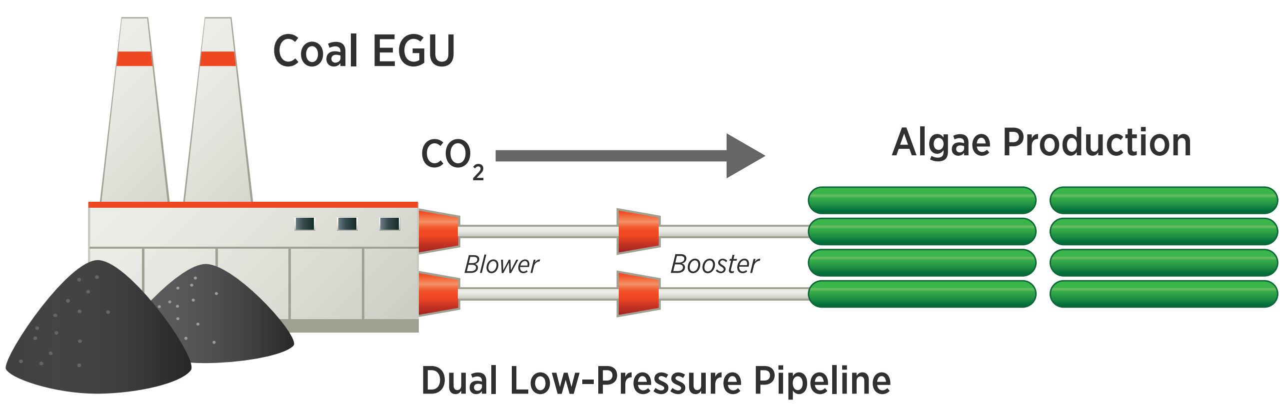


Figure 7.6 | Coal EGU-based CO_2 co-location using a dual low-pressure system with in-line boosters



Natural Gas EGU Co-Location

Natural gas–fired EGU plants are assumed to have a 5% pure CO_2 stream. Under the current-technology production scenario, the transport system is characterized by four low-pressure (20 psig) pipelines with blowers and in-line boosters as required by distance (to prevent pressure drops in the pipeline) (fig. 7.7). Under the future high-productivity scenario, the number of parallel pipelines increases to eight, as four additional pipelines were needed to minimize operational costs.

7.5.2 Biomass Assessment Tool

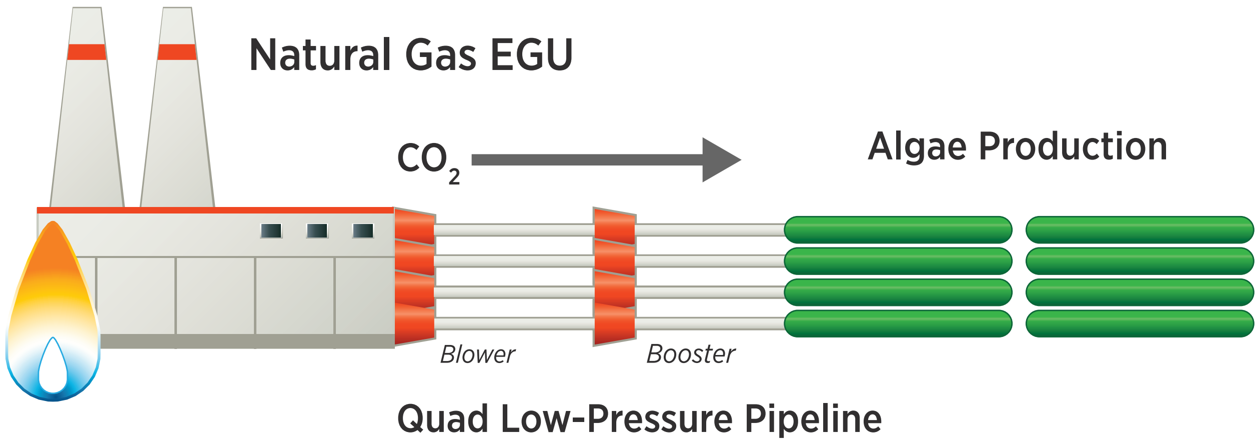
The BAT is an integrated model, analysis, and data management architecture that couples advanced spatial and numerical models to capture site-specific environmental conditions, production potential, resource requirements, and sustainability metrics for bioenergy feedstocks. The BAT operates at a high spatiotemporal resolution (e.g., 30–500 m depending on the dataset, hourly) within the CONUS. Various aspects of the BAT have been described and demonstrated in a number of published studies (Coleman et al. 2014; Venteris et al. 2012, 2013; Venteris, Skaggs et al. 2014b; ANL, NREL, and PNNL 2012; Wigmosta et al. 2011; Venteris, McBride et al. 2014; Venteris, Skaggs et al. 2014a; Venteris, Wigmosta et al. 2014).

The BAT integrates (1) a multi-scale land-suitability model; (2) an open-pond mass and energy balance pond model (Perkins and Richmond 2004) delivering hourly pond water temperature and evaporative water loss based on local weather data; (3) a biophysical growth model that incorporates pond temperature, optimal/sub-optimal temperature curves (appendix D), and photosynthetically active radiation to simulate strain-specific biomass growth and nutrient demand at an hourly time-step; (4) trade-off analysis routines to evaluate biomass production potential with available land, water, and nutrient resources; (5) water source and use intensity analysis for freshwater, seawater, and saline groundwater; (6) nutrient and CO_2 flue gas source, availability, and demand models; (7) least-cost transport models for water, nutrients, CO_2, and refinery access; (8) a partial techno-economic site scale-up model; (9) a land valuation/acquisition model; and (10) a surface leveling model that accounts for costs of site preparation.

7.5.3 Land Suitability

For the BAT (Wigmosta et al. 2011) land suitability analysis, we assume that each open-pond microalgae cultivation facility (unit farm, 1,200 acres) consists

Figure 7.7 | Natural gas EGU-based CO_2 co-location using a quad pipeline low-pressure system with in-line boosters

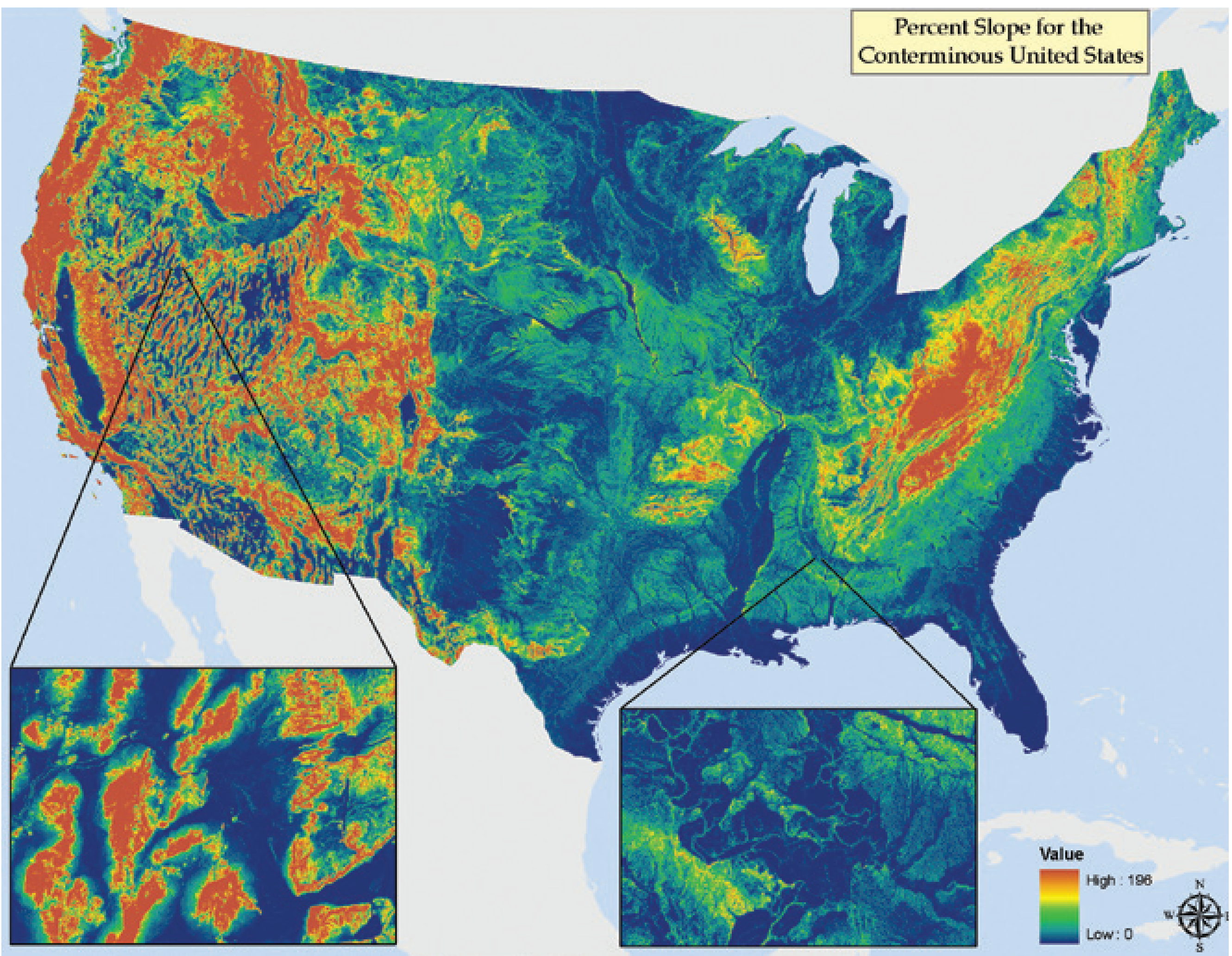


of one hundred 30 cm deep, 10-acre classic raceway style ponds (fig. 7.2) requiring 1,000 acres of land for ponds and another 200 acres for operational infrastructure. Additionally, the potential facilities and associated infrastructure are constrained by several topographic and land use/land cover criteria to determine potentially suitable lands.

The first major constraint is that suitable lands must be situated on relatively flat land, with a minimum 1,200 acre contiguous area and slopes of ≤1% (see figs. 7.8 and 7.9) to minimize initial site preparation/excavation and operational water pumping costs (Benemann et al. 1982; Maxwell, Folger, and Hogg 1985). Other pond designs that incorporate steeper slopes, terracing, and airlift pump systems are not considered in the current analysis (Beal et al. 2015; Huntley et al. 2015).

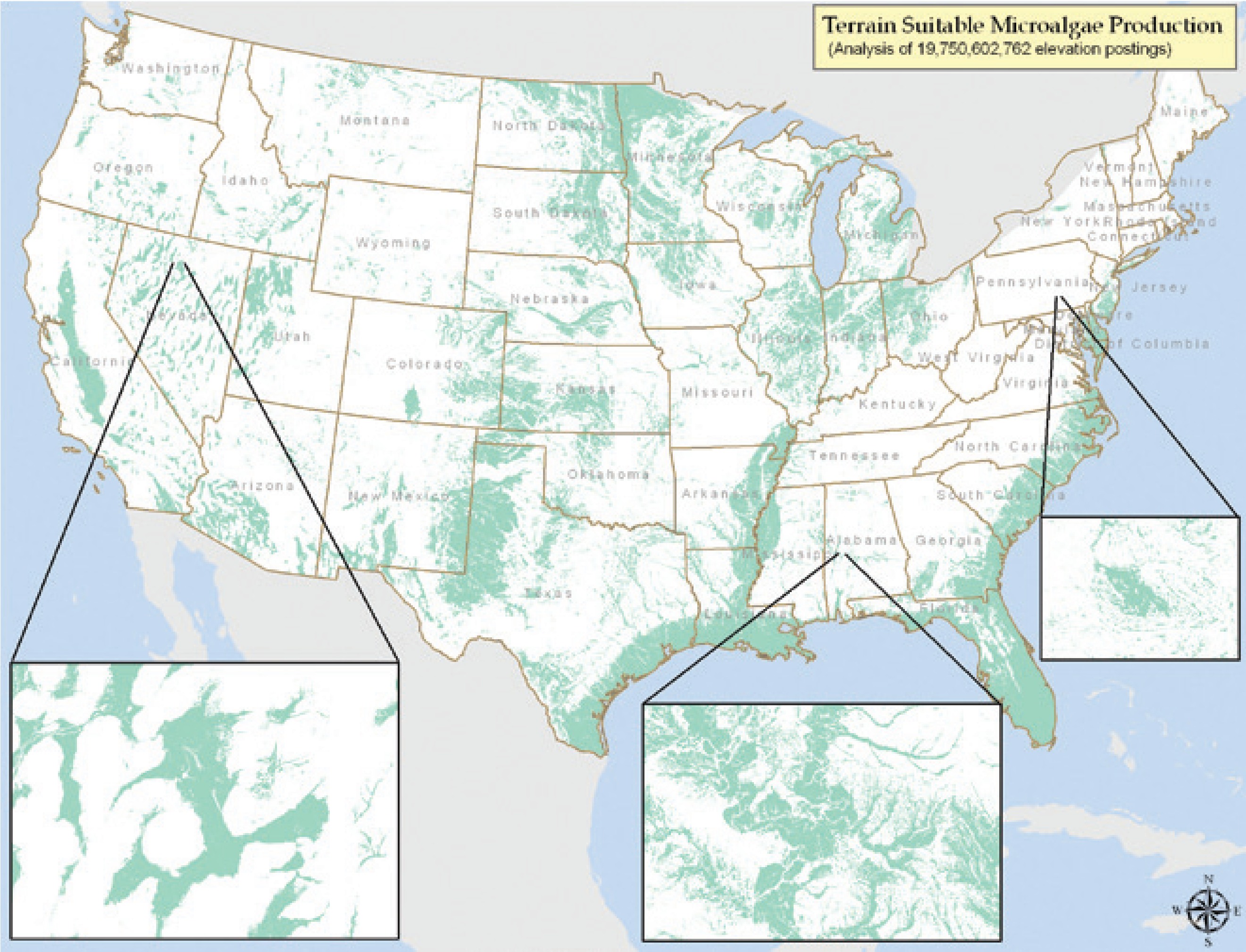
From the suitable slope areas, only non-agricultural, non-forested, undeveloped or low-density developed, non-sensitive, generally non-competitive land is considered for cultivation facilities. Specifically, this excludes open water, urban areas, airports, cultivated cropland and orchards (but not pastureland), forest/woodlands, federal and state protected areas such as national and state parks, wilderness areas, wildlife refuges, wetlands, riparian areas, and other areas that are deemed environmentally sensitive.

Figure 7.8 | A percent-of-slope analysis was conducted on 30 m USGS digital elevation models



Note: This high-resolution mosaicked dataset provides the basis for the ≤1% slope classification, the first level of land screening in the multi-criteria land suitability analysis.

Figure 7.9 | Reclassified slope data ranging from 0%–1% (green) provide the most terrain-optimal locations for open-pond development



Note: Keep in mind that the high-resolution analysis is not fully portrayed at the resolution and scale of this figure; thus, many suitable areas are not seen at the national scale. For example, see the insets of southeastern Pennsylvania and western Alabama.

7.5.4 CO_2 Co-Location Model

We used the database of stationary carbon sources obtained from the DOE National Energy Technology Laboratory's NATCARB v.1501 in addition to the database developed by Middleton et al. (2014), which captures the EPA Greenhouse Gas Reporting Program data. The Middleton et al. (2014) database considers only CO_2 point-sources with 25 kt/year of output, which represent 597 sources throughout the country. The remaining sources were supplemented with the NATCARB database. Plants that reported zero CO_2 production were assumed to be non-operating and were eliminated from the analysis. In addition, if a site was reported to already be providing CO_2 for another purpose (Middleton et al. 2014), it was not included in the analysis.

To assess the co-location potential of stationary CO_2 sources with algae cultivation—ethanol plant, coal EGU, and natural gas EGU sites are separated into their own GIS-based point datasets to enable independent analyses. For each of the unit farm data sets in the CONUS, the PNNL microalgae growth model (appendix D) was run for the selected strains, *Chlorella sorokiniana* (freshwater) and *Nannochloropsis* *salina* (saline water), to determine the 30-year average biomass production potential. The total annual carbon demand (Venteris, Skaggs et al. 2014b) for the produced biomass is calculated by Eq. (1):

$$D_{CO_2} = \frac{B * Wc_{Bio}}{E_{CO_2} * W_{CCO_2}} \quad (1)$$

where

D_{CO_2} = CO_2 demand (kg/year)

B = AFDW biomass (kg/year)

$W_{C_{Bio}}$ = Carbon fraction in biomass (0.55)

E_{CO_2} = CO_2 utilization efficiency (0.82)

W_{CCO_2} = Carbon fraction in CO_2 (0.273)

For the carbon demand, no CO_2 recycling is assumed (agnostic to the downstream processing pathway), 330 days of operation are considered, and CO_2 is used only during daylight hours. The daytime CO_2 use is consistent with several past studies: In Pate (2013), CO_2 is used based on 8 and 12 hours of daylight. In Beal et al. (2015), CO_2 delivery and use is a function of biomass productivity that is driven by the dominant controls of media temperature and available light. Lundquist et al. (2010) consider a balance of biomass productivity, CO_2 utilization efficiency, and pH constraints with a 10 hours/day delivery of CO_2. And Brune, Lundquist, and Benemann (2009) consider the ratio of sunlight hours to power plant operating hours (11–14 hours/day of sunlight vs. 18 hours/day for power plant), carbon storage in the pond, CO_2 transfer efficiency, pond outgassing rates, and pH limits. It is acknowledged that in colder regions, the number of days of operation will be lower, with productivities that may not justify operation; however, these low or zero productivities and associated CO_2 demands are reflected in total annual values.

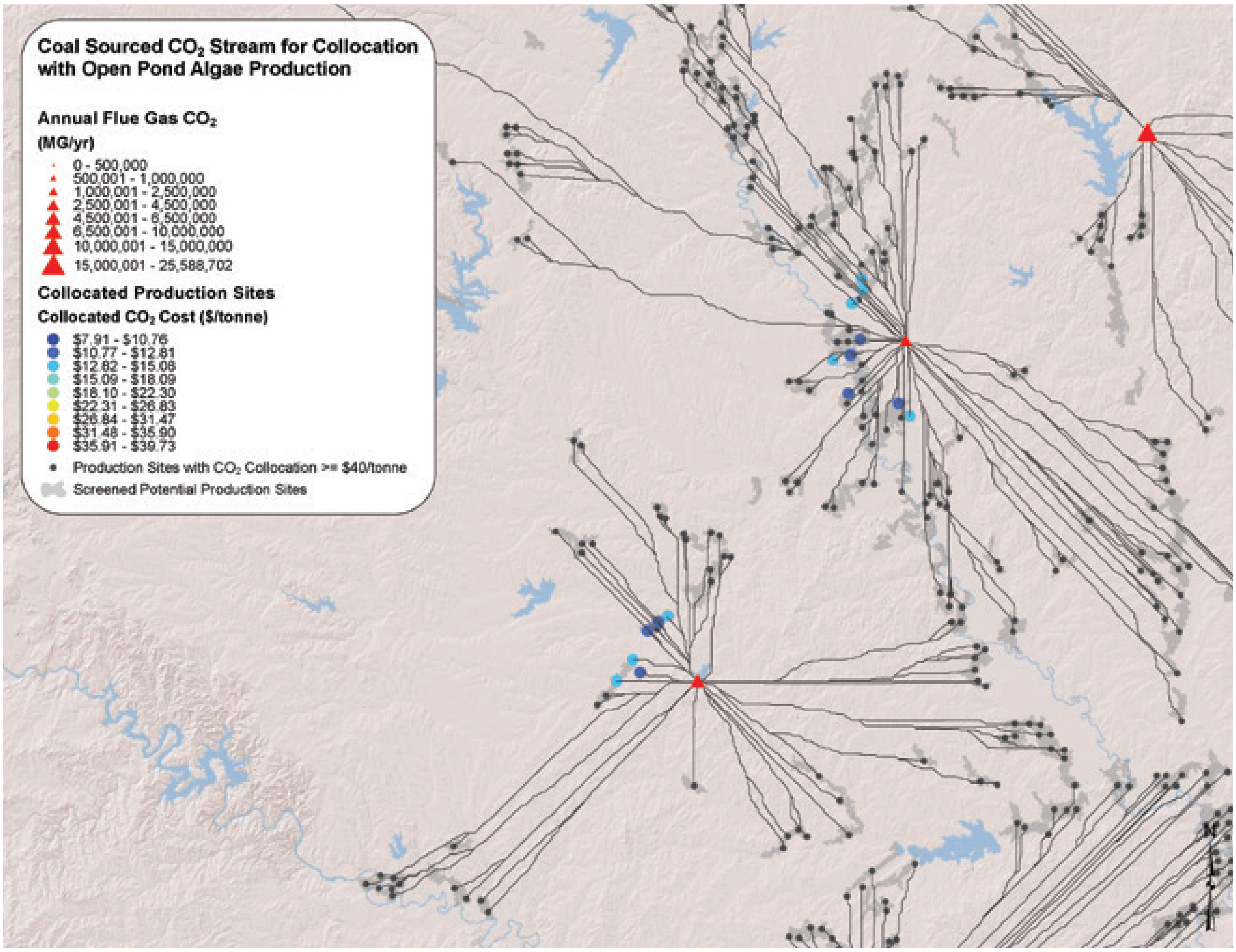
A GIS grid-based, cost-distance model is run to determine the least-cost pipeline routes from each CO_2 source to the unit farm. The flue-gas cost-distance model is based on an earlier work described in Venteris et al. (2013). The model will determine the closest distance between source and target and find the most cost-effective path while avoiding high-topography, sensitive, urban, and other unsuitable areas (see fig. 7.10).

Pipeline distances are determined along with capital costs (i.e., pipe length, material, sizing, compressor, blowers) and operational costs (i.e., transport energy) using estimates developed in section 7.4.1. The model supplies potential algal cultivation facilities with available CO_2 (as defined by the CO_2 demand) using the least expensive sources first (blend of the closest sites and total biomass production) and continues as long as it is technologically feasible. It is less expensive than commercial purchase at \$40 ton CO_2, and there is available supply. This is further illustrated in figure 7.11, in which an accounting takes place between site CO_2 demand and total available supply.

For a simplifying assumption in this analysis, we use 12 hours/day of daylight on average throughout the year for all CONUS sites. This value is based on the geographic center latitude of the CONUS, at 39.82°N (appendix D). For each flue gas source, we acknowledge operations are variable according to a cost-effective industrial process or, in the case of EGUs, as baseload, semi-baseload or peaking power capacity and demand require. For purposes of GHG emissions reporting, values are most typically provided as total tons per year; however, because algal photosynthesis is limited to daylight hours, CO_2 cannot be directly used 24 hours/day. We make the operational assumptions around flue gas availability and thus adjust total annual CO_2 output available for algal production as indicated below.

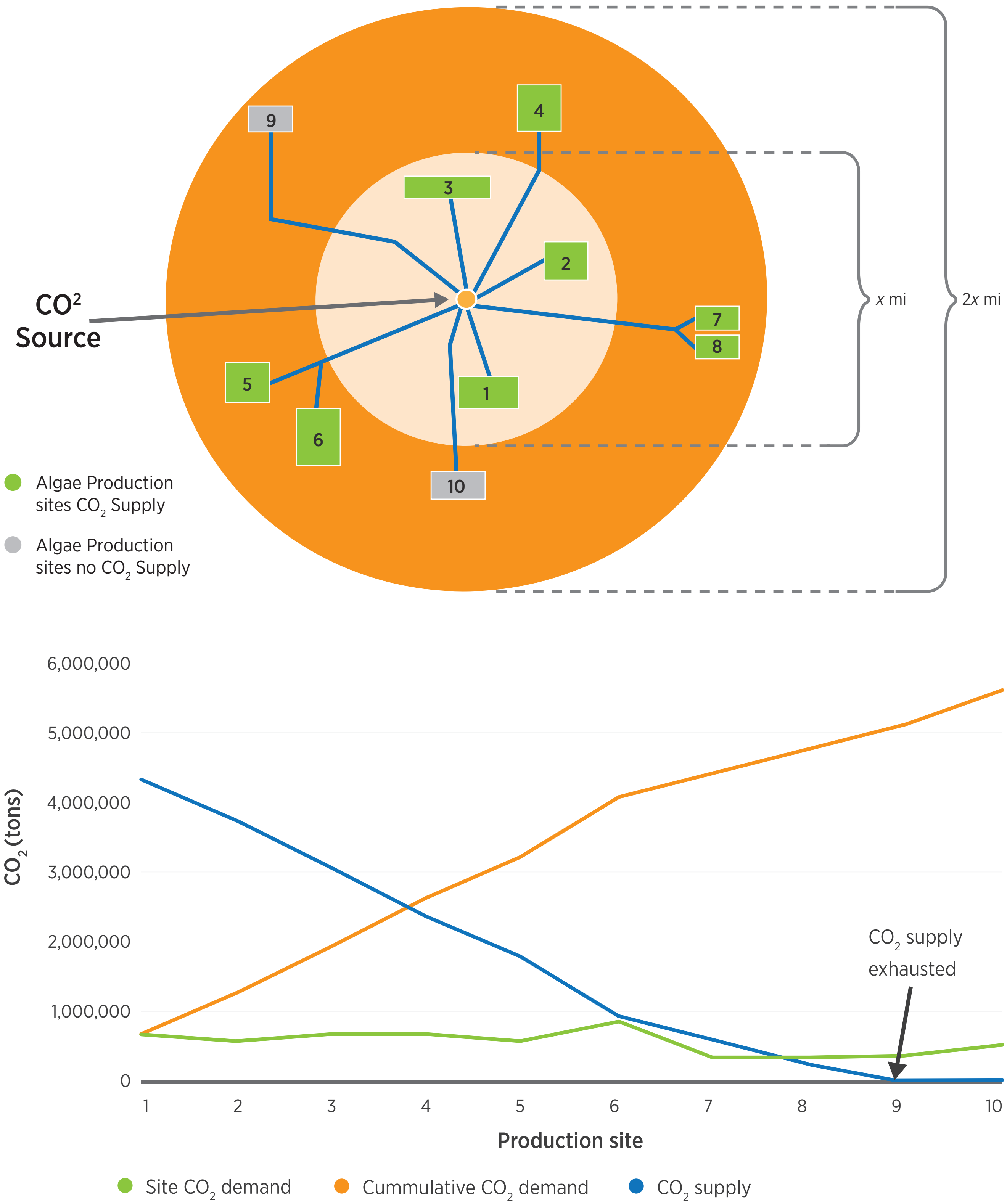
Ethanol plants are consistently operational 24 hours/day, 7 days/week and, assuming an annual average of 12 hours of daylight, can thus provide 50% of their total available CO_2 supply for algal production. EGUs are more complex and follow regional patterns that are temporally varying. In general, business weekdays between 7 a.m. and 10 p.m. are

Figure 7.10 | Example results of the flue-gas cost-distance model that routes pipelines from source (stationary CO_2 source) to target (potential algae cultivation facility)



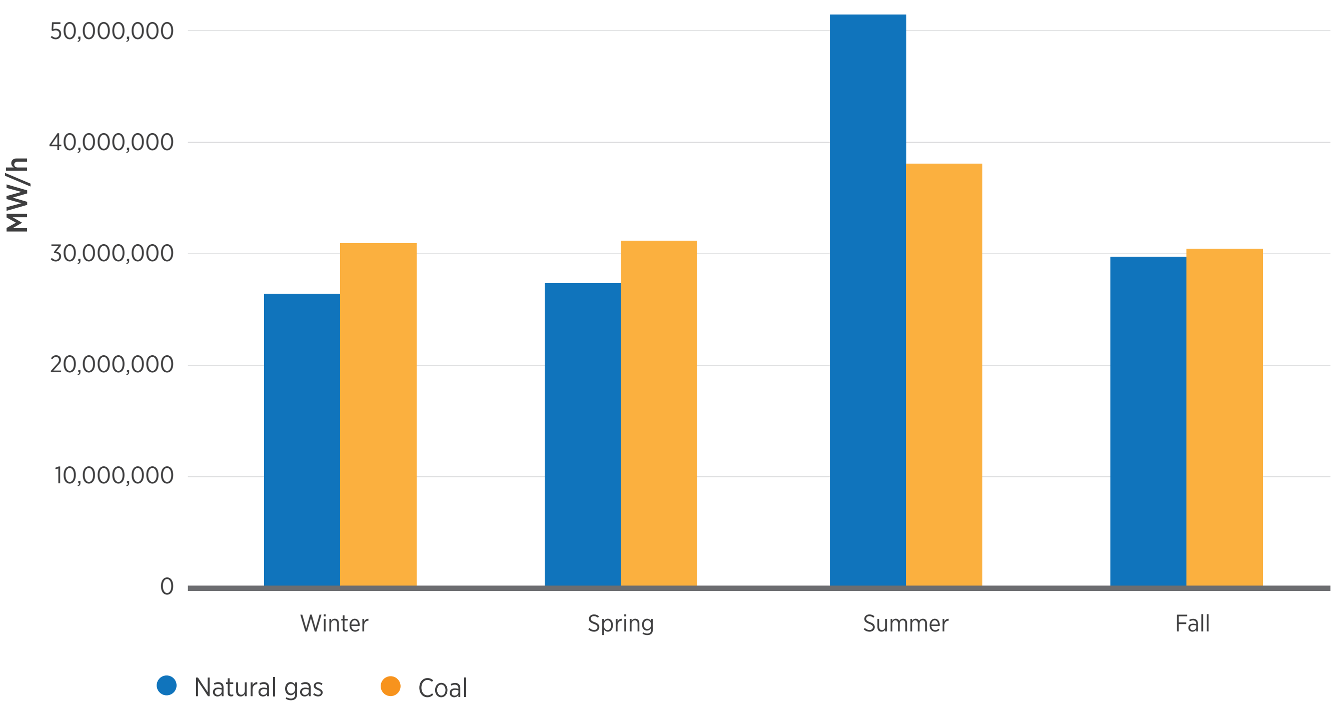
considered "on-peak" periods for power generation, whereas business days between 10 p.m. and 7 a.m. and all day on weekends are considered "off-peak." There are seasonal differences as well: summer and winter electricity demands are significantly higher than in spring and fall, when demand for cooling and heating, respectively, are not as great (fig. 7.12). In general, off-peak hours constitute 55% of the hours in a year, whereas on-peak hours represent 45%. In terms of actual power demand, on-peak hours make up 70% of the total power load and off-peak hours 30%. We assume a direct relationship between power generation and CO_2 output. Therefore, making adjustments considering the fraction of off-peak and on-peak hours with respect to CO_2 output, and factoring average daylight hours that overlap with off-peak and on-peak hours, we estimate that 30% of the total annual CO_2 emitted is available for algal production. Future detailed analysis could adjust available CO_2 values based on location, EGU function (i.e., base load, peaking power, load following), time of year, and fuel source. In addition, it is recognized that several technologies are available to continually capture, strip and store CO_2; these could be evaluated in future work.

Figure 7.11 | Site prioritization of CO_2 delivery to algae cultivation sites



Source: Pacific Northwest National Laboratory.

Figure 7.12 | Example of fuel-specific seasonal power production in the Gulf Coast region; for more northern latitude locations, the winter demand would be higher to meet heating needs



7.5.5 Model Assumptions

The BAT model was run to capture the site-specific biomass production potential, associated CO_2 demand, and pipeline routes under a current technology scenario and a future productivity scenario for algae strains *Chlorella sorokiniana* (freshwater) and *Nannochloropsis salina* (saline water). As with the DOE model harmonization study, a consumptive freshwater use constraint of no more than 5% of mean annual basin flow (cumulative for sites within a watershed) helped determine the number of sites allowed (ANL, NREL, and PNNL 2012). Because saline water resources are more plentiful, they were not constrained by required volume but rather by (1) locations where salinity ranges from 2 to 70 PSU[2] and (2) cultivation sites within 6.2 miles (10 km) proximal distance of acceptable salinity-range groundwater or seawater sources, to account partially for uncertainties in salinity ranges and provide economically viable water transport distances.

A common set of engineering assumptions were established for each CO_2 source and used for all sites in the CONUS based on average productivity values for the two strains and all sites (see section 7.5.1); however, growth rates, biomass production, and CO_2 demand were established as site-specific.

[2] Bartley et al. (2013) found that salinities of 22 PSU to 34 PSU provided the highest growth rates for *Nannochloropsis salina*; however, growth is possible between 8 PSU and 68 PSU. Abu-Rezq et al. (1999) found that ideal salinities for the same strain are between 20 PSU and 40 PSU. While the salinity range of 2 PSU to 70 PSU is broader than the ideal salinity target range for *Nannochloropsis salina*, it represents possible salinities that support growth of a wide range of other saline-based algae strains (Shen et al. 2015, Varshney et al. 2015, Kim, Lee, and Lee 2016). The wide salinity range also captures the uncertainties in the source data and geostatistical processing of saline water resources.

To develop the future production scenarios for *Chlorella sorokiniana*, a selection of the high-producing southeastern United States, Gulf Coast, and Florida sites were scaled from a mean annual productivity of 13.8 g/m²•day to 25 g/m²•day, resulting in an ~1.8x scale-up or a 55.2% improvement. This factor was used to scale all CONUS sites, which were then independently evaluated for co-location potential, including available CO_2 supply, required CO_2 demand, and capital expenditure and operating expenditure constraints. The *Nannochloropsis salina* strain performed at a mean annual productivity of 12.8 g/m²•day, and all CONUS sites were scaled to a 51.2% improvement in productivity or a 1.95x scale-up. For the future high-productivity scenarios, the CO_2 supply is assumed to remain the same as current supply.

- Each co-location scenario is run independently and is not competed to determine the economic tradeoff space. The model operates under numerous other assumptions captured below. Open ponds are operated at a 30 cm depth at an hourly time-step for 30 years.
- The common set of supply engineering designs is established for each of the three categories of waste CO_2 sources based on 1,000 acre pond units (100 ten acre ponds) with a mean annual productivity of 1.25 x 13.2 g/m²•day. Resulting gas flow rates used in this analysis are documented in table 7.4.
- Algal CO_2 uptake efficiencies are incorporated (not assuming 100% utilization) and are based on site-specific hourly growth model results (see Eq. [1]).
- If stationary waste-stream CO_2 sources are known to already be used for another purpose (e.g., carbon capture and storage, industrial gas supply, food industry, enhanced oil recovery), these sites are not included in this analysis.
- CO_2 is not assumed to be recycled (i.e., anaerobic digestion), thereby keeping this analysis agnostic to downstream processing pathways.
- The model for biomass production and CO_2 demand assumes 330 days of operation.
- CO_2 is used only during the daylight hours (average 12 hours assumed) when algae have active photosynthesis.
- Total CO_2 availability is constrained by the source operations and relationship to daylight hours. No specific considerations are made with regard to pH effects on the pond as result of CO_2 supply; the pH of the media is assumed to be constant where a balance of CO_2 supply is maintained according to biomass growth demand.
- Future high-productivity scenarios assume no change in the available CO_2 supply from the current scenario.
- Commercial CO_2 can be delivered at $40 per dry ton of CO_2; therefore, once this cost is exceeded for a unit farm, co-located CO_2 is no longer provided, even if there is available supply. (In Davis et al. (2016), this cost is $41 per dry ton in 2011 dollars.)
- Data from the NATCARB database provide total CO_2 emissions and do not distinguish between sites with multiple sources and purities of CO_2. We assume one source and purity as documented.
- Freshwater *Chlorella sorokiniana* strain model parameters are available in appendix D, table D.1.
- Saline *Nannochloropsis salina* strain model parameters are available in appendix D, table D.1.

7.5.6 Cost of Production: Economic Assumptions

Supply curves express price or cost per ton vs. cumulative supply of feedstock. The definition of a supply curve is described more fully in chapter 1. Costs of biomass are averaged at the county level. The minimum selling prices in this chapter assume a 10% internal rate of return.

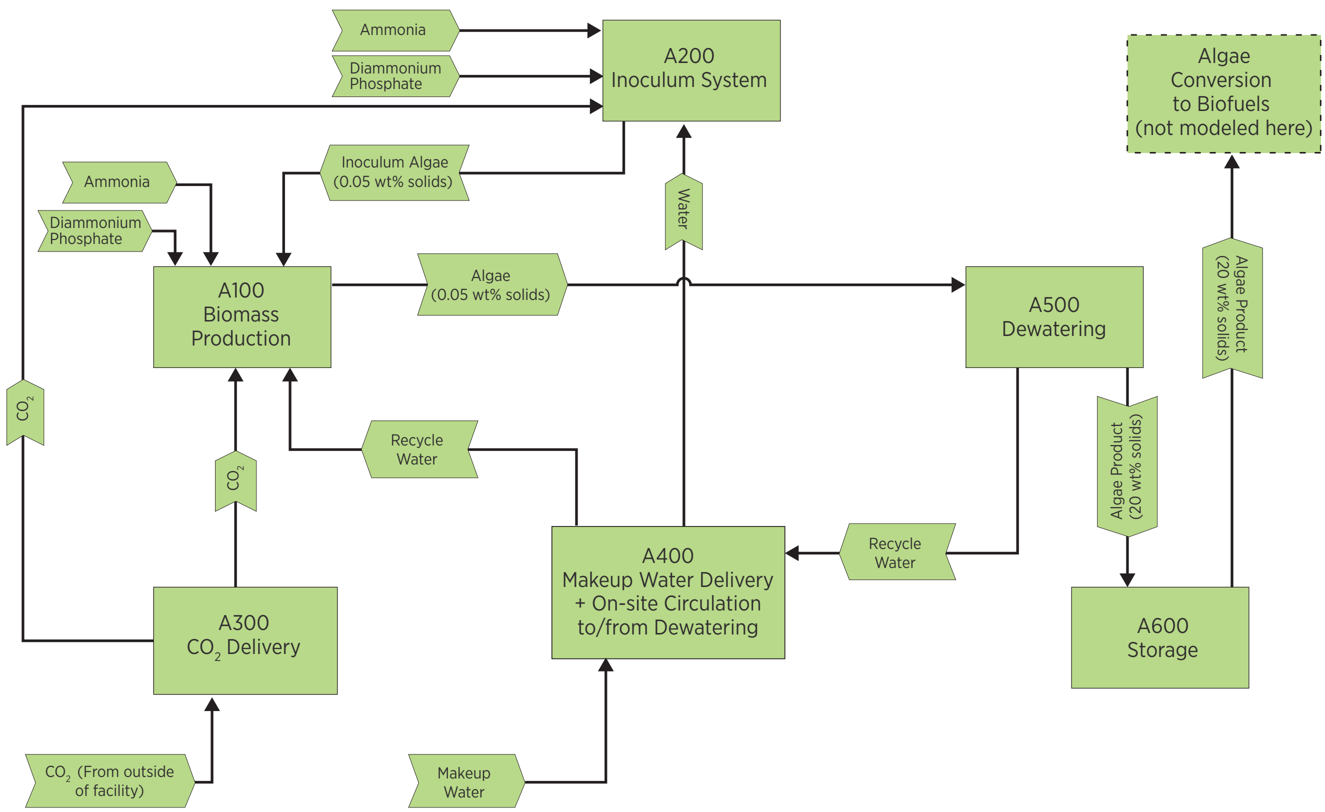
The basis for the cost assumptions for algae production is the NREL report *Process Design and Eco-*

nomics for the Production of Algal Biomass: Algal Biomass Production in Open Pond Systems and Processing Through Dewatering for Downstream Conversion (Davis et al. 2016). That report describes minimum biomass selling prices of $452–$545 per dry ton AFDW[3] (an average $491 per dry ton) for facilities with 10 acre pond designs that are generally consistent with assumptions in the BAT model. The basic design is depicted in figure 7.13.

The major contributors to the minimum biomass selling price of $491 per dry ton AFDW in the Davis et al. (2016) base case are $278 per dry ton for cultivation costs other than nutrients, $112 per dry ton for nutrients including CO_2, and $101 for dewatering and other costs. Based on additional analyses of capital and operational expenses, NREL has determined that $491 in 2011 dollars is equivalent to $494 in 2014 dollars. These costs assume a freshwater open pond/raceway cultivation system that has average costs of four pond designs and, unlike the strains assumed in this analysis, they project productivities for *Scenedesmus acutus (LRB-AP 0401)*.

This chapter uses a biomass product endpoint of 20% solids by weight, consistent with the assumptions in Davis et al. (2016). They assume in-ground gravity settlers, followed by hollow fiber membranes and centrifugation to concentrate (dewater) the harvested biomass; yet, they note that the dewatering perfor-

Figure 7.13 | Simplified flow diagram of the algae production process assumed in cost estimates



Source: Modified from Davis et al. (2016) figure 3.

[3] Dry tons throughout the chapter are equivalent to AFDW.

Table 7.5 | Assumptions Contributing to Current and Future Estimates of Algae Biomass Costs and Production Potential That Are Derived From Davis et al. (2016)

Topic	Assumption in Davis et al. (2016)	Change needed for current case	Change needed for future case
Facility size, cultivation area	500 ten-acre cultivation ponds per facility	100 ten-acre cultivation ponds per facility; $102 per dry ton added based on economy of scale losses in Davis et al. (2016)	100 ten-acre cultivation ponds per facility; $102 per dry ton added based on economy-of-scale losses in Davis et al. (2016)
Algae strain	Mid-harvest, high-carbohydrate *Scenedesmus acutus*	Used BAT-modeled productivities for *Chlorella sorokiniana* (freshwater) and *Nannochloropsis salina* (saline water); costs from base case in Davis et al. (2016 are adjusted upward by $3/ton for *Chlorella* and $35/ton for *Nannochloropsis*	BAT-modeled productivities used for *Chlorella sorokiniana* (freshwater) and *Nannochloropsis salina* (saline water); costs from base case in Davis et al. (2016) are adjusted upward by $3/ton for *Chlorella* and $35/ton for *Nannochloropsis*
Algal productivity	Cultivation productivity target of 25 g/m^2•day annual average across varying seasonal rates	Site-specific productivity for biomass growth and CO_2 demand modeled using BAT, whereas 13.2 g/m^2•day annual average is used for source-specific CO_2 transport engineering design; cost per dry ton adjusted based on productivity-price function from data in Davis et al. (2016)	Site-specific productivity for biomass growth and CO_2 demand modeled using scaled BAT results. Scaled using a factor of 1.8x for *Chlorella sorokiniana* and 1.95x for *Nannochloropsis salina* (25 g/m^2•d annual average for Gulf Region); source-specific CO_2 transport engineering design based on 25 g/m^2•day. Cost per dry ton adjusted regionally based on productivity-price function from data in Davis et al. (2016)
Freshwater	Minimal liners cover only 2%–25% of total pond area in four pond designs from which costs are derived	No change	No change
Saline water	No saline case; but costs are estimated for full liners at base case productivity	Estimated costs for both minimal liner and full liner cases used; $32 per dry ton added for blowdown waste disposal (Davis et al. 2016)	Estimated costs for both minimal liner and full liner cases used; $32 added per dry ton for blowdown waste disposal (Davis et al. 2016)

Table 7.5 *(continued)*

Topic	Assumption in Davis et al. (2016)	Change needed for current case	Change needed for future case
CO_2 delivery to facility gate	CO_2 costs estimated at $41/ton CO_2	CO_2 delivery costs estimated at $0/ton purchase price from waste stream, in addition to annualized capital expenses for infrastructure and operational costs for transport to facility gate, depending on transport distance and co-location scenario (i.e., CO_2 purity)	CO_2 delivery costs estimated at $0/ton purchase price from waste stream, in addition to annualized capital expenses for infrastructure and operational costs for transport to facility gate, depending on transport distance and co-location scenario (i.e., CO_2 purity)
Year dollars	2011 dollars	2014 dollars	2014 dollars

mance represents aspirational goals to meet cost targets. Like Davis et al. (2016), we assume that a nutrient recycle credit is applied to the downstream conversion process to reduce final fuel costs, rather than making an assumption about downstream nutrient recycles (based on a specific conversion pathway) to reduce biomass costs up front. We assume the same inoculum technology, water circulation pipelines, and product storage tanks as in Davis et al. (2016), and therefore, the same cost contributions to the total cost. And as in Davis et al. (2016), biomass is harvested and processed through three dewatering steps—gravity settling, hollow fiber membranes, and centrifugation—to concentrate the biomass from 0.5 g/L (0.05 wt % AFDW) to 200 g/L (20 wt %) in the product stream. Similarly, the same equity financing, depreciation, corporate tax, and working capital assumptions are used, as well as construction-time and start-up–time assumptions. Costs of conversion and refining of fuel are not included.

Some differences between the assumptions in this chapter and those in Davis et al. (2016) affect the cost per ton of algae biomass for the current or future cases. These differences are summarized in table 7.5. Some of the differences—for example, productivity estimates—relate to the different purposes of this chapter, one of which is to estimate current biomass potential, compared with that of the cultivation design case report, which is to describe “aspirational” targets in the future. For the current case, we assume lower site productivities than the target in Davis et al. (2016).

The economy of scale affects cost estimates. For example, dewatering equipment is more costly at the 1,000 acre pond scale than at the 5,000 acre pond scale assumed in Davis et al. (2016) (table 7.5). Also, pipeline circulation, storage, and labor and fixed operating costs are affected by the scale.

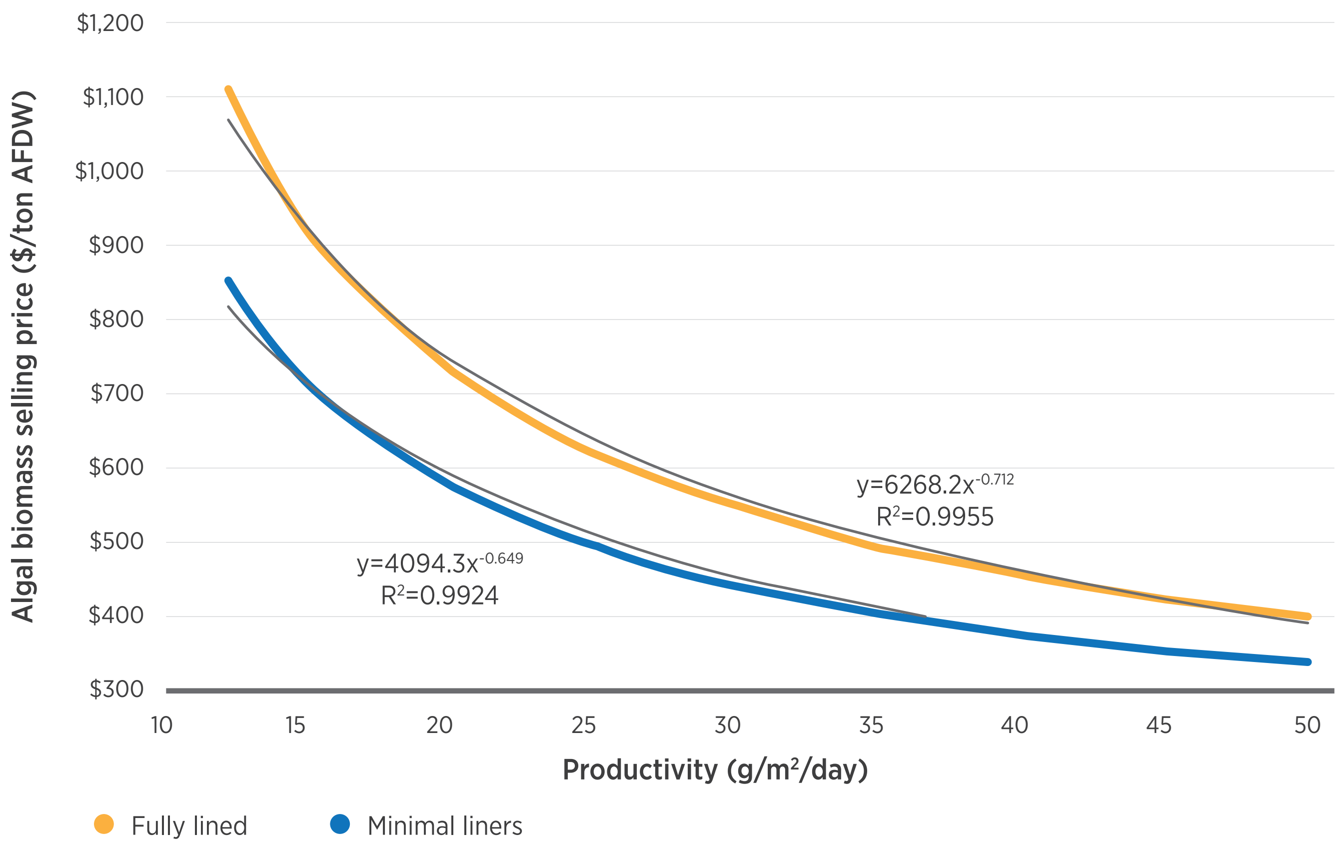
The use of saline water affects cost estimates. We consider a scenario that assumes that ponds must be lined if saline water is used. However, we recognize liners are not a requirement for every locale (see Open-Pond Production System in section 7.3.2), so we also consider a scenario wherein ponds are minimally lined, as with freshwater. Moreover, disposal costs cannot be assumed to be negligible for saline ponds and generally vary between those for injection wells and for ocean disposal. We make the more conservative assumption of the use of injection wells for all saline scenarios.

We estimate CO_2 costs in section 7.5.1 based on piping and compression needed for co-location scenarios. We replace the \$41/ton CO_2 cost for delivery to the facility gate from Davis et al. (2016) with values specific to co-location technology and distance.

An important assumption in Davis et al. (2016) is the "*n*th plant economics" stipulation, which assumes that a number of facilities using the same technology have been built and are operating, rather than assuming that a cultivation system or drying plant is the first of its kind. This avoids artificially inflating costs based on risk financing (which would require a higher than 10% initial rate of return), equipment over-design, process downtime, and so on. We use a 10% discount rate to be consistent with costs estimated in Davis et al. (2016). This rate is higher than the 6.5% that is assumed elsewhere in this report.

The association between minimum selling price per ton of biomass and productivity is generated based on figure 7.14. A power curve is used to fit the price-productivity data from Davis et al. (2016), with both minimal and full pond liners.

Figure 7.14 | Minimum biomass selling price per ton of biomass vs. productivity for the base case (minimally lined ponds) as presented in Davis et al. (2016) (blue) and with costs for fully lined ponds added as an option for Nannochloropsis salina (red). Model outputs are fit to power curves (thin black lines); the data are in 2011 dollars



Thus, the costs of biomass are estimated by the following equations, which adjust costs from the base case in Davis et al. (2016).

Freshwater: (2)

$$Y = (1+I)[(4094.3(X^{-0.649}) + E - B + C)] + FT\ .$$

Saline—minimally lined: (3)

$$Y = (1+I)[(4094.3(X^{-0.649}) + E - B + N + D)] + FT\ .$$

Saline—fully lined: (4)

$$Y = (1+I)[(6268.2(X^{-0.712}) + E - B + N + D)] + FT\ .$$

Where

C = cost per ton of biomass

I = inflation rate converting 2011 to 2014 dollars (1.006, cost index factor based on unpublished data from NREL and % allocation between capital and operating expenses)

X = average annual biomass productivity, $g/m^2 \cdot d$

E = economy-of-scale dollar loss for difference between 5,000 and 1,000 acres (102)

B = cost of CO_2 per ton of biomass in Davis et al. (2016) base case (91)

F = ton CO_2/ton biomass (2.2)[4]

T = cost per ton of co-located CO_2 in 2014 dollars

D = cost of blowdown disposal per ton of biomass for saline case in 2011 dollars (32)

C = additional cost for using *Chlorella* instead of *Scenedesmus* (3)

N = additional cost for using *Nannochloropsis* (with additional ash content and different nutrient content) instead of *Scenedesmus* (35)

7.6 Results

7.6.1 Cost-Effective Distance for Co-Location

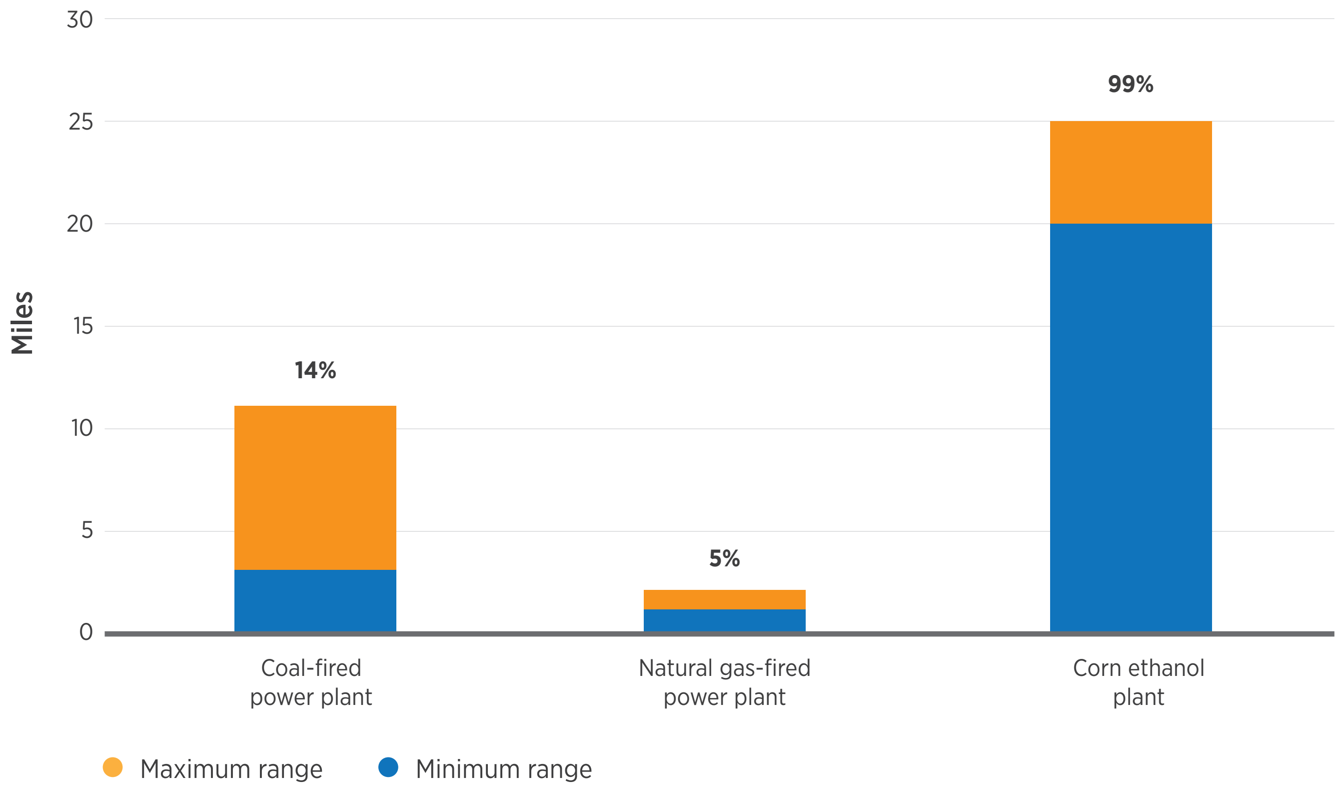
Table 7.6 presents results for cost-effective distance for co-location of CO_2 with algae cultivation. The range of costs includes system designs that minimize capital cost and system designs that minimize operating electricity for the compressors. Clearly, pure CO_2 can be transported cost-effectively for longer distances than EGU flue gases. Increasing the productivity in the future also increases the CO_2 requirements and the pipeline cost, reducing the cost-effective transport distance (relative to commercial CO_2) for all but the ethanol plant as a co-location source. The purity of CO_2 in the flue gas determines the cost-effective distance (fig. 7.15). The cost-effective distance for transporting flue gas from the natural-gas-fired EGU is the lowest.

Table 7.6 | Cost-Effective Distance for Co-Location of CO_2 with Algae Cultivations

CO_2 source	Cost-effective distance	
	Current productivity	Future productivity
Coal-fired EGU	3–11 miles	<5 miles
Natural gas-fired EGU	<1 mile	<0.5 miles
Ethanol plant	>20 miles	>20 miles

[4] Note that this value was used in Davis et al. (2016), so we use it here; but elsewhere in this analysis (i.e., in the BAT analysis), 2.45 is used.

Figure 7.15 | Cost-effective distance for CO_2 transport from co-located source to algae facility



More detailed results are included in appendix D. These costs and distances are incorporated in further analysis using the BAT to show potential savings for co-location in appropriate geographical locations.

7.6.2 Results of Land Suitability Analysis

This suitability analysis identified 74,606 unit farms throughout the CONUS (using assumptions defined in section 7.5.3), totaling approximately 139,886 mi2 (362,304 km2), that are potentially suitable for large-scale open-pond microalgae production (fig. 7.16). The suitable areas are ultimately represented by points that represent each unit farm within a suitable area polygon to enable model functions such as least-cost routing (fig. 7.17), to honor land-use restrictions. A subset of the total unit farm populations was selected based on the potential for co-location with key sources of waste CO_2 streams, as described in Section 7.3. Site selection criteria are identical to those identified in Wigmosta et al. (2011) and ANL, NREL, and PNNL (2012), with the exception that forested lands are also excluded.

7.6.3 Biophysically Based Production Estimates

This section provides BAT model analysis results for site-specific biomass production supported by CO_2-based co-location constrained by available supply and transport economics. In total, 12 scenarios are evaluated. Both current and future productivities are modeled for both *Chlorella sorokiniana* and *Nannochloropsis salina* with consideration of three CO_2 co-location options (i.e., ethanol, coal EGU, natural gas EGU) (scenarios shown in fig. 7.1). The site-specific results are ultimately aggregated to the county scale to estimate minimum selling prices at which the biomass can be obtained.

Figure 7.16 | The results of the BAT land characterization and suitability model resulted in 74,606 suitable "unit farms" (1,200 acres) totaling approximately 139,886 mi² (362,304 km²)

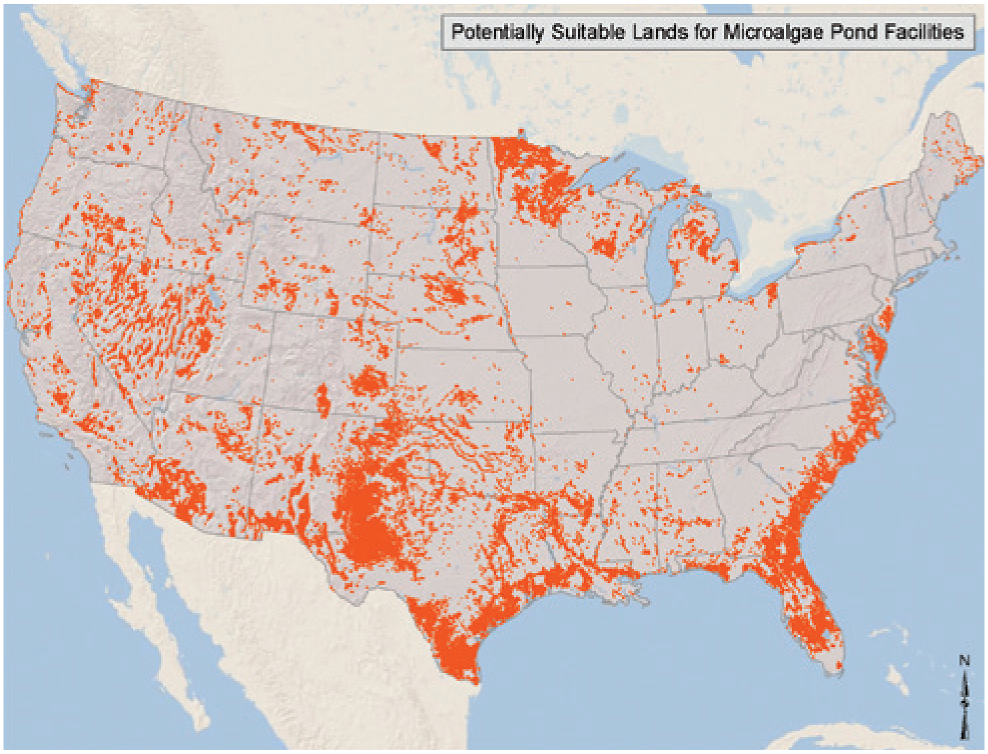
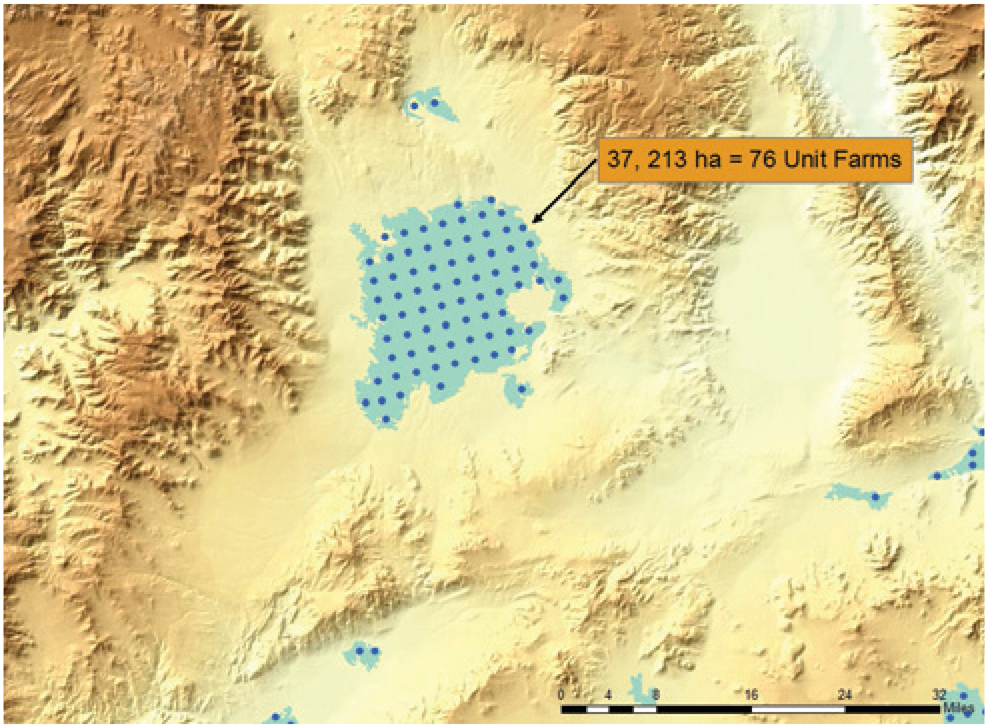


Figure 7.17 | Suitable land areas disaggregated to point-based "unit farms" representing 1,200 acres (1,000 acres of pond area) are used in the scenario modeling



The established scenarios in this chapter are designed to be independent; thus, the resulting biomass produced from *Chlorella sorokiniana* may not be added to the biomass produced from *Nannochloropsis salina*. In addition, results from one waste stream CO_2 type (i.e., ethanol, coal EGU, natural gas EGU) cannot be accurately combined with another. For example, across scenarios, a given production facility may have the opportunity to draw upon multiple sources of waste CO_2 or could grow either a freshwater-based or saline-water-based strain. Future efforts could evaluate economic and sustainability trade-offs between biomass production/strain type and co-located waste resources to identify the ideal combination for an enterprise of production facilities. Summary results of all scenario runs are presented in table 7.7. Additional results for each scenario can be found in appendix D.

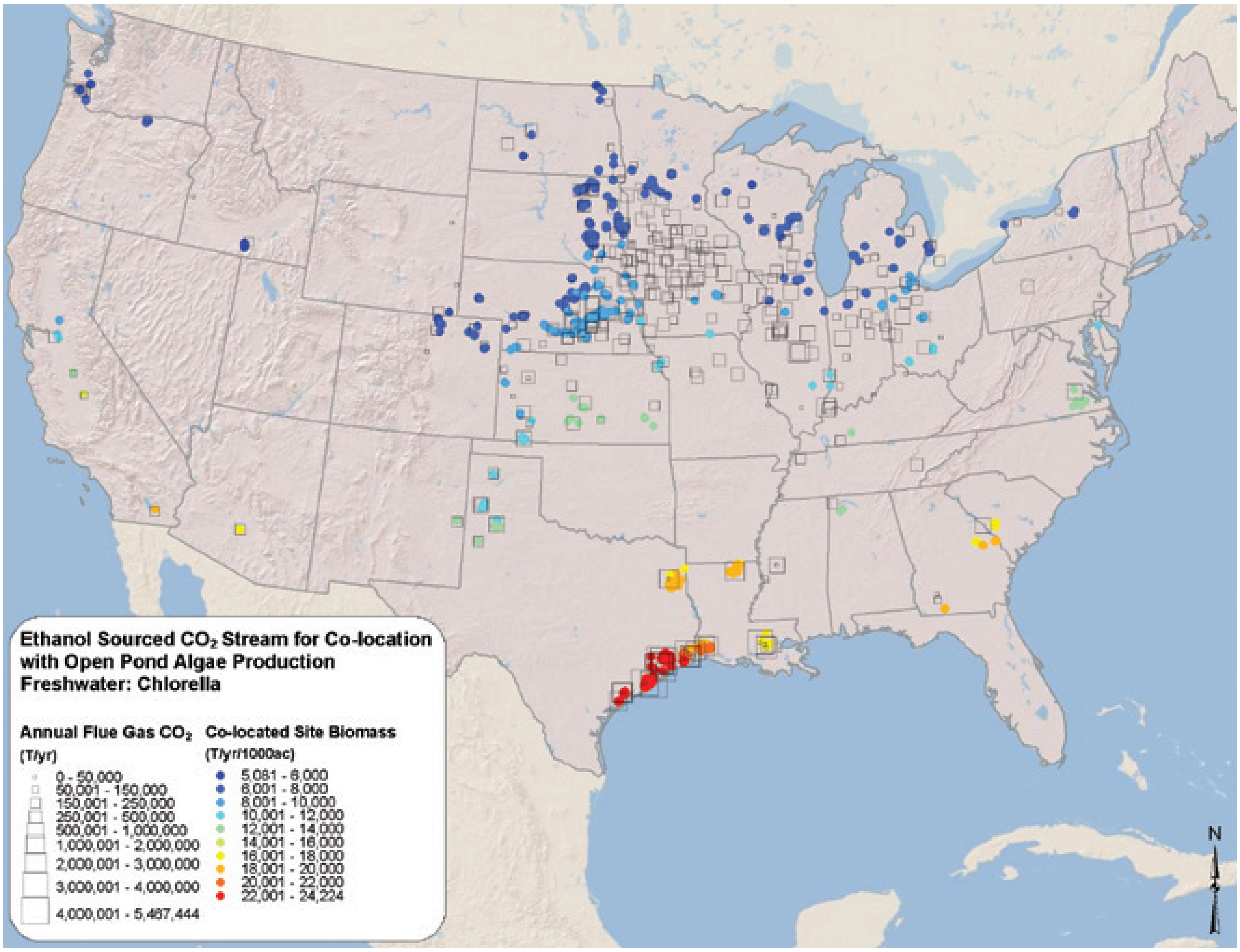
Table 7.7 | Summary Results for Potential Algae Biomass from CO_2 Co-Location with Ethanol Production, Coal EGUs, and Natural Gas EGUs Using *Chlorella sorokiniana* (freshwater) or *Nannochloropsis salina* (saline) Strains Under Current and Future Productivities

	Chlorella sorokiniana			*Nannochloropsis salina*		
	Ethanol production	Coal EGU	Natural gas EGU	Ethanol production	Coal EGU	Natural gas EGU
Current productivity						
Total annual biomass (million tons/year)	11.88	18.54	14.99	10.35	54.40	21.24
Total cultivation area (acres)	904,699	1,256,971	789,610	792,612	3,348,586	1,095,846
Total CO_2 used (million tons/year)	29.21	45.61	36.87	25.45	133.80	52.23
Percent of total CO_2 in CONUS used in co-located algae production	19.3%	1.7%	8.9%	16.8%	4.91%	12.6%
Average distance from CO_2 source to algae facility (miles)	15.2	6.2	4.8	16.0	8.9	6.7
Average cost of co-located CO_2 ($/ton)	$10.67	$19.48	$31.58	$10.92	$21.67	$34.43

Table 7.7 *(continued)*

	Chlorella sorokiniana			*Nannochloropsis salina*		
	Ethanol production	Coal EGU	Natural gas EGU	Ethanol production	Coal EGU	Natural gas EGU
Future productivity						
Total annual biomass (million tons/year)	13.11	10.03	--	11.35	12.35	--
Total cultivation area (acres)	508,393	257,199	--	435,336	299,231	--
Total CO_2 used (million tons/year)	32.24	24.66	--	27.91	30.38	--
Percent of total CO_2 in CONUS used in co-located algae production	21.3%	0.9%	--	18.5%	1.1%	--
Average distance from CO_2 source to algae facility (miles)	14.5	3.8	--	14.6	4.4	--
Average cost of co-located CO_2 ($/ton)	$7.79	$24.04	--	$8.01	$33.43	--

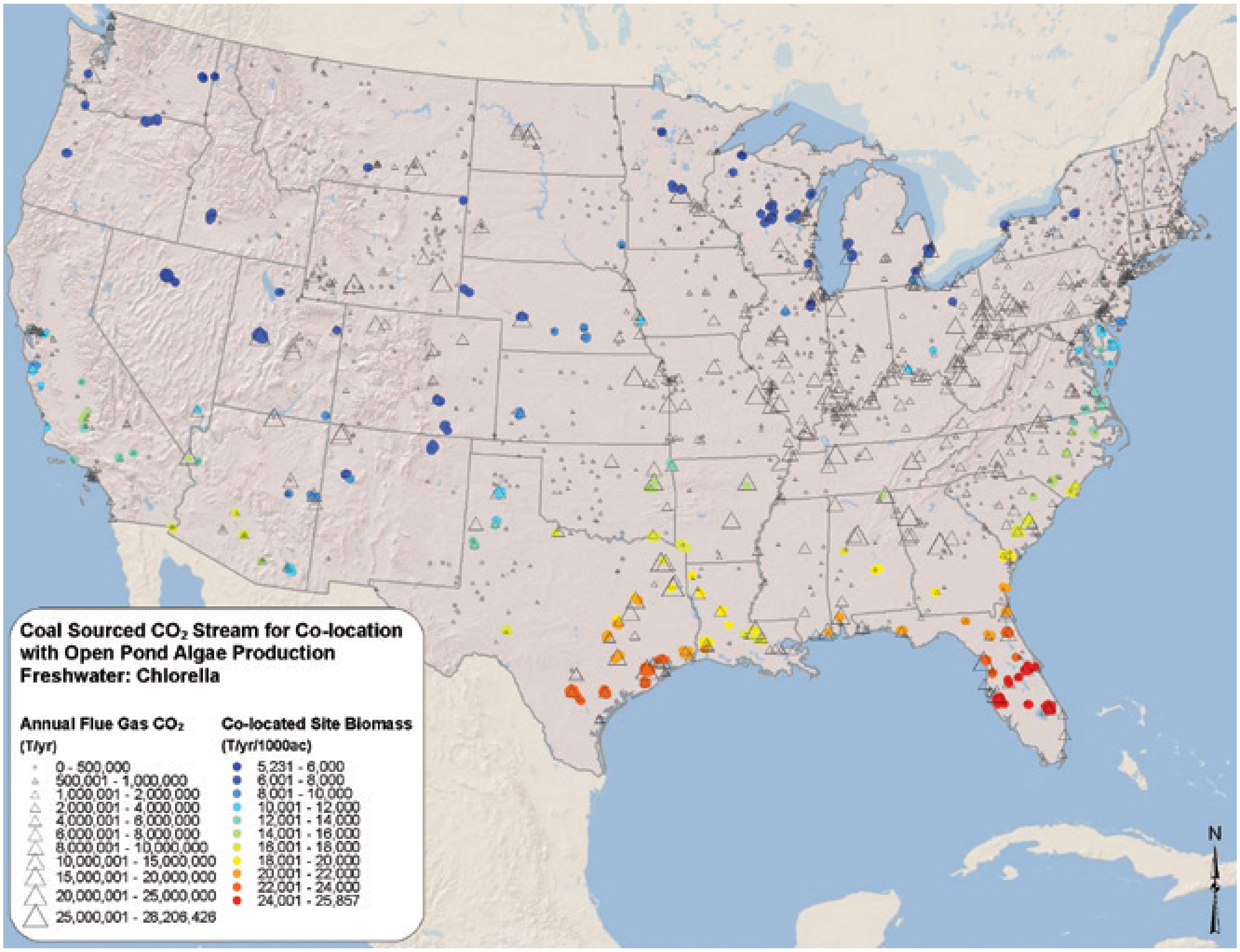
Figure 7.18 | CO_2 co-location opportunity for ethanol production and algae cultivation with *Chlorella sorokiniana*; colored dots represent co-located biomass potential



Ethanol Production Plant Co-Location—Freshwater Open-Pond Scenario (Chlorella sorokiniana): Current Productivity

CO_2 from a total of 117 of 317 total ethanol production plants (37%) is available for cost-effective co-location with algae production sites under the current-productivity assumptions. A total of 904 unit farm sites make use of 29,209,615 tons/year or 19.3% of the total available CO_2 supply (fig. 7.18). Collectively, these algae unit farms produce ~12 million tons/year of biomass with CO_2 delivery costs averaging \$10.67/ton of CO_2 (table 7.7). Additional details are available in table 7.E.1. The large majority of ethanol production sites are located in the upper Midwest, where meteorological conditions are not as favorable for algae production as in the southern CONUS. Under a closed-pond or PBR scenario, these northern locations would be more favorable than they are for open-pond algae production.

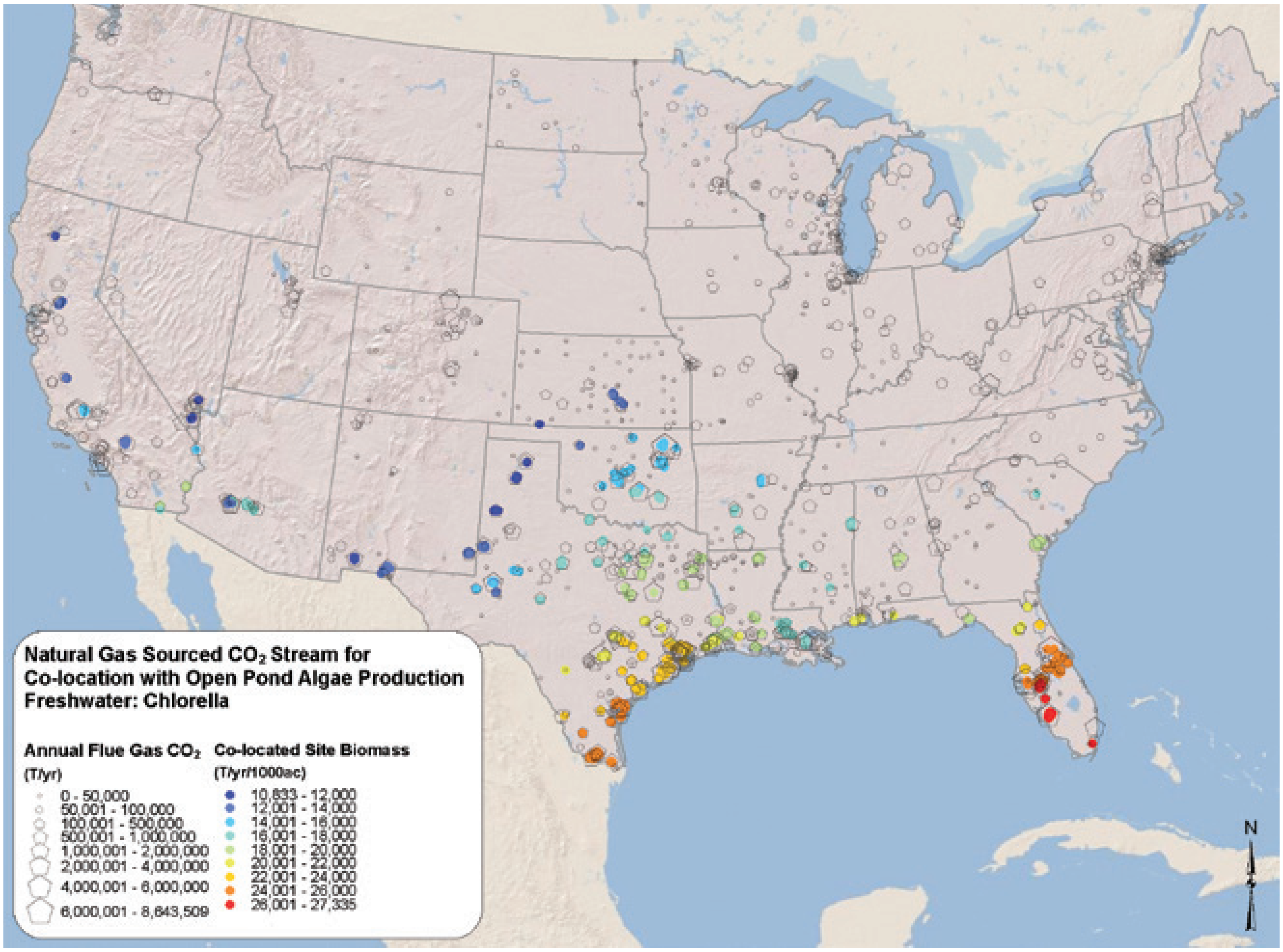
Figure 7.19 | CO_2 co-location opportunity for coal-fired EGUs and algae cultivation using freshwater strain *Chlorella sorokiniana*; colored dots represent co-located biomass potential



Coal EGU Co-Location—Freshwater Open-Pond Scenario (Chlorella sorokiniana): Current Productivity

CO_2 from a smaller fraction of coal EGUs than ethanol plants is available for cost-effective co-location—189 of 1,339 total power plants (14.1%), under the current assumptions, using only 1.7% (~46 million tons/year) of the total available CO_2 supply (table 7.7). The minimum unit of farm land footprint and general land suitability for algal cultivation facilities are not always well aligned. A total of 1,256 algae cultivation unit farms have potential for cost-effective co-location with the 189 coal EGUs, producing a total annual biomass yield of 18.54 million tons/year (fig. 7.19). Across all sites, CO_2 delivery costs an average \$19.48/ton of CO_2 with an average delivery distance of 6.2 miles (table 7.7). With the large number of coal EGUs in the CONUS, there is a good geographic distribution that can take advantage of more favorable meteorological conditions. The large majority of highly productive co-located plants are found in southeast Texas and Florida and along the eastern seaboard. Additional results are available in table 7.E.2.

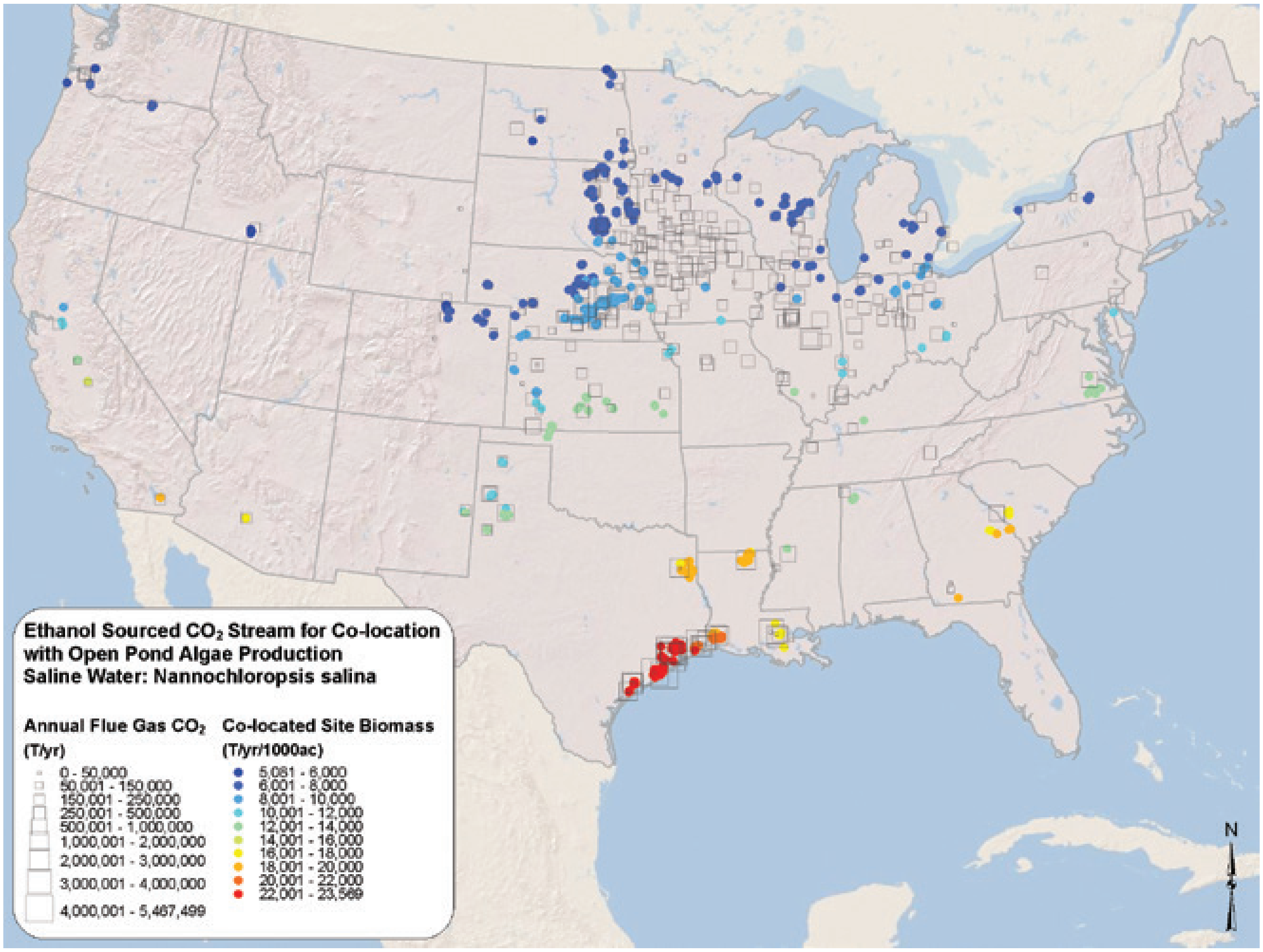
Figure 7.20 | CO_2 co-location opportunity for natural gas EGUs and algae cultivation with *Chlorella sorokiniana*; colored dots represent co-located biomass potential



Natural Gas EGU Co-Location—Freshwater Open-Pond Scenario (Chlorella sorokiniana): Current Productivity

CO_2 from a total of 176 of 1,132 (15.5%) total natural gas EGUs is available for cost-effective co-location under the current assumptions. This is a small fraction of the number of power plants; and, as with coal EGUs, the minimum unit of farm land footprint and general land suitability for algal cultivation facilities are not always well aligned. A total of 789 unit farm sites make use of ~37 million tons/year or 8.9% of the total available CO_2 supply (fig. 7.20). Collectively, these sites produce ~15 million tons/year of biomass with CO_2 delivery costs averaging $31.58/ton of CO_2 (table 7.7). As expected, as the CO_2 concentration in the flue gas decreases, the cost per ton of CO_2 increases, since much of the piping and energetics are involved primarily in transporting N_2, rather than CO_2. The average transport distance across all sites is 4.8 miles (table 7.7). Additional analysis results are available in table 7.E.3. The large majority of co-located natural gas EGUs are located in areas with favorable meteorological conditions (fig. 7.20), allowing for reasonable biomass production.

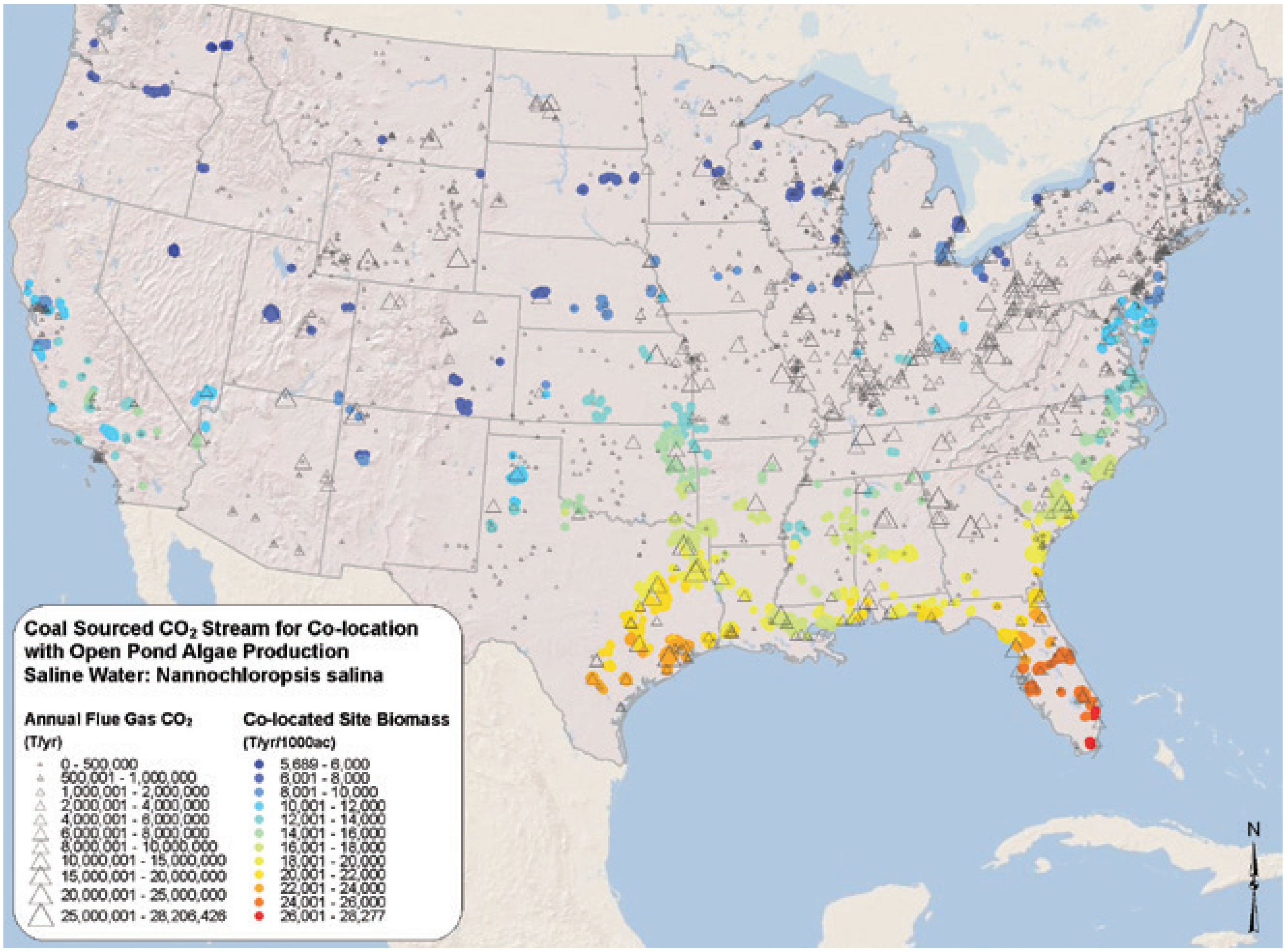
Figure 7.21 | CO_2 co-location opportunity for ethanol production and algae cultivation with *Nannochloropsis salina*; colored dots represent co-located biomass potential



Ethanol Production Plant Co-Location—Saline Water Open-Pond Scenario (Nannochloropsis salina): Current Productivity

CO_2 from a total of 134 of 317 ethanol production plants in the CONUS (42%) is available for cost-effective co-location with saline water sources under the current assumptions. A total of 792 unit farms make use of ~25 million tons/year or 16.81% of the total available CO_2 (fig. 7.21). Collectively, these sites produce ~10 million tons/year of biomass with CO_2 delivery costs averaging \$10.92/ton of CO_2 (table 7.7). Additional details are available in table 7.E.4. The large majority of ethanol production sites are located in the upper Midwest where meteorological conditions are not as favorable for production as in the southern CONUS. However, the biomass is generated primarily in the southern United States, along the coast of Texas (fig. 7.21).

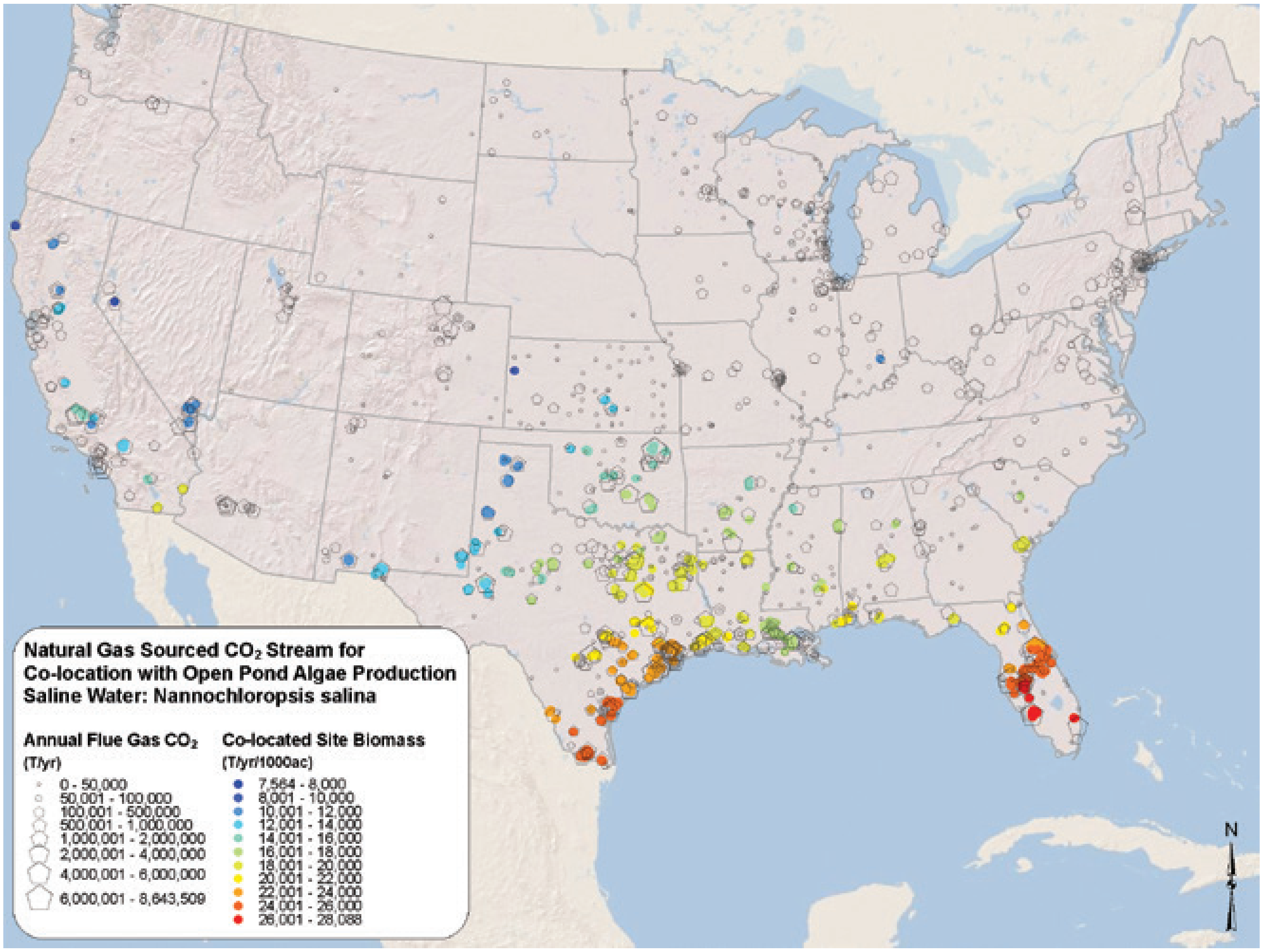
Figure 7.22 | CO_2 co-location opportunity for coal-fired EGUs and algae cultivation with *Nannochloropsis salina*; colored dots represent co-located biomass potential



Coal EGU Co-Location—Saline Water Open-Pond Scenario (Nannochloropsis salina): Current Productivity

As with the other coal EGU scenarios, CO_2 from only a small fraction of coal EGU sites is available for cost-effective co-location; however, because of the larger saline water supply, an additional 57 sites (compared with the freshwater, current productivity scenario) are sourced for CO_2, bringing the total to 246 or 18.4% of the total number of EGUs in the CONUS. As a result of the increased number of sources near suitable land, under current assumptions, the total CO_2 supply used increases (compared with freshwater *Chlorella sorokiniana*) by approximately 88 million tons/year under the current assumptions for a total of ~134 million tons/year or 4.9% of the total available supply. The number of algae cultivation unit farms more than doubles (2.6x) with the addition of more coal EGU sources for a total of 3,346 co-located unit farms. These sites produce a total annual biomass of ~54 million tons/year, an increase of 35.8 million tons compared with the freshwater sites (fig. 7.22). Across all sites, CO_2 delivery costs average \$21.67/ton of CO_2 with an average delivery distance of 8.9 miles (table 7.7). Additional results are available in table 7.E.5.

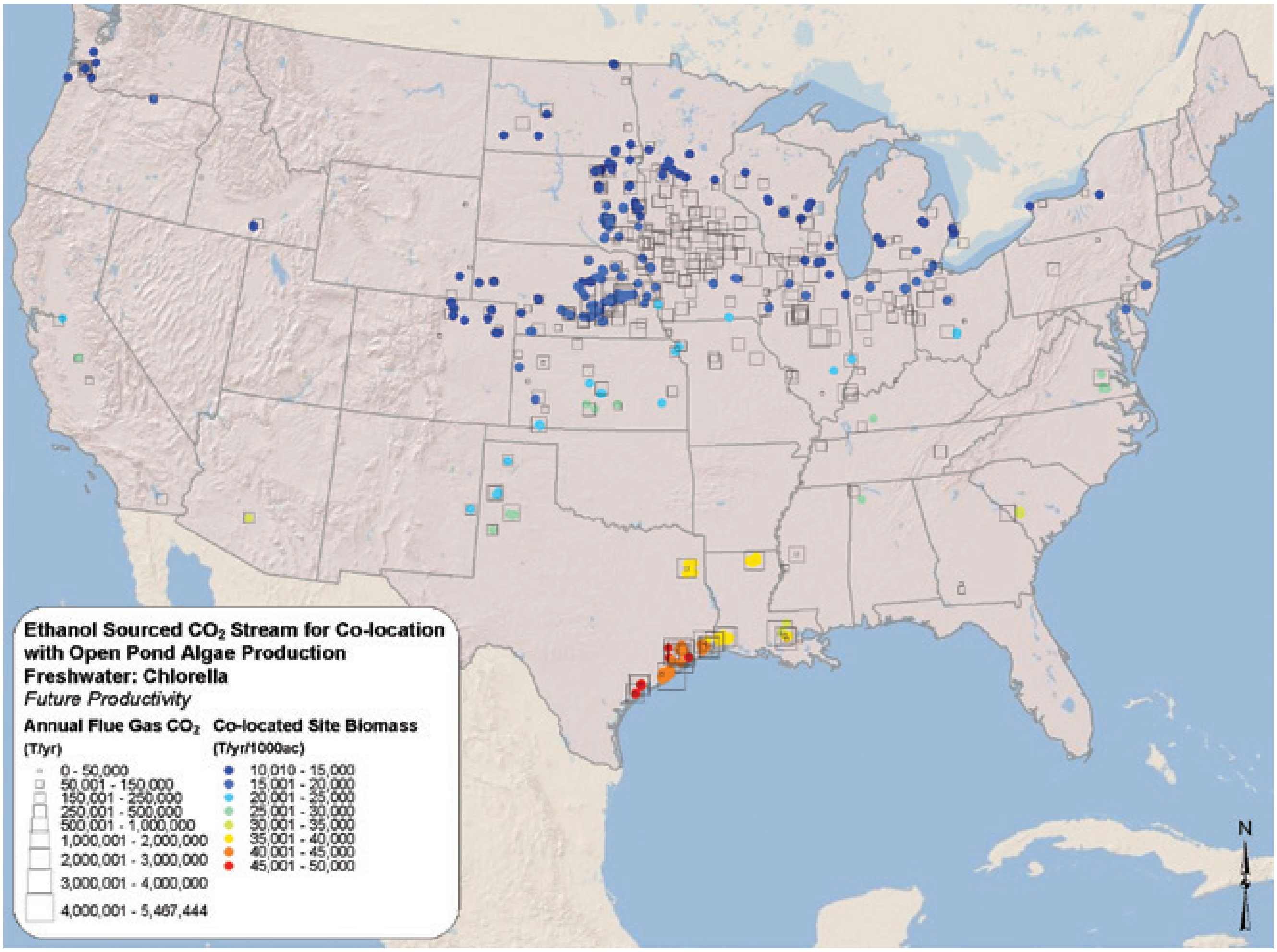
Figure 7.23 | CO_2 co-location opportunity for natural gas–fired EGUs and algae cultivation with *Nannochloropsis salina*; colored dots represent co-located biomass potential



Natural Gas EGU Co-Location—Saline Water Open-Pond Scenario (Nannochloropsis salina): Current Productivity

Co-location of algae facilities with 151 out of 1,132 natural gas EGUs (13.3%) is established under the current assumptions. This is a small fraction of the total EGUs and CO_2 output available; and as with coal EGUs, the minimum unit of farm land footprint and general land suitability for algal cultivation facilities are not always well aligned. The 1,095 unit farm sites make use of ~52 million tons/year or 12.6% of the total available CO_2 supply (fig. 7.23). These unit farms produce a total of ~21 million tons/year of biomass with CO_2 delivery costs averaging $34.43/ton of CO_2 (table 7.7). The average transport distance between natural gas EGU and algae unit farm across all unit farms is 6.7 miles. Additional results are available in Table 7.E.6. As with other natural gas EGU scenarios, the large majority of co-located sites are in the southern United States and generally have favorable meteorological conditions (fig. 7.23) and relatively high yields.

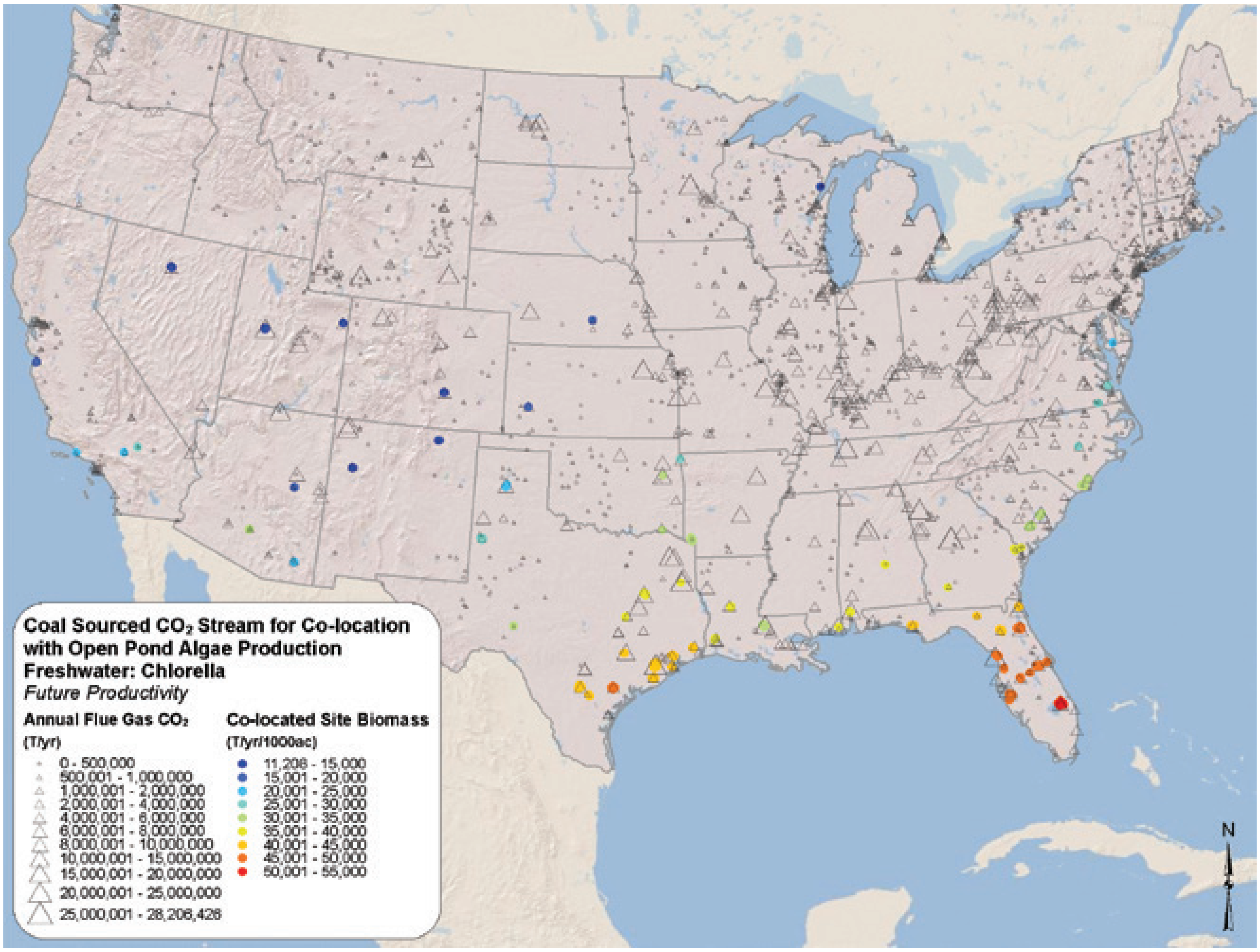
Figure 7.24 | CO_2 co-location opportunity for ethanol production and algae cultivation with *Chlorella sorokiniana* under the future productivity scenario; colored dots represent co-located biomass potential



Ethanol Production Plant Co-Location—Freshwater Open-Pond Scenario (Chlorella sorokiniana): Future Productivity

For *Chlorella sorokiniana* under the future high-productivity scenario, CO_2 from a total of 141 of 317 total ethanol production plants (44%) is available for cost-effective co-location under the future productivity assumptions. A projected 508 unit farms make use of ~32 million tons/year or 21.3% of the total available CO_2 supply (fig. 7.24). Collectively, these sites produce ~13 million tons/year of biomass with CO_2 delivery costs averaging $7.79/ton of CO_2 (table 7.7). Additional details are available in table 7.E.7. Although the mean annual productivity doubles, the number of unit farms that could use a cost-effective CO_2 co-location supply to support the productivity shrinks by nearly 400. However, the overall produced-biomass productivity is higher by nearly 1.2 million tons, and CO_2 streams from additional 23 ethanol plants are used.

Figure 7.25 | CO_2 co-location opportunity for coal EGUs and algae cultivation with *Chlorella sorokiniana* under the future productivity scenario; colored dots represent co-located biomass potential



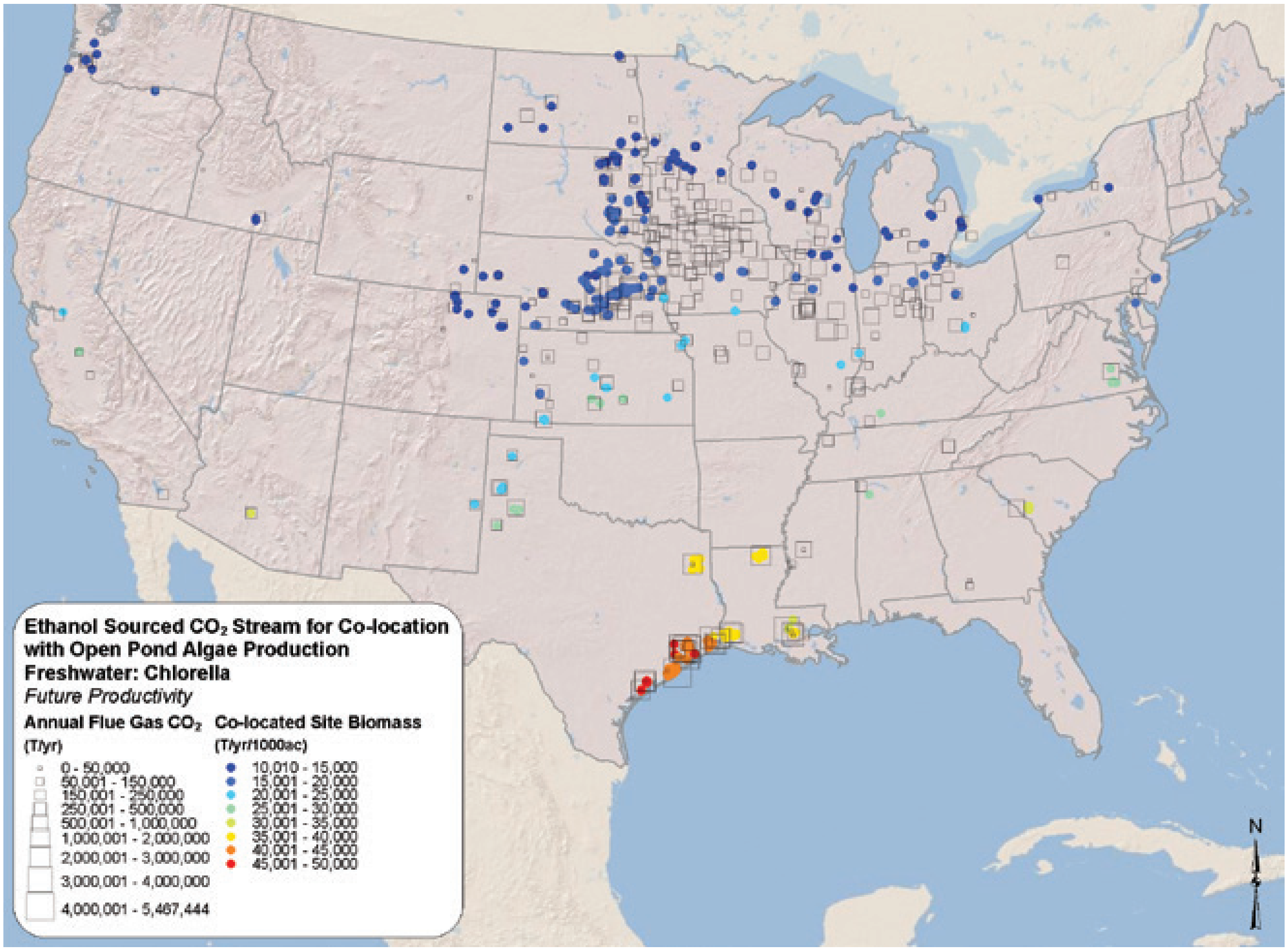
Coal EGU Co-Location—Freshwater Open-Pond Scenario (Chlorella sorokiniana): Future Productivity

Of the available coal EGU sites in the CONUS, a small total of 68 of 1,339 plants (5.1%) are co-located with algae production under the future productivity assumptions, using only 0.91% (~25 million tons/year) of the total available CO_2 supply. A projected 257 algae unit farms receive the co-located CO_2 supply, producing a total annual biomass of ~10 million tons/year (fig. 7.25). Across all sites, CO_2 delivery costs average \$24.04/ton of CO_2 with an average delivery distance of 3.8 miles (table 7.7). With the large number of coal EGUs in the CONUS, there is a good geographic distribution that can take advantage of more favorable meteorological conditions. The majority of co-located high-yield cultivation sites are found in the Gulf States. Additional results are available in table 7.E.8.

Natural Gas Production Plant Co-Location—Freshwater Open-Pond Scenario (Chlorella sorokiniana): Future Productivity

The operating expenditure costs of operating eight parallel pipelines for the low-CO_2-concentration flue gas from natural gas EGUs cannot economically compete with CO_2 at \$40/ton; therefore, no sites are selected.

Figure 7.26 | CO_2 co-location opportunity for ethanol production and algae cultivation with *Nannocloropsis salina* under the future productivity scenario; colored dots represent co-located biomass potential



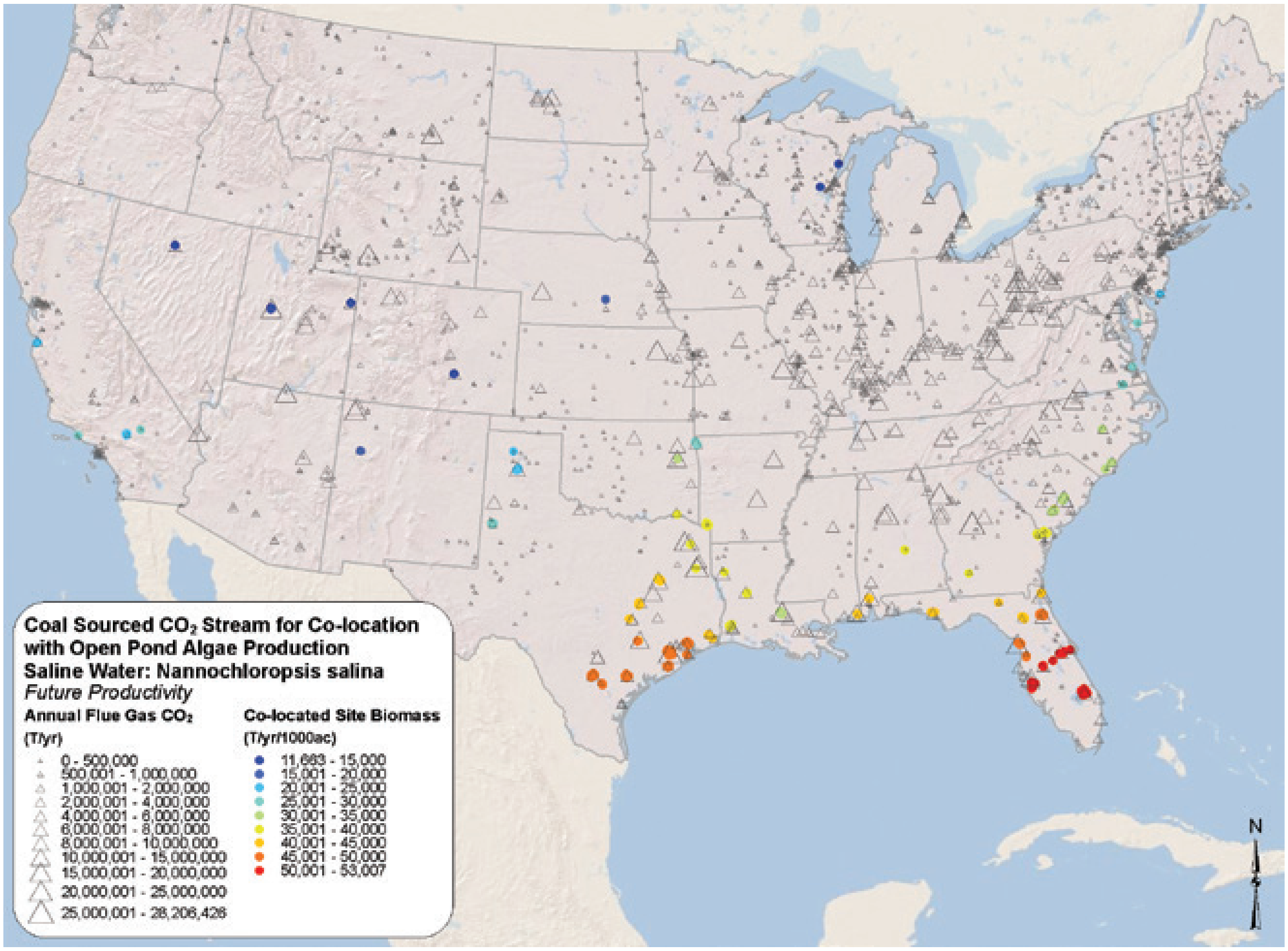
Ethanol Production Plant Co-Location—Saline Water Open-Pond Scenario (Nannochloropsis salina): Future Productivity

Under the future high-productivity scenario using the *Nannochloropsis salina* strain, CO_2 from 127 of 317 (40.1%) of CONUS-based ethanol production plants is available for cost-effective co-location. A projected 435 unit farms use ~28 million tons/year or 18.45% of the total available CO_2 supply (fig. 7.26). Collectively, these cultivation sites produce ~11 million tons/year of biomass with CO_2 delivery costs averaging $8.01/ton of CO_2 (table 7.7). Additional details are available in table 7.E.9. The co-located unit farms are predominantly in the upper Midwest; however there is a strong presence of highly productive sites along the Texas Gulf Coast.

Coal EGU Co-Location—Saline Water Open-Pond Scenario (Nannochloropsis salina): Future Productivity

CO_2 from a small fraction of coal EGU sites is available for cost-effective co-location under the *Nannochloropsis salina* future productivity scenario, where CO_2 is used from only 70 of the 1,339 total coal EGUs (5.2%). Under the improved productivity assumptions, the selected algae production sites

Figure 7.27 | CO_2 co-location opportunity for coal EGUs and algae cultivation with *Nannochloropsis salina* under the future productivity scenario; colored dots represent co-located biomass potential



(unit farms) use 1.1% (~30 million tons/year) of the total CONUS-available CO_2 supply. A projected 299 algae unit farms produce a total annual biomass of ~12 million tons/year (fig. 7.27). Across all sites, CO_2 delivery costs average $33.43/ton of CO_2 with an average delivery distance of 4.35 miles (table 7.7). The cost is higher than for the same strain under the current productivity scenario as a result of the increased volumes of CO_2 being moved and consequent higher pipeline costs. The dominant majority of co-located coal EGU sites are located in the southeastern United States, where favorable productivities are observed. Additional results are available in table 7.E.10.

Natural Gas Production Plant Co-Location—Freshwater Open-Pond Scenario (Chlorella sorokiniana): Future Productivity

The operating expenditure costs of operating eight parallel pipelines for the low CO_2 concentration flue gas from natural gas EGUs could not economically compete with CO_2 available at $40/ton; therefore, no biomass is available from algae unit farms co-located with natural gas plants at high future productivities. This finding would not necessarily hold if CO_2 were stored at night or if natural gas plants were built in new locations.

7.6.4 Economic Availability: National Supply Curves

The unit farm location and BAT yield results, as well as co-location savings that are outputs of the BAT model, are used, along with the equations presented in section 7.5.6, to develop cost-biomass supply relationships at the county level. The variables include three co-location scenarios (coal EGUs, natural gas EGUs, and ethanol plants), freshwater and saline water, full liners and minimal liners for saline scenarios, and current and future productivities.

Table 7.8 shows the range of minimum selling prices per dry ton for co-located algae biomass potential. The lowest price per ton of biomass is for future productivity of *Chlorella sorokiniana* under the ethanol co-location scenario. The median of the minimum selling price for each scenario is much closer to the lowest minimum selling price of biomass than to the highest minimum selling price of biomass.

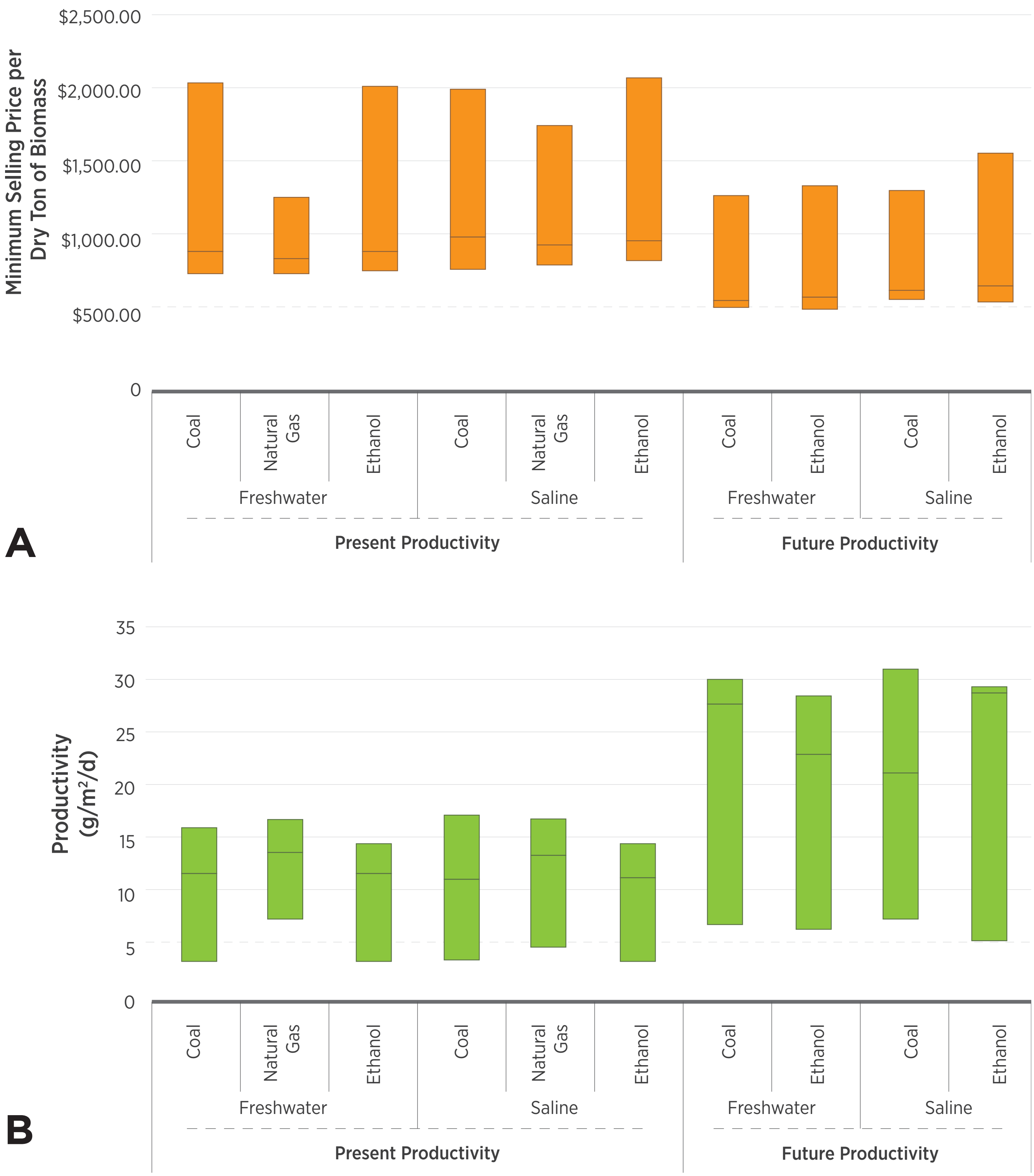
Figure 7.28*A* depicts the minimum selling prices at which biomass becomes available for the different scenarios. Clearly, biomass is available at lower prices in the future productivity scenarios. Figure 7.28*B* shows the productivities associated with the costs in figure 7.28*A*. Costs are lower at higher productivities. Productivities associated with minimum, maximum, and median costs per ton, as well as the Federal Information Processing Standard codes for the counties in which the productivities are observed, are presented in appendix D. On the following pages, we provide examples of price-supply curves for algal biomass.

Table 7.8 | Minimum Selling Prices of Algae Biomass Produced Using Co-Located CO_2 ($/ton biomass) for *Chlorella sorokiniana* (example freshwater strain) and *Nannochloropsis salina* (example saline strain)

Scenario (time)	Scenario (culture medium)	Source of CO_2	Minimum	Median[a]	Maximum
Present productivity	Freshwater	Coal	$ 719	$ 881	$ 2,030
		Natural gas	$ 724	$ 829	$ 1,243
		Ethanol	$ 753	$ 871	$ 2,010
	Saline (minimally lined)	Coal	$ 755	$ 977	$ 1,987
		Natural gas	$ 791	$ 913	$ 1,741
		Ethanol	$ 817	$ 949	$ 2,078
	Saline (fully lined)	Coal	$ 936	$ 1,248	$ 2,745
		Natural gas	$ 977	$ 1,148	$ 2,334
		Ethanol	$ 1,032	$ 1,218	$ 2,889
Future productivity	Freshwater	Coal	$ 498	$ 541	$ 1,258
		Ethanol	$ 490	$ 564	$ 1,327
	Saline (minimally lined)	Coal	$ 550	$ 599	$ 1,294
		Ethanol	$ 540	$ 632	$ 1,546
	Saline (fully lined)	Coal	$ 653	$ 709	$ 1,698
		Ethanol	$ 649	$ 764	$ 2,074

[a]The median is the minimum selling price below which half of the biomass would be available.

Figure 7.28 | Minimum, maximum, and median (bottom, top, and middle of bars) of minimum selling prices of algae biomass (*A*) and associated algae productivities (*B*) for algae production facilities co-located with EGUs or ethanol plants. The distribution of productivities is based on the geographic distribution of CO_2 co-location facilities.



Note: The example species modeled for freshwater media is *Chlorella sorokiniana* and for saline water is *Nannochloropsis salina*. The median minimum selling price is the price at which half of the potential biomass is available across the United States.

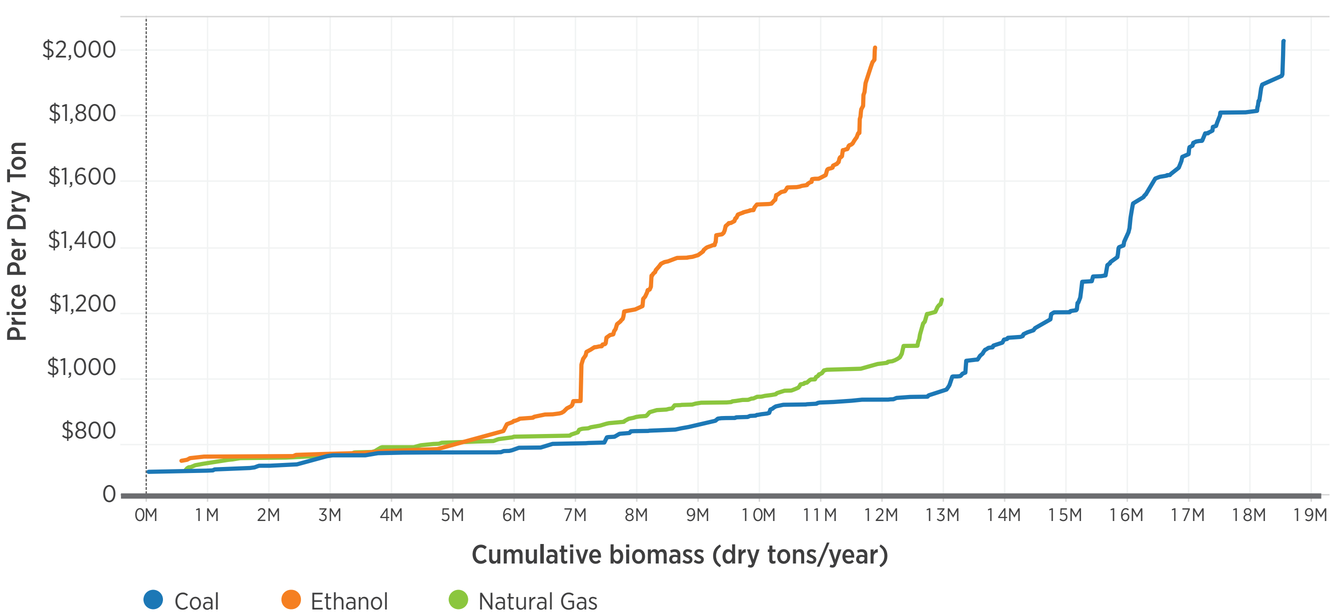
Current Chlorella sorokiniana (Freshwater) Algal Biomass Potential with CO_2 Co-Location

The projected available biomass of *Chlorella sorokiniana* at different minimum selling prices in the United States, assuming current productivities, is depicted in figure 7.29. The data represent algae production facilities co-located with coal EGUs, natural gas EGUs, and ethanol plants. Because simulations of each co-location scenario are run independently, the cumulative biomass supplies will have some uncertainty, as there may be some overlap in locations supplied by each type of CO_2 source.

Figure 7.30*A* depicts the projection of total potential tons of algae biomass by county from freshwater algae production systems in the United States under the current-productivity scenario using the example of coal EGUs as CO_2 sources. Coal EGU-fed production is not distributed randomly across the United States, but rather is clustered along coastlines and waterways and in some southwestern counties. Figure 7.30B depicts the related biomass supply curve of minimum selling price vs. dry tons of algae. The least expensive biomass for *Chlorella* production at present productivities uses CO_2 from the flue gas of coal-fired EGUs (table 7.8).

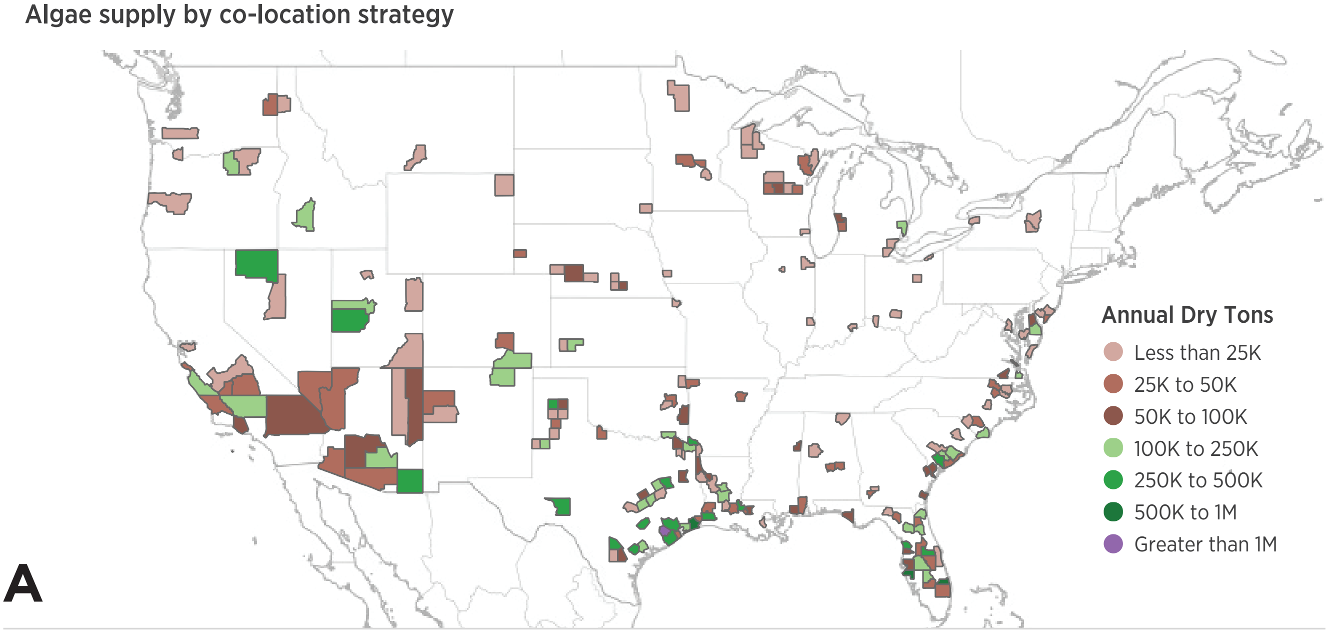
Figure 7.30 and an interactive visualization depict the national distribution of algae unit farms supplied by natural gas EGUs and ethanol production plants, analogous to the coal example. The interactive visualization shows variables for biomass and price results, as well as spatially explicit information. The data project significant geographic diversity for *Chlorella sorokiniana* biomass co-location potentials in the United States. Counties in Florida, Texas, and southern Arizona are among those with the highest biomass productivity rates, which are due to potentially available production sites, CO_2 co-location in the Midwest, especially the western part of the Midwest, is from ethanol plant co-location. Algae biomass potential in the western states is dominantly from co-location with coal-fired EGUs.

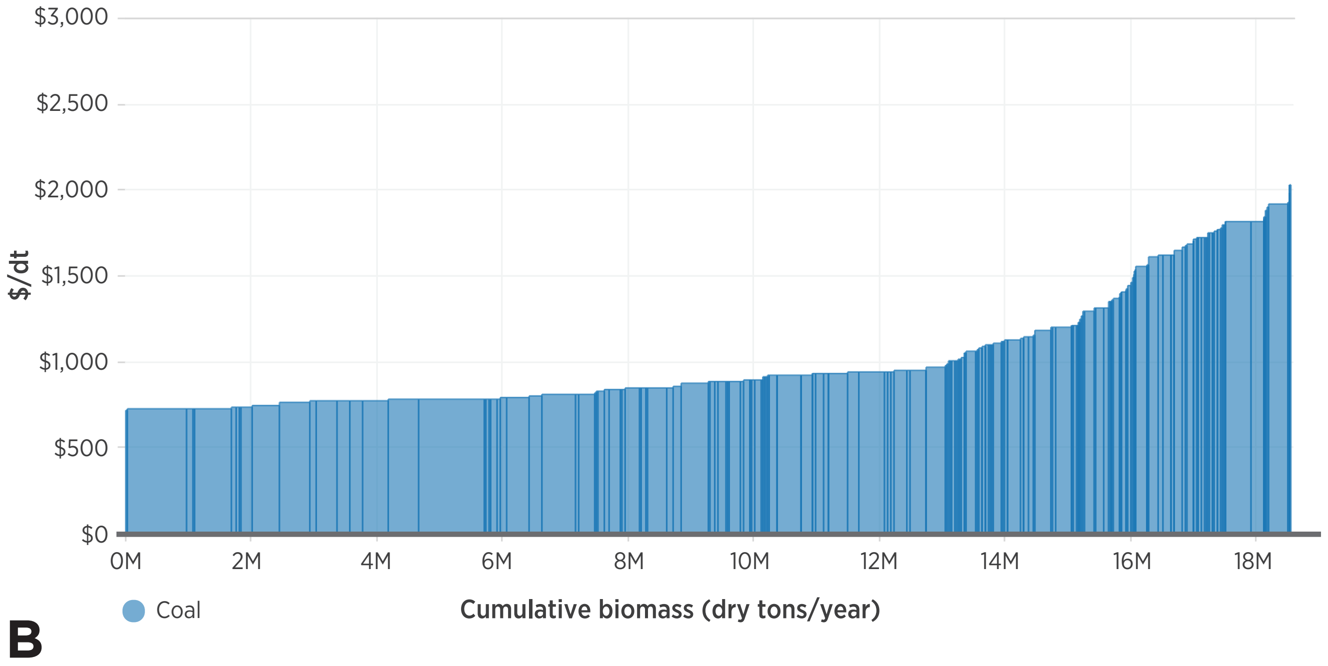
Figure 7.29 | Minimum selling price per dry ton vs. cumulative total biomass for each co-location strategy using *Chlorella sorokiniana* at present productivities[5]



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

Figure 7.30 | Potential biomass supply under coal co-location scenario at current productivity levels using *Chlorella sorokiniana*. *A*, Geographic distribution of potential algae supply. *B*, Supply curve of marginal price ($/AFDW ton) vs. million AFDW tons *(B)*.[6]





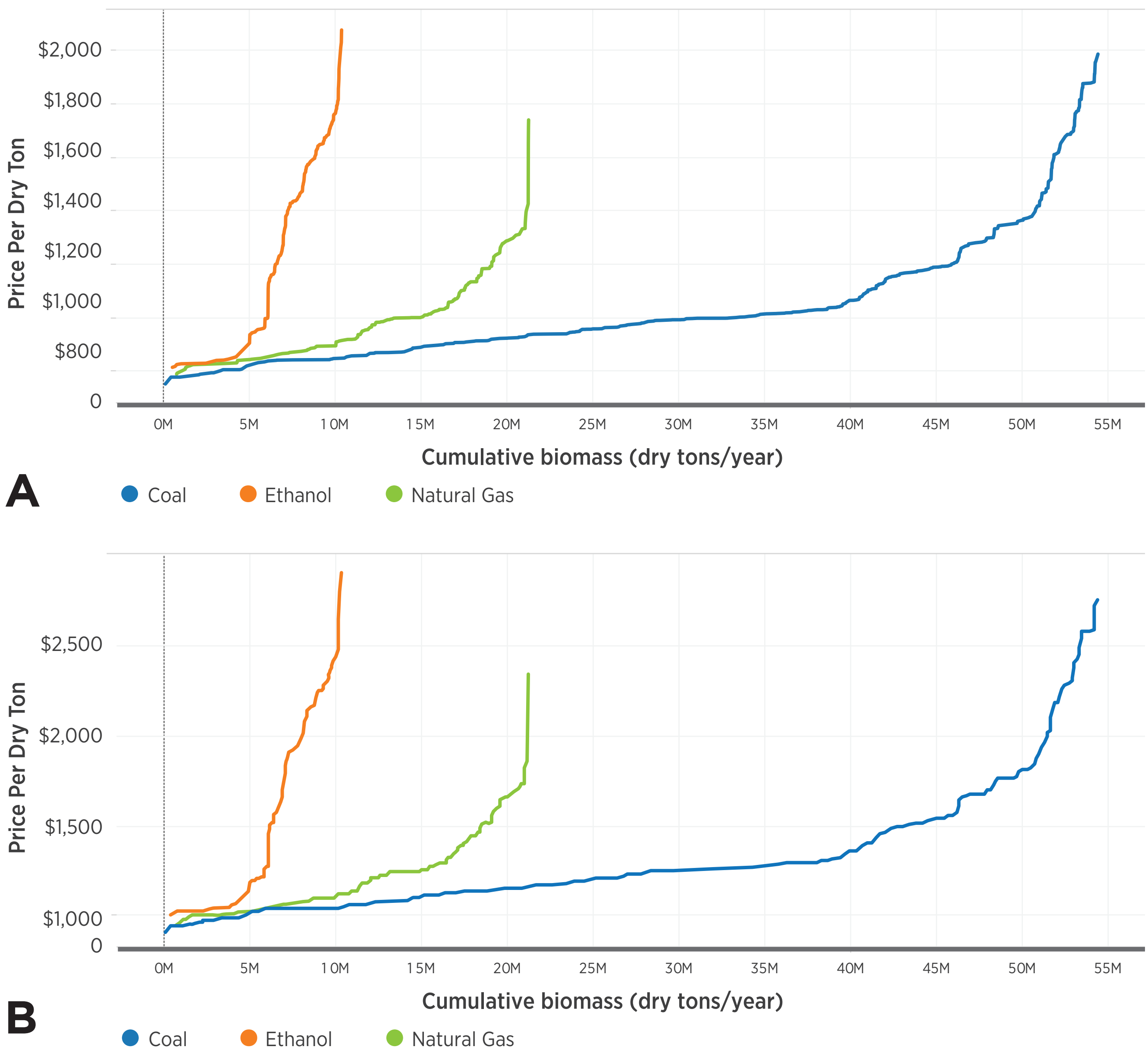
[6] Interactive visualization: https://bioenergykdf.net/billionton2016/7/1/tableau

Biomass co-located with ethanol plants becomes available at close to $800 per AFDW ton (fig. 7.29). Ethanol plants are dominantly located in the cooler climates of the upper Midwest; therefore, annual biomass productivity in an open-pond system is lower than in the warmer Gulf region.

Current Nannochloropsis salina (Saline Water) Algal Biomass Potential with CO_2 Co-Location

The projected available biomass of *Nannochloropsis salina* at different minimum selling prices in the United States is depicted in figure 7.31. The data

Figure 7.31 | Minimum selling price per dry ton vs. cumulative total biomass for each co-location strategy using *Nannochloropsis salina* at present productivities for *(A)* minimally lined ponds and *(B)* fully lined ponds.[7]



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

represent algal biomass at facilities co-located with natural gas EGUs, coal-fired EGUs, and ethanol plants. Biomass for minimally lined ponds is presented in figure 7.31*A* and for fully lined ponds in figure 7.31*B*. The greatest amount of biomass, nationally, is available using coal EGUs as a CO_2 source; the least is available from ethanol plant sources. For current productivities, the full liner adds more than $200/ton of algae biomass.

Figure 7.32*A* depicts total potential tons of algae biomass by U.S. county produced from *Nannochloropsis salina* (saline media); the example of natural gas EGUs as the source of CO_2 with minimal pond liners is shown. Natural-gas–fed production is centered in the south-central United States, with additional production in California and Florida. Figure 7.32*B* depicts a biomass supply curve of minimum selling price based on CO_2 co-location with natural gas EGUs vs. AFDW tons of algae biomass.

Future *Chlorella sorokiniana* (Freshwater) Algal Biomass Freshwater Potential with CO_2 Co-Location

The projected available biomass of *Chlorella sorokiniana* at different minimum selling prices in the United States, assuming future productivities, is depicted in figure 7.33. The data represent algal biomass at facilities co-located with coal EGUs and ethanol plants. The biomass does not reflect any co-location with natural gas, because the power required to transport sufficient CO_2 for the high-productivity scenario brought the cost of CO_2 above the $40 commercial purchase price. When productivity is increased in the future, the lowest costs are substantially lower than under current productivity levels, a cost savings of more than $200 per ton (table 7.8).

The geographic distribution of production, as well as the curve of minimum selling price vs. biomass supply for *Chlorella sorokiniana* in the example scenario of co-location with ethanol plants, is shown in figure 7.34. Biomass becomes available at the lowest price when ethanol plants are the source of CO_2 (fig. 7.34). About 5 million tons of biomass is available at $500/ton. While much of the production is in the upper Midwest, the least expensive production is on the coast of Texas. Ethanol plants as CO_2 sources are associated with the least expensive biomass in all future productivity scenarios.

Future *Nannochloropsis salina* (Saline Water) Algal Biomass Freshwater Potential with CO_2 Co-Location

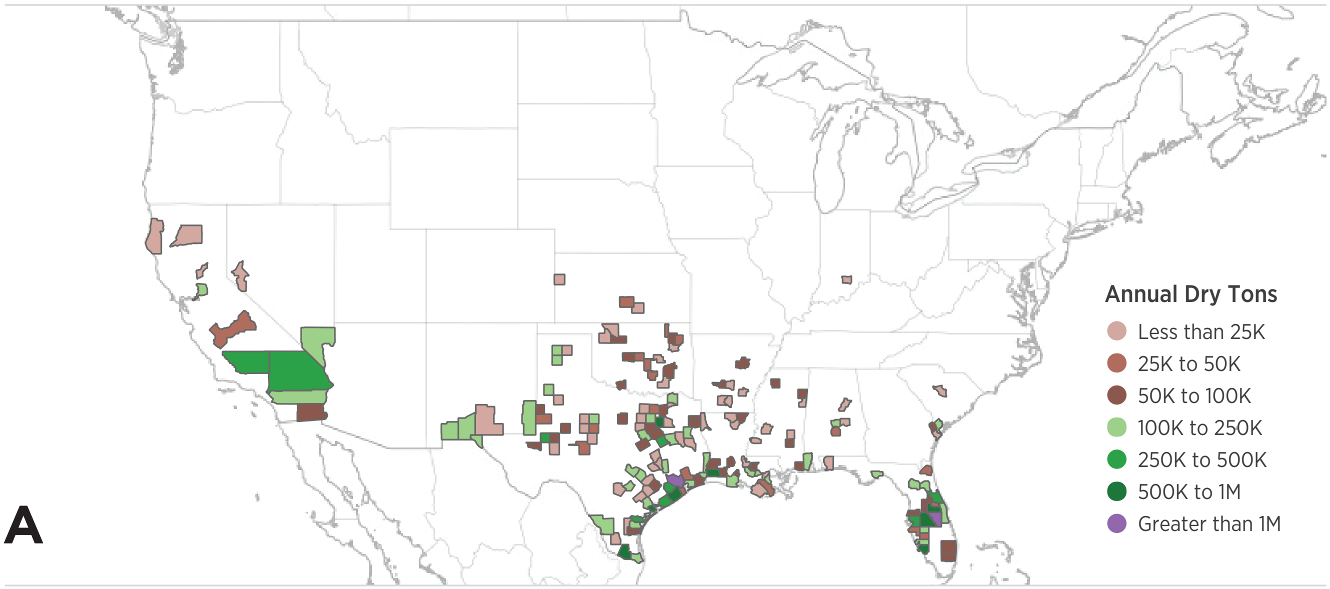
The projected available biomass of *Nannochloropsis salina* at different minimum selling prices in the United States, assuming future productivities, is depicted in figure 7.35. The data represent algal biomass at facilities co-located with coal EGUs and ethanol plants. More biomass is available at the national scale when CO_2 is obtained from coal EGUs than from ethanol plants. As with the future freshwater scenario, the biomass does not reflect any co-location with natural gas. At future productivities, the liner is less expensive than at current productivities, with the highest-productivity site having liner costs at close to $100 per ton of biomass.

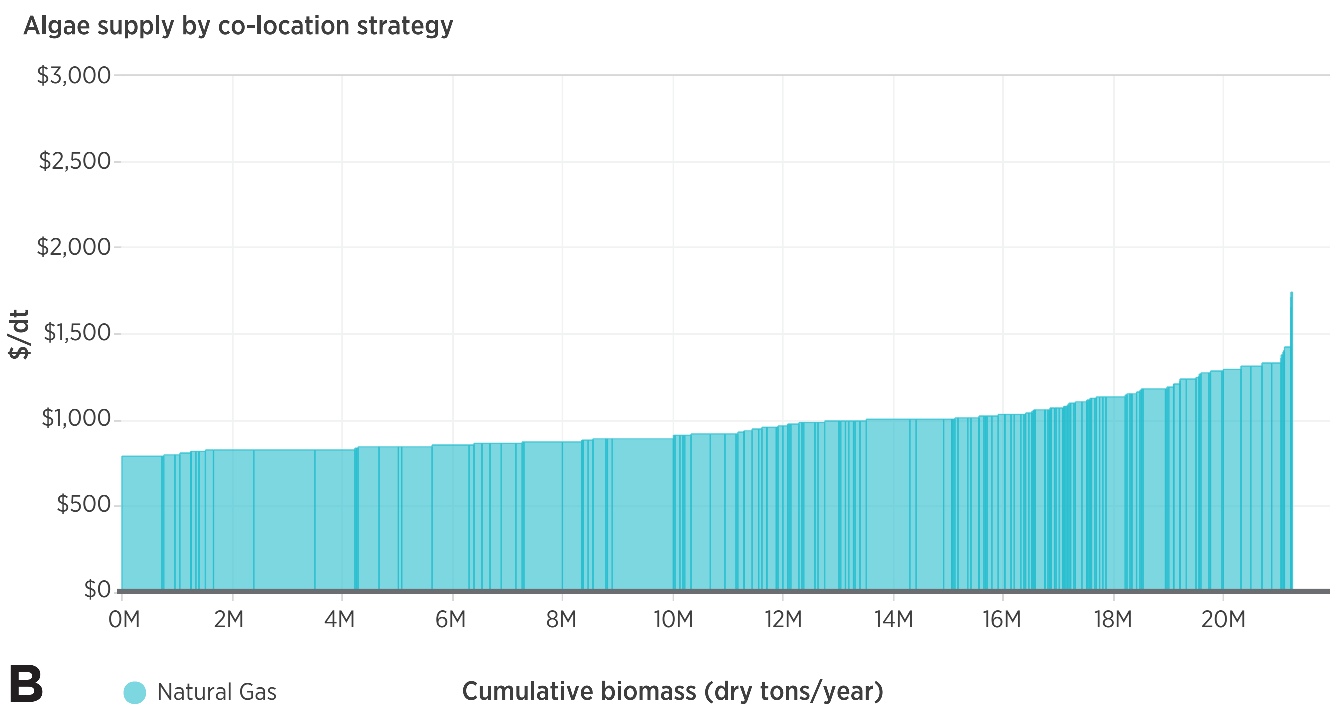
Cost Savings

One of the goals of this chapter is to determine the potential cost savings associated with co-location with CO_2. Cost savings are show in table 7.9. For the present and future productivities, the highest cost savings are projected for ethanol plants as a CO_2 source. However, total costs of biomass associated with ethanol plant CO_2 sources are generally highest for the present-productivity scenarios.

Additional types of cost savings in the scenarios considered in this chapter are projected if (1) higher productivities, such as those assumed for the future, are attained; (2) a freshwater strain is used instead of a saline strain, because of the increased disposal costs, throughput costs (increased ash content), and difference in nutrient requirements of the latter; or (3) minimal rather than full liners are selected.

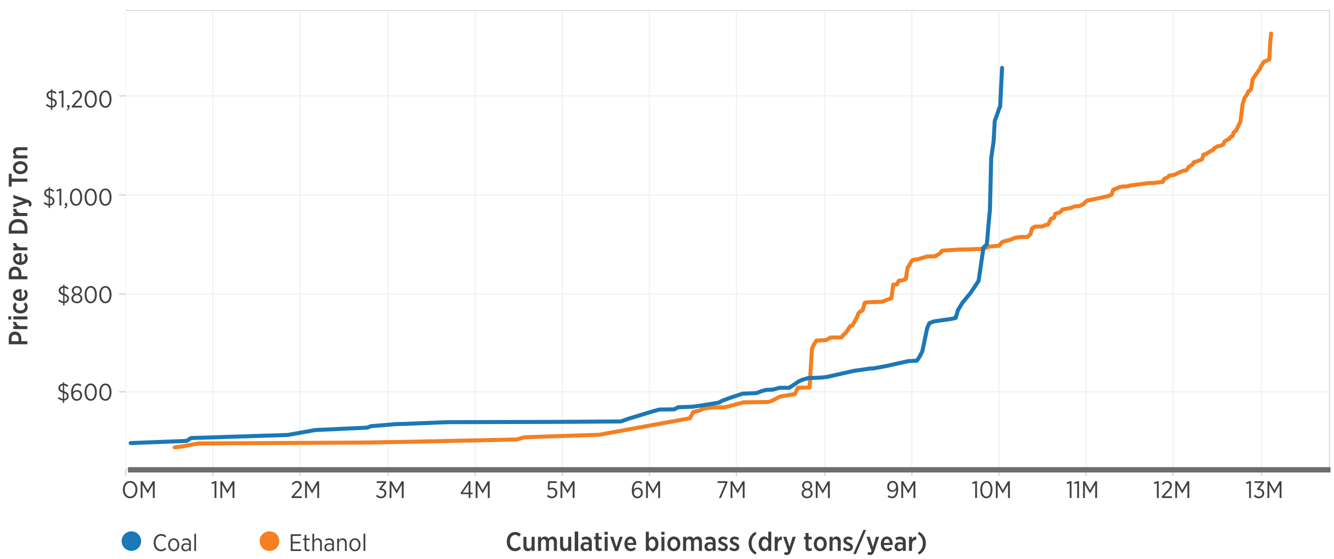
Figure 7.32 | Potential biomass supply under natural gas EGU co-location scenario at current productivity levels using saline media. *A*, Geographic distribution of potential algal biomass supply. *B*, Supply curve of marginal price ($/AFDW ton) by supply (million AFDW tons), including costs for minimal pond liners only.[8]





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

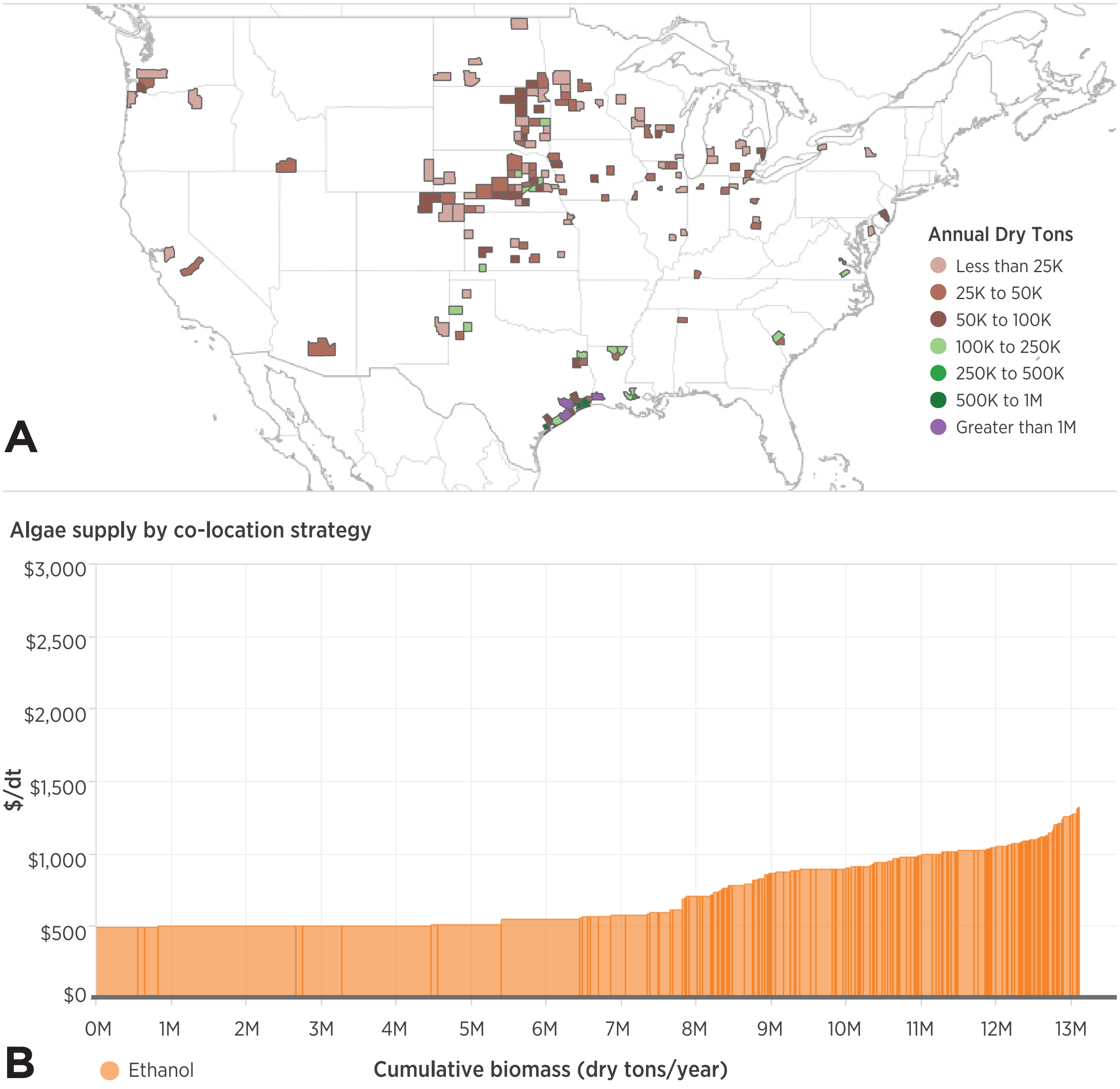
Figure 7.33 | Minimum selling price per dry ton vs. cumulative total biomass for each co-location strategy using *Chlorella sorokiniana* at future productivities[9]



Note: The biomass does not reflect any co-location with natural gas, because the power required to move sufficient CO_2 for the high-productivity scenario brought the cost of CO_2 above the $40/ton commercial purchase price.

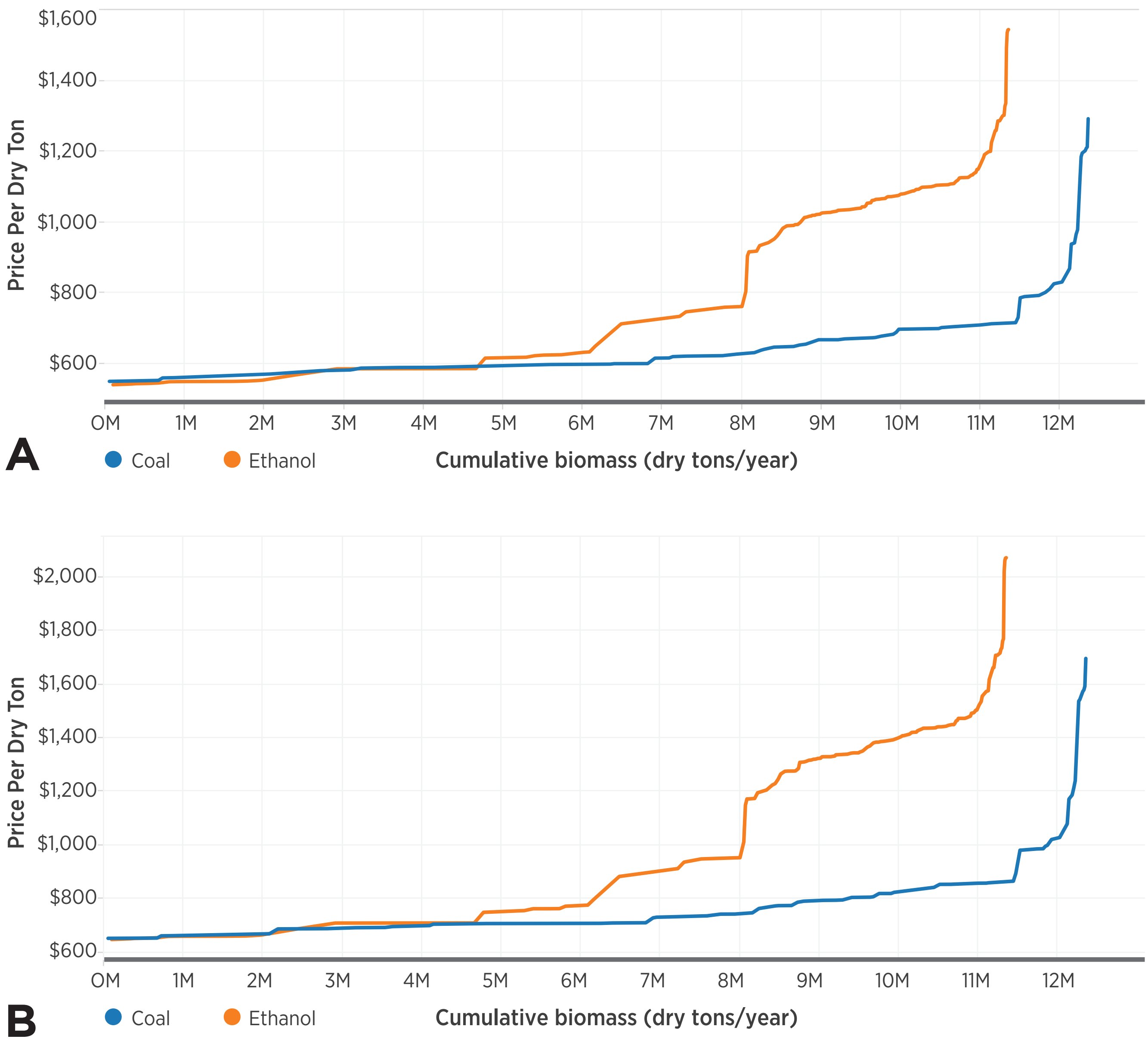
[9] Interactive visualization: https://bioenergykdf.net/billionton2016/7/3/tableau

Figure 7.34 | Potential biomass supply under ethanol plant co-location scenario at future productivity levels using *Chlorella sorokiniana* in freshwater media. *A*, Geographic distribution of potential algae supply. *B*, Curve of marginal minimum selling price ($/AFDW ton) vs, supply (million AFDW tons)[10]



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

Figure 7.35 | Minimum selling price per dry ton vs. cumulative total biomass for each co-location strategy using *Nannochloropsis salina* at future productivities for *(A)* minimally lined ponds and *(B)* fully lines ponds.[11]



Note: The biomass does not reflect any co-location with natural gas, because the power required to move sufficient CO_2 for the high-productivity scenario brought the cost of CO_2 above the $40/ton commercial purchase price.

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

Table 7.9 | CO_2 Co-Location Cost Savings in Open-Pond Algae Production Systems with *Chlorella sorokiniana* (example freshwater strain) or *Nannochloropsis salina* (example saline strain)

Scenario (time)	Scenario (water medium)	Source of CO_2	Mean cost ($/ton CO_2)	Mean cost savings ($/ton biomass)
Present and future productivities	NA	Purchase (assumption)	41.00	NA
Present productivities	Freshwater	Ethanol	10.67	69.66
		Coal	19.48	52.04
		Natural gas	31.58	27.84
	Saline	Ethanol	10.92	69.16
		Coal	21.67	47.66
		Natural gas	34.43	22.14
Future productivities	Freshwater	Ethanol	7.79	75.42
		Coal	24.04	42.92
	Saline	Ethanol	8.01	74.98
		Coal	33.43	24.14

7.7 Discussion

This section discusses the implications, caveats and limitations, and uncertainties of the presented results. It also discusses briefly how coproducts and future policies could affect the production costs and prices of algal biomass and presents plans for future resource analysis.

It is important to reiterate that the chapter provides an estimate of biomass potential at given minimum selling prices. The market for algae-based biofuel is still developing, and the conversion of biomass to biofuel remains an active area of research that is often carried out by the same companies that are cultivating the biomass. This is a different model from the terrestrial feedstock model, in which typically the companies that handle conversion are distinct from the producing farms.

Although there is algae biomass potential, biomass for use in the algal biofuel pathways discussed here is not yet economically sustainable. Co-location of facilities with a CO_2 source can provide significant cost savings; but other advances, such as increases in productivity, are necessary for an economically viable industry.

7.7.1 Implications of Results

The potential biomass estimated from the three CO_2 co-location scenarios could complement the potential terrestrial biomass resources. For the present-productivity scenarios, annual algae biomass is estimated at up to 46 million tons from *Chlorella sorokiniana* (freshwater)[12] or up to 86 million tons from *Nannochloropsis salina* (saline water)[13] from co-location with the three selected CO_2 sources.

Under higher-productivity rates that are anticipated in the future, up to 23 million tons per year could be cost-effectively produced from *Chlorella sorokiniana* or up to 24 million tons annually from *Nannochloropsis salina* from co-location with the three CO_2 sources. The lower future biomass totals are largely due to the increased cost of moving larger quantities of CO_2, which often exceeds the $40/ton purchase price of CO_2 under the implemented technology assumptions. If CO_2 capture and delivery technology becomes cheaper, then the number of sites where potential algae production is co-located with the CO_2 sources considered in this report could be expanded. Even if the benefit of co-location with some CO_2 sources is reduced in the future, that does not imply that the total algae biomass potential would be reduced in the future. Clearly, increasing productivity would decrease the overall cost and price of biomass.

Lands on which terrestrial biomass is produced are not excluded from the potential land base for algae production, so there could be some overlap between the lands used for production of potential terrestrial biomass in chapter 4 and those used for potential algae production in this chapter. However, a previous analysis determined that there would be little competition between algae and terrestrial biomass for specific pastureland sites (Langholtz et al. 2016). Therefore, we assume that the addition of potential algal biomass to potential terrestrial biomass in this report should not lead to a large error in the total, beyond that associated with the uncertain productivities in the future and other uncertainties described below.

The combination of production systems (secretion and other PBR systems described below) and co-location options not quantified in this study (including other CO_2 co-location sources and waste nutrient co-location; see section 7.7.5), as well as the potential for capturing and storing CO_2 24 hours/day, 7 days/week, could represent substantial additional production potential and cost reductions. Of course, the use of commercial CO_2, including in combination with co-located CO_2, could also significantly increase the total national production potential. Moreover, the land suitability criteria used here (e.g., slope) do not necessarily apply to PBRs or terraced open-pond systems. Algae could be grown in offshore membrane enclosures as well (NASA 2012). Additional algae biomass potential could come from innovative cultivation management practices; these include algal crop rotation, in which strains are used to maximize productivity based on seasonal meteorological conditions; polyculture, in which multiple strains are combined to increase productivity and decrease susceptibility to pathogens and predators; and/or thermal management of media, in which, for example, heat is conserved overnight (Waller et al. 2012) or co-located waste heat is used to maintain ideal growing temperatures. As noted earlier, biomass for heterotrophic fuel production is not considered.

Even with the benefit of co-location for CO_2, algal biomass has higher production costs than terrestrial feedstocks. Under current productivities, algae estimated costs reported here range from $719 to almost $3,000 per dry ton, compared with terrestrial feedstocks largely available at farmgate and roadside prices ranging from $30 to $60 per dry ton, as

[12] "Up to" is used because the co-location scenarios were independent and not competed, so there may be some overlap in productivity from these three scenarios.

[13] These biomass values should not be added because some of the biomass potential estimated for *Chlorella sorokiniana* occurs on the same lands as that estimated for *Nannochloropsis salina*.

reported in chapters 3 and 4. This is not surprising, given the early development state of algae production technologies, as well as the need to handle a large amount of water and to build an engineered pond. The cost of algal biofuel is very sensitive to the cost of algal biomass (cultivation and dewatering) (Davis et al. 2016).

However, it is important to note that the harvested algae at the end of this analysis are more "finished" than the terrestrial biomass. That is, algae producers are economically closer to a finished fuel product than are terrestrial biomass producers. Davis et al. (2016) estimate that at a $430 per dry ton minimum biomass selling price for either the algal lipid extraction or hydrothermal liquefaction conversion pathway, the lowest fuel cost would be $4.35 to 4.49/gasoline gallon equivalent. (The fuel price would be higher at the minimum biomass selling prices estimated in this chapter, with lower productivity assumptions in the present scenarios; smaller facility sizes; and, in some of the saline cases, full pond liners.)

The cost of transporting CO_2 is an important determinant of the cost of biomass. And the purity of the CO_2 being transported is a major factor affecting the feasible transport distance: with a higher-purity CO_2 stream, energy is not being spent to transport unnecessary gases (i.e., N_2). Thus, different sources of CO_2 are associated with different transport distances, resulting in different costs (and minimum selling prices) of biomass production.

The cost-effective transport distances for CO_2 are greatest for ethanol plants. But the lowest-cost biomass potential is from coal EGU co-location scenarios, rather than ethanol plant scenarios, despite the higher costs of moving the impure flue gas. The main reason is that ethanol plants tend to be located in cool locations, rather than on the Gulf Coast or in Florida, where production facilities have the highest productivities. In other words, the gains in productivity for warmer locations outweigh the CO_2 cost savings differential from the higher-purity CO_2 from ethanol plants, given the dramatic cost dependencies on productivity (particularly at lower productivity values). If PBRs or even covered ponds were considered, more biomass would be available at lower prices from cultivation facilities co-located with EGUs or ethanol plants.

Although EGUs would appear to be ideal sources of CO_2 for algae because they are ubiquitous, and because minimizing, eliminating, or using their GHG emissions is desirable, the dilute gas stream increases the infrastructure required for transport and use. On the other hand, the CO_2 stream from ethanol plants (considered here), as well as from cement plants, ammonia plants, and steam methane reformers (producing hydrogen), is pure enough that it can simply be captured and transported. However, many pure CO_2 waste streams may already be supplying industry as a commercial product (Middleton et al. 2014).

For future productivities, the minimum selling price is as low as $489 per dry ton for *Chlorella sorokiniana* biomass produced in freshwater media using CO_2 from an ethanol plant. The cost savings for increasing the productivity substantially is much higher than the cost savings for co-location with the CO_2 sources considered in this chapter. Davis et al. (2016) estimate that if productivity could be increased from an annual average of 25 to 35 g/m^2•day, then the minimum biomass selling price would decrease by $90 per dry ton. Productivity has an even greater effect on price at lower productivities, with a reduction from 25 to 15 g/m^2•day, giving a penalty of $220/ton of biomass (Davis et al. 2016). Cost would be very sensitive to changes in the low productivities observed in the upper Midwest. When productivity is low, the efficiency of pond usage (i.e., capital) is poor.

It is notable that at the future productivities assumed here, under our technology assumptions, there is no cost savings for algae co-located with natural gas. The power requirements to pipe sufficient CO_2 to meet higher biomass productivities are very costly with respect to energy. This might not be the case if an alternative technology were used, in which flue gas stream is captured 24/7, CO_2 is stripped, and purified gas is transported as a gas or even absorbed in water and then transported. The transport of supercritical CO_2 is more efficient than transport of CO_2 as gas; but in general, compressing CO_2 to a supercritical state is expensive (from an energy and cost perspective). Supercritical, high-pressure transport of purified CO_2 via flue gas carbon capture would allow for decoupling the algae farm from the CO_2 source, thereby allowing for longer transportation distances and considerably higher potential for national-scale biomass production than do estimates constrained to co-location scenarios.

As expected, biomass of *Nannochloropsis salina* from the saline production systems is not as economically viable as *Chlorella sorokiniana* biomass produced in freshwater culture. The high cost of algal biomass from the saline scenarios with liners shows the importance of technology development in that area. Costs of blowdown waste disposal could be reduced as well, and some may already be lower than the assumptions in this analysis. There will always be extra costs for handling higher-ash saline cultures. Incorporating the externality costs and benefits of using saline water in place of freshwater could influence these results and is a research gap.

Economies of scale are also important. In line with Davis et al. (2016), we assume 10-acre ponds, yet cultivation ponds specific to biofuel production that are greater than 2–3 acres are not common today. If smaller ponds were assumed, economies of scale would be reduced.

The current results suggest that DOE's targets of modeling a sustainable supply of 1 million tonnes

Text Box 7.2 | Photobioreactors and Secretion of Fuel Products

PBRs are closed production systems that allow regulation of the culture environment, including light, temperature, water supply, pH, and biomass density. PBRs are found in a wide variety of engineered configurations and may be constructed as tubes, cylinders, helical tubes, or flat plates. Most systems use pelagic cyanobacteria (water columns) that secrete ethanol or hydrocarbons, whereas others grow microalgae as a biofilm (Schnurr, Espie, and Allen 2014). At both commercial and research sites, it is common to have a hybrid system of PBRs and open ponds, in which the bioreactors are used as nurseries to cultivate pure stocks of algae to a given concentration (0.5–1.0 g/L), after which they are used to inoculate the open ponds.

Arizona State University Algae Testbed Public-Private Partnership flat-panel photobioreactor

PBRs have many advantages in that they are generally less prone to biological invasions such as by pathogens, lose very little water to evaporation (if cooling water is not required), maintain higher temperatures than open ponds during cold seasons, and can potentially use industrial waste heat. Less frequent harvesting than for pond/raceway systems is required if ethanol or hydrocarbons are secreted by cyanobacteria. Conducting conversion in the cultivation system could reduce fuel costs.

However, PBRs may present operational challenges associated with overheating and fouling. PBRs require significant capital investment and have yet to be demonstrated for large-scale energy production.

(1.1 million tons) of AFDW cultivated algal biomass by 2017 and of modeling a sustainable supply of 20 million tonnes (22 million tons) of AFDW cultivated algal biomass by 2022 should be achievable. Definitions of "sustainable" will be discussed in Volume 2 of this report, which is focused on the sustainability implications of the potential biomass results.

As Davis et al. (2016) note, some major ways to decrease the costs of algal pond systems, moving into the future, would be to increase productivity, to use large ponds and overall facility and farm sizes to maximize economies of scale, and to avoid fully lined ponds. The decreased costs in the future scenario reiterate the importance of productivity in determining costs. Alternatively, considering smaller farms may result in more potential sites and broader co-location potential and thereby lead to greater overall biomass potential.

7.7.2 Applicability, Limitations, and Uncertainties

Various algae production technologies and designs have different capital and operating costs (Abodeely et al. 2014; Davis, Aden, and Pienkos 2011; Venteris, Skaggs et al. 2014b) and may benefit in varying degrees from different co-location strategies. Depending on the extent of the supply chain considered, related production options include algal strain(s) used, cultivation technology, harvest and dewatering technology, fuel upgrading process, and system water and nutrient recycling options.

One important assumption is the use of open-pond/raceway systems rather than PBRs or hybrid PBR-open-pond systems (Beal et al. 2015). The results of this analysis are not relevant to PBRs. PBRs would have a distinct advantage, compared with open pond/raceway systems, if facilities were co-located with CO_2 in cooler climates, because temperature could be controlled and waste heat from co-located facilities could potentially be used (see text box 7.2).

Regional issues will also affect costs. In the current analysis, both capital expenditure (piping and blowers) and operating expenditure (energy requirements) costs will be impacted by the distance from the CO_2 source and the purity of the CO_2. Pipe size is optimized accordingly to fit the spatial relationship between site and CO_2 source.

The most important regionally sensitive variable is actual biomass productivity, which is simulated here, and which will affect the projected biomass and significance of CO_2 savings. Cultivation productivity is the strongest cost driver, especially below an annual average productivity of 25 g/m^2•day (Davis et al. 2016).

Many caveats and limitations apply to the curves of minimum selling price versus potential biomass supply. They are most applicable to the modeled cultivation systems assumed in the BAT model and in Davis et al. (2016), including inoculum technologies. The biomass yield results are most applicable to species assumed in the production model: a *Chlorella sorokiniana* strain for freshwater media and *Nannochloropsis salina* for saline media. The base case costs that were taken from Davis et al. (2016) assume the use of *Scenedesmus acutus (LRB-AP 0401)*, a freshwater strain, to determine nutrient and CO_2 requirements; so adjustments to the other strains introduce some uncertainty into the supply curves.

Results are applicable to co-location conditions assumed here. Sources include ethanol plants, coal-fired EGUs, and natural gas EGUs. Costs of transporting dilute CO_2 restrict the number of potential co-located unit farms, but these costs could change with new technologies in the future. The assumption that CO_2 is not stored at night is a major assumption affecting results. Some algae companies are storing CO_2 at night, which could decrease CO_2 transport system costs and increase potential biomass production, compared with the assumptions in this chapter.

Many uncertainties in the assumptions in this chapter potentially affect the accuracy of results:

- **Productivity.** Although the BAT biomass productivity model has been validated against numerous observation data sets, values simulated by the BAT model have a degree of uncertainty; and we have not optimized the strain choice for regional and/or seasonal productivity. It is possible to improve upon less favorable thermal growth conditions with particular open-pond designs (e.g., ARID Pond) (Khawam et al. 2014, Waller et al. 2012). Many additional factors could affect productivity. For example, crash frequency is not considered in productivity estimates. Also, if flue gas is used, contaminants could cause productivity to increase or decrease (Napan et al. 2015). Future productivities assumed in these analyses are already found in open-pond systems at some highly suitable locations, but scientific advances are needed to achieve this value in other locations. The year that future productivity levels assumed in this chapter will be achieved is uncertain.
- **Facility size.** Whereas Davis et al. (2016) assume 5,000 acre cultivation facilities, we assume 1,000 acre cultivation facilities, with an additional 200 acres of infrastructure, for both current and future cases. In doing so, some economies of scale (for dewatering equipment, circulation pipelines, storage and labor/fixed operating costs) are reduced (compared with Davis's estimates at the 5,000 acre scale) and are approximately quantified, resulting in an approximate increase of $102 per ton (Davis et al. 2016), adjusted for 2014 dollars. Moreover, this decrease in economies of scale could add significant costs to conversion pathways, considering final dollar-per-gallon fuel costs. However, there would be an advantage in the biophysical potential of decreasing the minimum facility size so that more lands with co-location potential could be included in the BAT-based resource analysis, particularly with respect to coal EGUs, where the total CO_2 utilization is limited under this analysis.
- **Pond liner.** As in Davis et al. (2016), we assume that liners are not needed for freshwater ponds, except for portions of the ponds/raceways that are vulnerable to erosion. Freshwater ponds are assumed to self-seal in all soils, although in reality, sandy soils are less likely to seal than clay soils. Venteris, McBride, et al. (2014) identify some locations where natural soil conditions would minimize water losses and water quality concerns below freshwater ponds. Ongoing research is investigating soil and substrate requirements for sealing. The assumption that only saline cultivation systems may require liners may not be conservative, as some soils may not seal, and current environmental regulations may require liners for permitting. Also, carbon sources may be needed for microbial sealing, which would add costs. Moreover, pond liners might need to be replaced within the 30 year facility lifetime.
- **Capital and operating costs.** Capital costs for the current case are taken from Davis et al. (2016) and adjusted to 2014 dollars. Uncertainties in these values could be large. Some of the costs, especially savings at scale, are uncertain. Also, the costs of distributing dilute CO_2–containing flue gas from coal-fired EGUs or natural gas EGUs would be higher than the base case of purified/concentrated CO_2 in Davis et al. (2016). Moreover, capital and operating costs for the future scenario are not altered from present costs. Therefore, future costs are highly uncertain; and some costs could be reduced and others increased, depending on the future year. Fertilizer costs in the future are uncertain.
- **Water availability.** A key assumption is that biomass production is not constrained by local water policies, but rather is constrained consistently across the nation to use only 5% of available

mean annual surface water flow within an HUC-6 (hydrologic unit code–6) scale watershed (ANL, NREL, and PNNL 2012). That is a questionable assumption, given competition over freshwater and restrictions on new development in some parts of the country. Accounting for the externality costs of freshwater use would reduce its economic competitiveness over saline water.

- **Water sources.** The use of seawater instead of saline groundwater would alter costs of supply and disposal; however, these costs would be site-dependent with respect to ocean access and water transport distances.
- **Nutrient sources.** If wastewater is used, nutrients would be cheaper than the costs used in this analysis, with potential for wastewater credits; but costs for piping to the production site would have to be added. Lundquist et al. (2010) suggest that operating expenses may be 10% lower if waste treatment is used as a source of nutrients.
- **Pipeline size.** CO_2 pipelines are sized based on average annual productivity values for all sites, with a 1.25 multiplier for peak periods and an assumption that CO_2 is used only during the daytime. For lower-productivity sites, smaller pipelines with slightly lower costs could be used, compared with the costs estimated in our analysis. Pipelines may be under-sized in the summer months and over-sized in the winter months. Higher production (and thus CO_2 demand) will occur during the warmer, longer-light summer months. A site- or region-specific engineering design based on biomass production and CO_2 supply can provide a better estimation of biomass potential. Pipeline costs may be lower than those assumed here if pipelines are connected between adjacent unit farms, becoming smaller as they feed fewer unit farms. Technologies are available (e.g., bicarbonate absorption stack) to capture and store waste CO_2 24/7 in a water medium and then transport the water instead of the gas, but this approach is not considered here because the costs are unknown. Reducing the sizing of the piping required could lead to lower costs and more production locations.
- **Flue gas-related costs.** CO_2 purification costs for flue gas are not included. Also, the cost of distributing CO_2 through on-site pipelines to individual ponds could be higher for flue gas than for ethanol, whereas we use the same estimate for all CO_2 sources. Relevant research and development supported by DOE's Office of Fossil Energy is directed towards reducing the cost of CO_2 capture. Future improvements in carbon capture could influence future opportunities for siting algae.
- **Competition for CO_2.** Competition for CO_2 is possible from enhanced oil recovery in regions with oil fields. Although CO_2 is often obtained from natural underground "domes" of CO_2, it can also be obtained from EGUs and industrial plants and compressed and transported by pipeline to oil fields. In those regions, CO_2 costs might be higher than those assumed here, although we eliminate source plants from our analysis that have a known competitive use of CO_2. Competition for CO_2 is also possible from medical or food production industries. However, these uses should not require a large portion of the available CO_2 and should not affect pricing substantially.
- **Productivity-cost relationship.** Because uncertainties may be highest at low productivities, the highest costs in the supply curves may be the most uncertain. Regional costs would vary somewhat, with the most extreme case (Hawaii) presented as a scaling factor in Beal et al. (2015).
- **Waste disposal costs.** As in Davis et al. (2016), the analysis assumes that costs for blowdown brine disposal would add about $32 per dry ton to the cost of biomass production using saline water, but this value is a conservative estimate

from deep-well injection, highly variable and uncertain. The cost would depend on local geology. The net seasonal water evaporation rates across the country could differ from those assumed in Davis et al. (2016) and used to generate this cost. The actual waste disposal cost could be much lower for regions located in close proximity to a coast or where waste could be reinjected in the well. For strains with a lower range of salinity tolerance, the blowdown fraction would need to be adjusted. As in Davis et al. (2016), we acknowledge that blowdown streams removed from the primary dewatering clarified recycle line could contain low salt levels, but we do not include these costs.

- **Power.** We use power costs from Davis et al. (2016) in both the current and future cases. Actual power costs will vary by region; for example, Beal et al. (2015) note that the energy to supply water to the production site varies regionally. Costs of power in the future are even more uncertain. It is possible that renewables would provide less costly power in the coming decades. Beal et al. (2015) consider the use of wind power in techno-economic assessments of algae and find a per-kilowatt-hour cost savings in Hawaii but not in Texas. Moreover, Lundquist et al. (2010) note that wastewater credits can reduce electricity costs. Energy return on investment and potential economic ramifications are not investigated here.
- **Future conditions.** As in other chapters, the future scenario assumes that land use/land cover categories (agriculture, urban, and forest area) do not change in the future. Algae production is excluded from agricultural, forest, and high-density developed land. The assumed biomass potential could be quite different if the areas of these land use/land cover classes change. Moreover, many coal-fired EGUs are expected to shut down in the future. Estimated facility retirement dates are not included in this analysis.
- **Financial assumptions.** The internal rate of return and discount rate of 10% is adopted from Davis et al. (2016). This is higher than the discount rate (6.5%) assumed in analyses of terrestrial feedstocks. However, it is lower than the cost of capital that might be required for risk financing. Therefore, this rate constitutes a large source of uncertainty in the analysis. Moreover, in the techno-economic analyses for several complete algal biofuel supply chains in Beal et al. (2015), the minimum biocrude price is highly sensitive to the discount rate, as well as the interest rate, loan term, and tax rates.
- **CO_2 policies.** Cap-and-trade programs are in effect in California and in the northeastern United States that could decrease CO_2 costs. The U.S. Clean Power Plan[14] could also affect future CO_2 costs, at least from EGUs. It is unclear whether various CO_2 producers are likely to give or sell CO_2 to algae production facilities. It is also unclear who will bear the cost for integration. At present, only EGUs are included in the Clean Power Plan.

7.7.3 Logistical Considerations

Nutrient recycling can reduce costs. When the full algae-to-biofuels process is considered, CO_2 can be generated for recycling by combusting the methane produced in anaerobic digestion. We assume that any nutrient recycling credit would be applied on the downstream conversion process to reduce final fuel or product costs (Davis et al. 2016) because previous DOE design case reports on conversion processes assume that recycling would reduce fuel costs rather than biomass costs (Davis et al. 2014, Jones et al.

[14] At the time of publication, the Clean Power Plan was in judicial review.

2014) and because the specific degree of recycle potential is dependent on a particular conversion technology pathway. Davis et al. (2016) estimate a credit of $14/ton for 90% nitrogen recycling if it is credited to biomass costs. Heat from CO_2-containing gases transported short distances might be used to aid in drying algae. A portion of the CO_2 may also be used to increase the shelf life of wet algae in storage (Isenberg 1979, Floros and Newsome 2010).

7.7.4 Importance of Coproducts to Economics

Coproducts are increasingly understood to be important to the economics of algal biofuels and the viability of the algal biofuel industry. Numerous coproducts are possible if the lipid fractionation pathway is used. If hydrothermal liquefaction is used, algal biomass could be co-processed with less expensive feedstocks such as terrestrial biomass or waste grease (Jones et al. 2014).

Table 7.10 | Microalgae Products and Prices

Product	Substitutes	Price	Unit[a]
Biodiesel	Diesel	$2.27	USD/gal
Bio-ethanol	Gasoline	$3.96	USD/gal
Bio-methane (fuel)	Liquified petroleum gas	$1.92	USD/gal
Jet fuel (bio-jet)	Jet fuel	$2.49	USD/gal
Electricity	Fossil energy	$0.13–$0.21	USD/kWh
Bio-methane (electricity)	Natural gas	$0.05–$0.06	USD/kWh
Biofertilizers	Synthetic fertilizers	$0.25–$0.63	USD/kg
Biostimulants	Growth promoters	$37.50–$312.50	USD/kg
Biopesticides	Synthetic pesticides	$5.00	USD/acre
Bioplastics	Fossil based plastics	$1.75	USD/kg
Food	Proteins, carbohydrates, oils	$50.00	USD/kg
Beta-carotene	Synthetic/natural	$275.00–$2,750.00	USD/kg
Omega-3 polyunsaturated fatty acids	Fish	$50.00	USD/g
Aquaculture	Fishmeal/fish oil	$68.75–$625.00	USD/kg
Livestock feed	Soybean meal	$300.00	USD/Mg
Feed additives	Botanicals, antibiotics	$20.00	USD/kg

Source: Data from Van der Voort, Vulsteke, and de Visser (2015).

[a]Original prices in Euro are converted to U.S. dollars (USD) using a conversion factor of 1.25.

Example prices of fuel products and potential co-products are shown in table 7.10. The price of animal feed has a strong influence on techno-economic analyses for algal biofuel production (Beal et al. 2015)). According to one source, about 30% of the world's algae-produced biomass is sold as animal feed (Lum, Kim, and Lei 2013). While the portion of biomass used for animal feed has regulatory toxicant limits, and feed used for poultry has protein limits (Spolaore et al. 2006), animal feed coproducts can be produced with biomass from the algal biofuel supply chain.

7.7.5 Summary and Future Resource Analysis Research

The potential biomass estimated from the three CO_2 co-location scenarios could complement the substantial terrestrial biomass resources. For the present-productivity scenarios, annual algae biomass is estimated at up to 46 million tons from *Chlorella sorokiniana* (freshwater) or up to 86 million tons from *Nannochloropsis salina* (saline water) based on co-location with the three selected CO_2 sources (table 7.11). Under the technology assumptions used here, the co-location benefit is lower at future, higher productivities because of an increased cost of transporting the CO_2. As expected, higher productivities lead to lower overall minimum selling prices of algae biomass. Costs of biomass grown in saline media are somewhat higher than those of biomass grown in freshwater media, and full liners add substantial costs. Under both high and low productivity scenarios, prices are substantially higher than those at which terrestrial biomass is potentially available, but less processing is required to convert algae biomass to biofuel.

The combination of production systems and co-location options not quantified in this study could represent substantial additional production potential and

Table 7.11 | Summary of Biomass Potential from Co-Location (million tons/year) with CO_2 in Open Ponds Using *Chlorella sorokiniana* (example freshwater strain) or *Nannochloropsis salina* (example saline strain)

Scenario	Ethanol plant	Coal EGU	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

Co-located algae biomass potential with CO_2 sourced from natural gas plants is reduced to 0 at future productivities because of the increased cost of moving larger quantities of impure CO_2, which makes purchasing CO_2 more economically efficient. However, future research and development should reduce the costs of capturing and transporting CO_2 from flue gas.

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

cost reductions. Of course, the use of commercial CO_2, including in combination with use of co-located CO_2, could also significantly increase the total national production potential.

Future research could consider the effects on production costs of additional production technologies and scales of production, as well as additional co-location scenarios and specific technologies (such as technologies for nighttime storage of CO_2). Some of these may decrease minimum selling prices and increase the projected biomass production further. Tradeoffs in productivity and ultimate costs between freshwater and saline conditions and algal strains will be examined.

A research priority is to include PBRs and hybrid systems in future analyses as soon as peer-reviewed cost data, including capital and operating expenses, are available and there is consensus on an appropriate design on which to focus. The costs of CO_2 delivery from EGUs and ethanol plants to PBRs with higher annual productivity have already been estimated, but results are not reported here because baseline capital and operating costs of PBRs are not well established. Ongoing research is estimating these costs.

Potential resource co-location scenarios include the use of CO_2 from cement plants, hydrogen production, ammonia fertilizer facilities, refineries, sugar mills, and other point-source production facilities. Some algae companies are already planning to co-locate facilities with cement plants. Future analysis will more specifically capture daily site CO_2 usage based on modeled daily/hourly CO_2 output and hours of potential CO_2 utilization by algal production facility.

As CO_2 purification technologies improve, they should become less expensive, expanding the number of economically efficient co-located algae production sites. Moreover, as utilities and other industries have increasing incentives for CO_2 utilization, it may become possible to decouple the CO_2 source spatially from the site of algae production. This would expand the range of sites available for algal biofuel production, (including remote sites), increase the algae biomass potential nationally, and decrease GHG emissions. Furthermore, some facilities could be co-located with flue-gas-derived CO_2 and use supplemental commercial CO_2 where needed.

Waste heat is another potential focus of co-location. Ethanol plants and EGUs, as well as other industrial plants, produce waste heat, which must be managed by some type of cooling system. Often the thermal management of waste heat, especially for an EGU, involves cooling water, sometimes from a nearby open source but often provided by a closed loop with cooling towers. The use of waste heat could reduce the need for thermal management by the source facility and lead to enhanced productivity for algal biomass facilities in the cold seasons, especially for PBRs. Because the co-location distance limits for CO_2 are lower for EGUs, using waste heat from these plants could be even more useful for reducing costs and determining feasible locations for co-location than using waste heat from ethanol plants. Also, heat from the EGU can be used in the downstream drying process. This concept has not yet been evaluated.

Aquatic nutrient loading, as well as fertilizer costs, can be reduced by sourcing nutrients from effluent streams of municipal waste treatment plants or confined animal-feeding operations. Future research could investigate the economic benefits of these co-location examples as well.

The implications of these results for environmental sustainability (i.e., water quantity and quality, soil quality, air quality, biodiversity, GHG emissions, and productivity) are discussed in *BT16* Volume 2. The discussion of sustainability of the production of algal biomass will be qualitative, as few data are available related to the sustainability of large-scale production of algae for fuel.

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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]

[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.

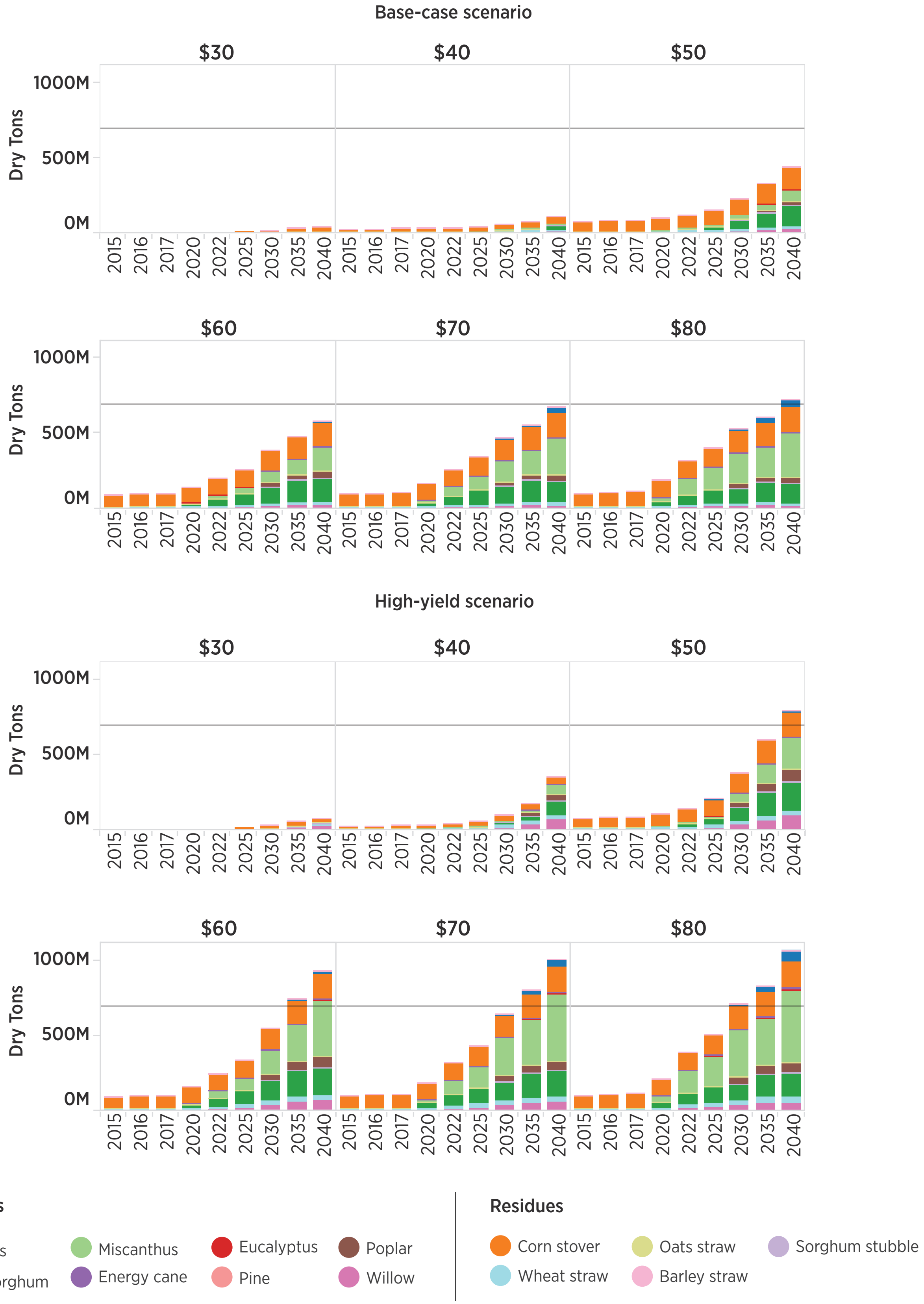
Table 8.1 *(continued)*

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]



[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.

[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*

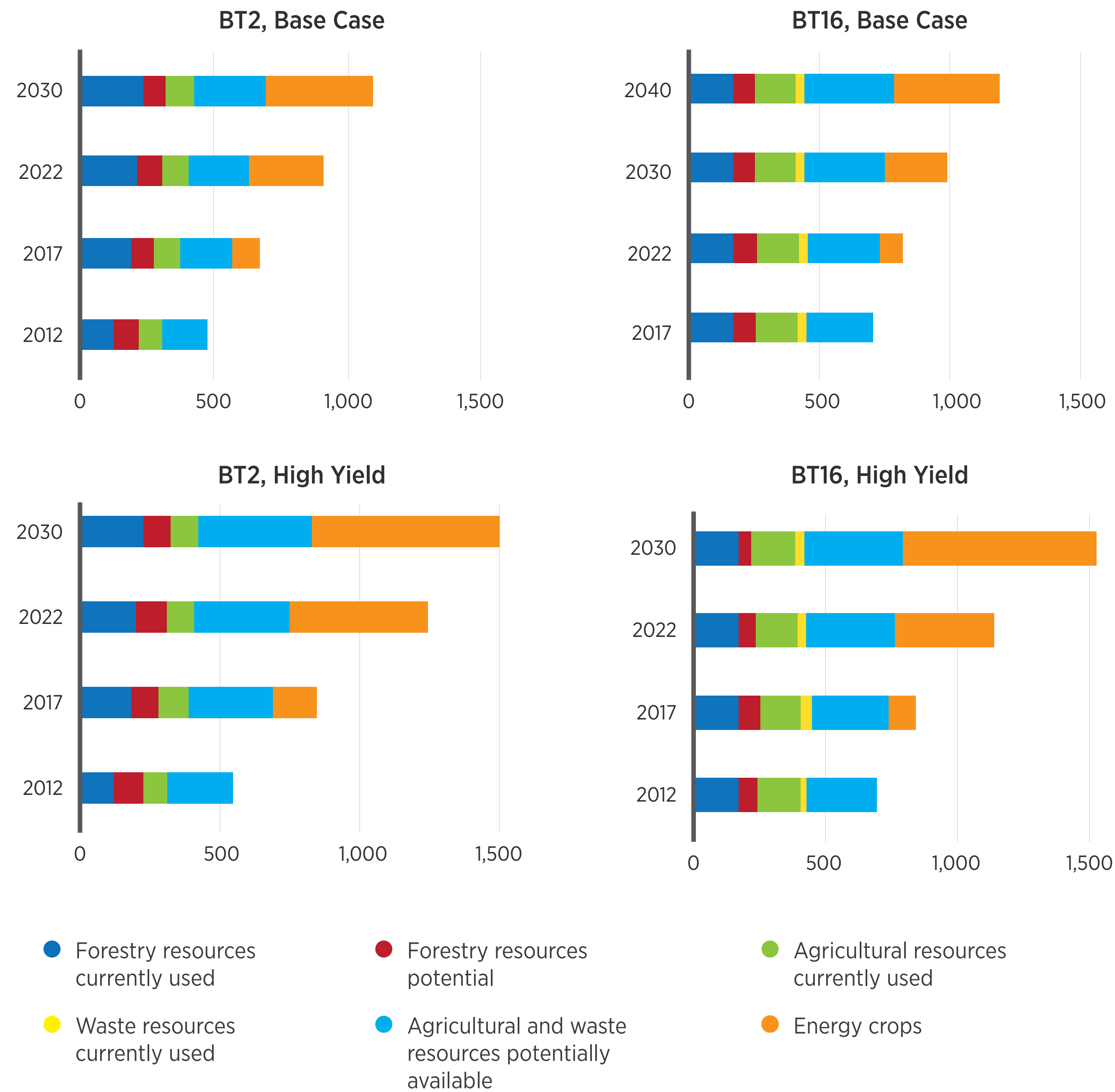
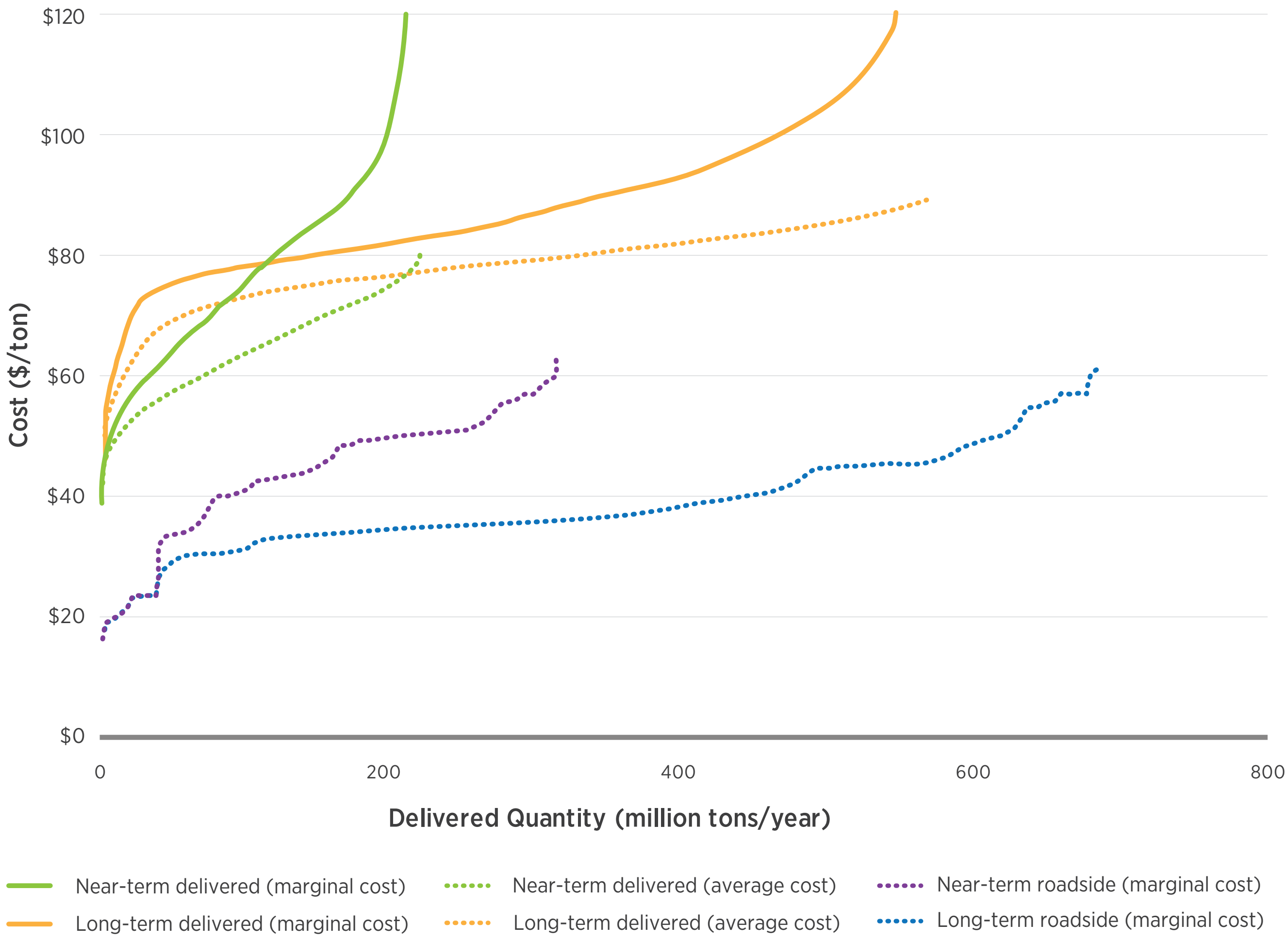


Figure 8.3 | Marginal and weighted average costs ($/dry ton) of select herbaceous and woody feedstocks at the roadside and delivered to the reactor throat (base case)



8.1.2 Delivered Supplies: Advancing Resources from Roadside to the Biorefinery

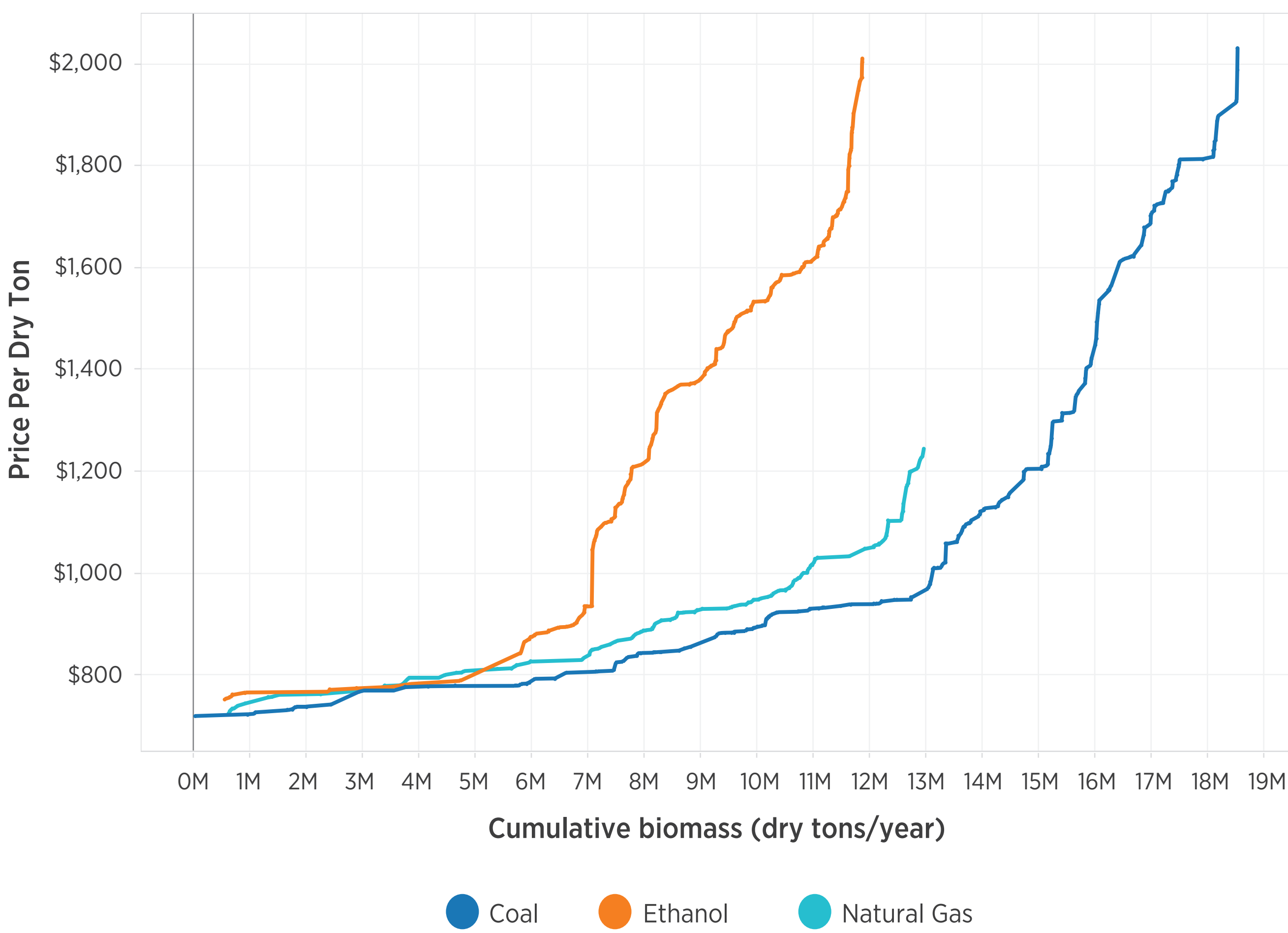
Chapter 6 advances the analysis beyond the roadside with a scenario analysis of the potential economic availability of delivered supplies. A spatially explicit resource allocation model was used to quantify transportation costs and to characterize quantities and costs of resources as delivered to a grid 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]



[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:

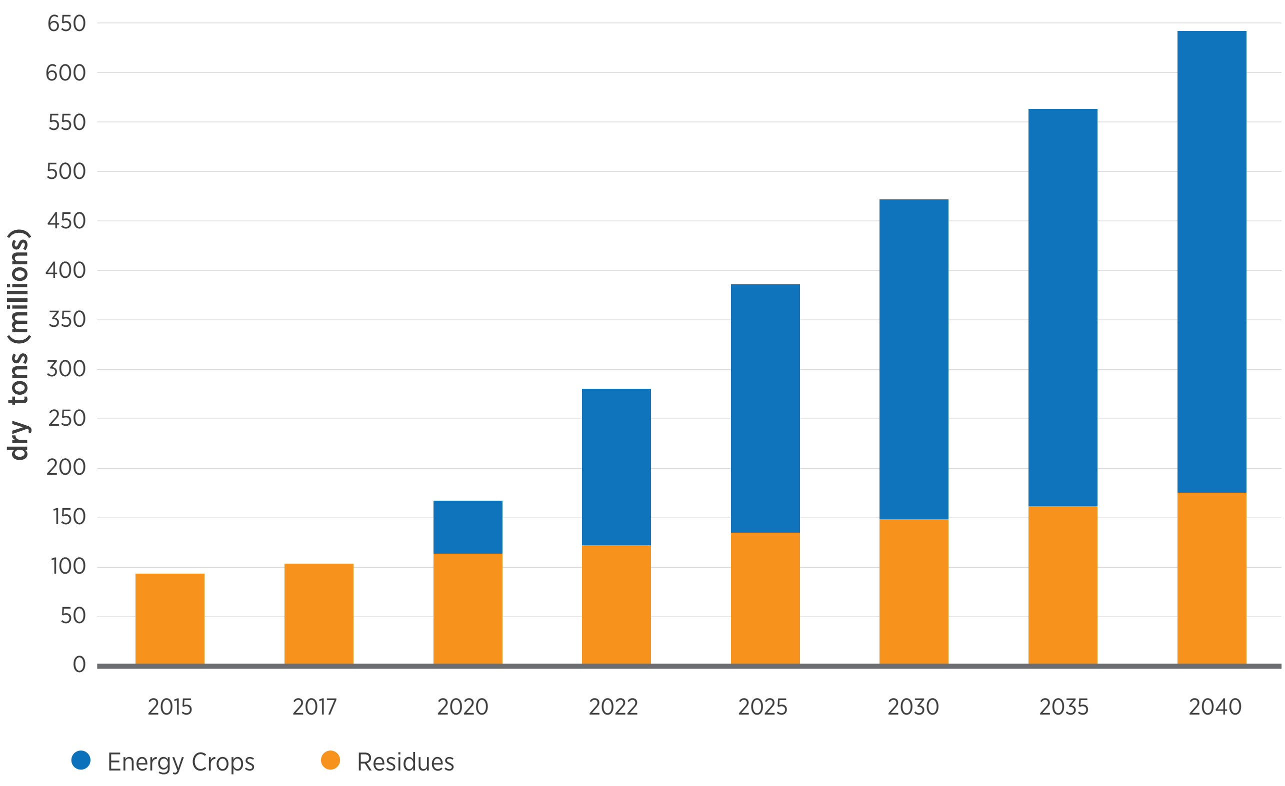
Residues and wastes are available now; energy crops offer growth potential

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.

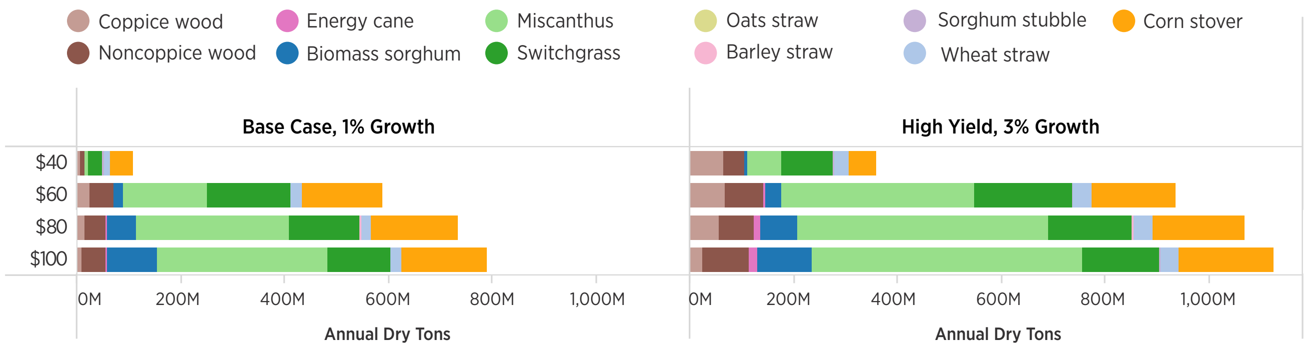
Feedstock availability is a function of market, innovation, and time

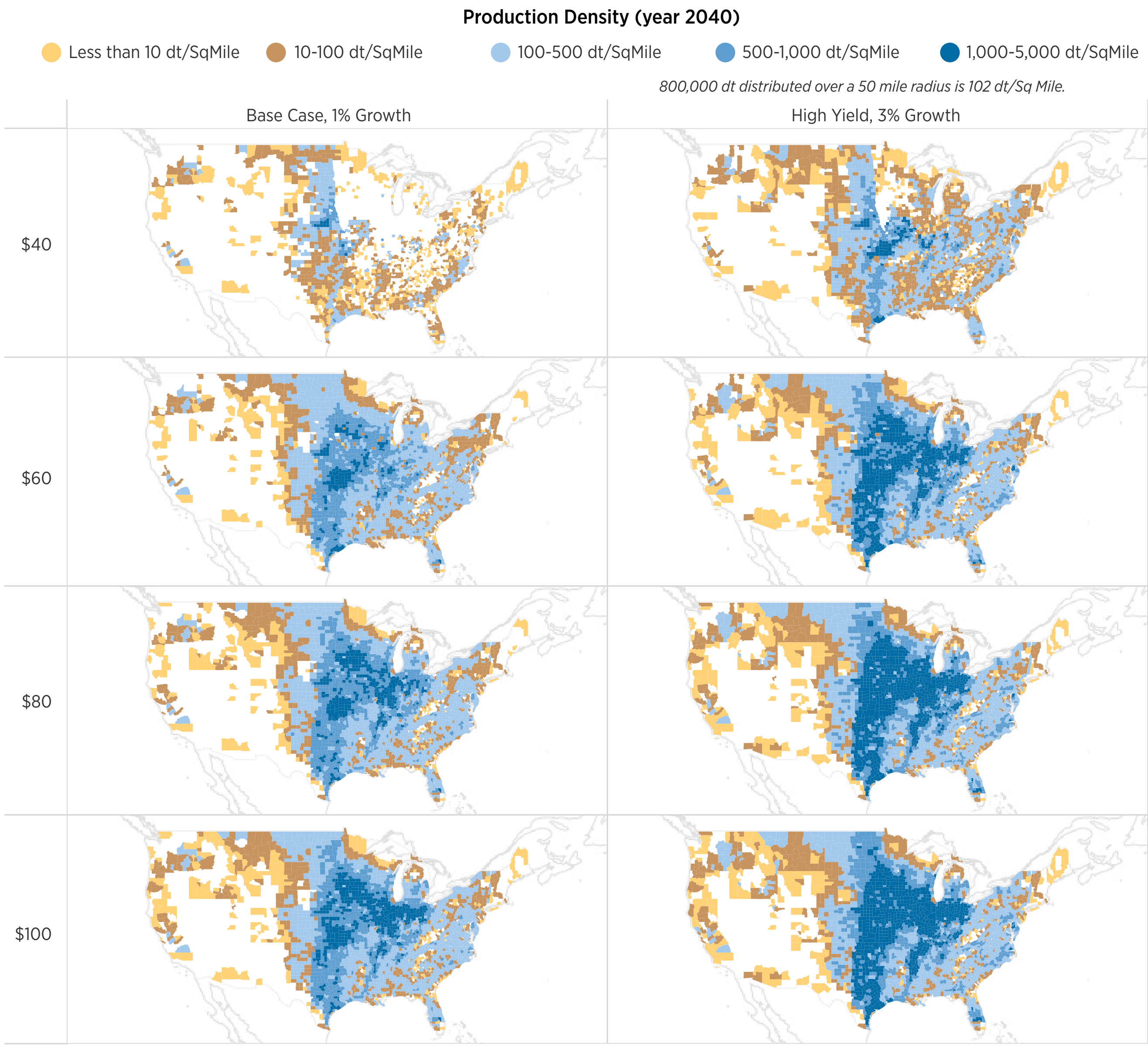
Future biomass availability is largely determined by potential profitability to biomass producers. This profitability increases with higher market prices and with innovations that reduce costs or improve efficiency. Innovation is demonstrated in this report in the form of high-yield scenarios, where 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.

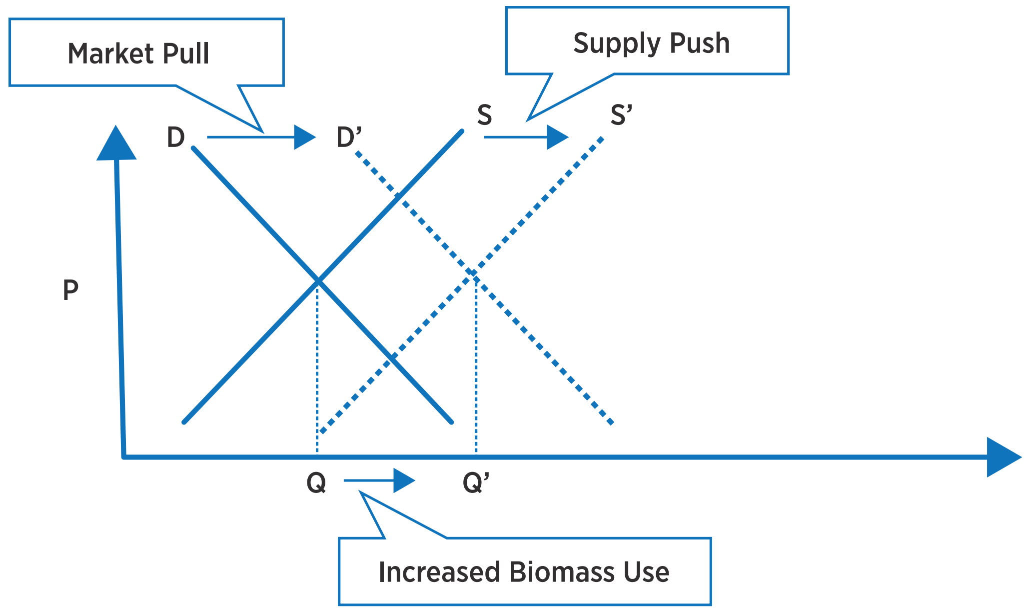
The chapters identify specific research needs focused on reducing uncertainties in assumptions, updating assessments with new information, and identifying key implications of the biomass estimates:

- **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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Appendices

Appendix A

Appendix to Chapter 2 - Biomass Consumed in the Current Bioeconomy

Table A-1 | Fuel-Related Conversion Factors and Other Values

Parameter or conversion factor		Reference
Fuels	Conversion efficiency (gallons/ton)	
Corn grain to ethanol	118	RFS2, USDA, Mueller and Kwik (2013), GREET
Cellulosic biomass to ethanol	85	*BETO Multi-Year Program Plan*
Biogenic MSW to ethanol	85	Assumed based on cellulosic
Cellulosic biomassto hydrocarbon drop-in blendstocks	56	*BETO Multi-Year Program Plan*
Vegetable oils and other fats, oils, and greases to biodiesel	267	2011 *Billion-Ton Update*

Table A-2 | Power-Related Energy Contents

Source	Energy Content	Reference
Biogenic municipal solid waste	9.80 MM Btu/ton	Calculated from EPA Advanced Sustainable Materials Management 2015
Other waste biomass	9.8 MMBtu/ton	Calculated from EPA Advanced Sustainable Materials Management 2015
Landfill gas	488.20 Btu/million cubic feet	Calculated from EIA 2015 *Electric Power* Annual, tables 5.5, 5.6, 5.7, and 5.8
Animal manure	885 Btu/lb (dairy heifer) to 2,949 Btu/lb (poultry	GREET biogas output and default assumptions applied by animal to estimate the total biomass digested
Woody biomass	13.00 MMBtu/ton	Conservative average (various sources)

Table A-3 | Distribution of Biopower Energy to Electric and Thermal Use by Sector

	Electric sector (%)		Industrial sector (%)		Commercial sector (%)	
Electrical vs. thermal output[a]	Electricity	Thermal	Electricity	Thermal	Electricity	Thermal
Biogenic portion of MSW	96.5	3.5	4.1	95.9	67.5	32.5
Other waste biomass	70.4	29.6	13.2	86.8	79.8	20.2
Landfill gas	99.9	0.1	96.8	3.2	98.2	1.8

[a] Tables 5.5, 5.6, 5.7, and 5.8 of the EIA 2015 *Electric Power Annual* report the consumption of wood/wood waste biomass, landfill gas, biogenic municipal solid waste, and other waste biomass for electricity generation, useful thermal output, and total output in billion Btu. An analysis of this data allows for the distribution of energy generated for electrical or thermal output to be determined for 2013 data. This energy distribution relationship is assumed to remain constant and is applied to future biopower projections.

Table A-4 | Power-Related Conversion Efficiencies

Parameter or conversion factor			Reference
Power / Conversion efficiency[a]	Electric[b] (%)	Thermal[c] (%)	
Biogenic municipal solid waste	25	45	2015 *Annual Energy Outlook*
Other waste biomass	25	45	2015 *Annual Energy Outlook*
Landfill gas and anaerobic digester gas	30[d]	78[e]	EIA 2015 *Electric Power Annual*
Woody biomass	25	60	2015 *Annual Energy Outlook*

[a] Depending on the technology and combustion method, electrical and thermal conversion efficiency may vary. For thermal conversion efficiency, a conservative estimate of 45%, based on the annual fuel utilization of woody biomass, was used as a simplifying assumption for biogenic municipal waste.

[b] Electrical conversion efficiency calculation: Table A16 of the EIA *Annual Energy Outlook* reports the renewable electrical generation for biogenic municipal solid waste and for wood and other biomass, whereas table A17 reports renewable energy consumption for electric power. These values were used to estimate an electrical conversion efficiency of 26% of biogenic municipal solid waste.

[c] Thermal efficiencies are conservative estimates based on the annual fuel utilization efficiency of woody biomass, which range from 45% to 90% for conventional and state-of-the-art technology, respectively (see energy.gov/energysaver/furnaces-and-boilers).

[d] Electrical conversion efficiency calculation: Table 8.2 of the EIA *Electric Power Annual* reports the average tested heat rates by technology and energy source from 2007 to 2013. Natural gas combustion via gas turbine was used to estimate an electrical conversion efficiency of 30% for landfill gas and anaerobic digester gas.

[e] A conservative estimate of 78%, based on the annual fuel utilization efficiency of a mid-efficiency natural gas boiler, was used as a simplifying assumption for landfill gas and anaerobic digester gas.

Appendix B

Appendix to Chapter 3 - At the Roadside: Forest Resources

ForSEAM Model Constraints (Eq. A1–A18)

Timber land and harvest intensity constraints

(A1). $$\left(X_{i,j,k,o,m,c,p,t} + XCTL_{i,j,k,o=1,m,c,p,t}\right)\alpha_{i,j,k,c,t} \leq \omega_{i,j,k}A_{i,j,k,o,m,t}\alpha_{i,j,k,c,t}$$

$$\forall \text{ all } i,j,o,m,t,k=1,c=1,p=1$$

(A2). $$\sum_{c=1}^{2}\left[X_{i,j,k,o,m,c,p,t} + XCTL_{i,j,k,o=1,m,c,p,t} + Z_{i,j,k,o,m,c,t}\right]\alpha_{i,j,k,c,t} \leq \sum_{c=1}^{1}\omega_{i,j,k}A_{i,j,k,o,m,t}\alpha_{i,j,k,c,t}$$

$$\forall \text{ all } i,j,o,m,t,k=2,p=2$$

(A3). $$Z_{i,j,k,o,m,c,t}\alpha_{i,j,k,c,t} \leq \omega_{i,j,k}A_{i,j,k,o,m,t}\alpha_{i,j,k,c,t} \; \forall \text{ all } i,j,m,t,k=3,c=1$$

(A4). $$X_{i,j,k,o,m,c,p,t} = XCTL_{i,j,k,o,m,c,p,t} \; \forall \text{ all } i \in (NC, IW), j, m, c, t, o=1, k=1,2$$

(A5). $$U_{i,j,k,o,m,n,c,t} \leq \sum_{p=1}^{2} X_{i,j,k,o,m,c,p,t} \; \forall \text{ all } i,j,m,c,t,k=1,3$$

Proportion of thinning and clear-cut

(A6). $$\sum_{c=1}^{1}\sum_{m=1}^{2}\sum_{p=1}^{2}\left(X_{i,j,k,m,c,p,t} + XCTL_{i,j,k,o,m,c,p,t} + Z_{i,j,k,c,t}\right)$$

$$= r_{i,j}\sum_{c=1}^{2}\sum_{m=1}^{2}\sum_{p=1}^{2}\left(X_{i,j,k,o,m,c,p,t} + XCTL_{i,j,k,o=1,m,c,p,t} + Z_{i,j,k,c,t}\right) \; \forall \text{ all } i,j,t,o,k=2$$

Growth constraint

(A7). $$\sum_{si}\sum_{c=1}^{2}\sum_{p=1}^{2}\left(X_{i,j,k,o,m,c,p,t} + XCTL_{i,j,k,o=1,m,c,p,t}\right)\alpha_{i,j,k,c,t} + \sum_{c=1}^{2} Z_{i,j,k,o,m,c,t}\beta_{i,j,k,c,t} + \sum_{c=1}^{2} U_{i,j,k,o,m,c,t}\theta_{i,j,k,c,t} \leq \sum_{si}\bar{G}_{i,j,k,o,m} + g_{i,j,k,m}A_{i,j,k,o,m,t} \; \forall \text{ all } si,j,o,m,t,k$$

Inter-period stand diameter class determination

(A8). $$A_{i,j,k,o,m,t} = A^{0}_{i,j,k,o,m} \; \forall \text{ all } i,j,k,o,m,n,t=1$$

(A9). $$A_{i,j,k,o,m,t} =$$

$$A_{i,j,k,o,m,t-1} - \sum_{c=1}^{2}\left(X_{i,j,k,o,m,c,p=1,t-1} + XCTL_{i,j,k,o=1,m,c,p=1,t-1}\right) + \left\{A_{i,j,kk,o,m,t-1} - \sum_{c=1}^{2}\left[\sum_{p=1}^{2}\left(X_{i,j,kk,o,m,c,p,t-1} + XCTL_{i,j,kk,o,m,c,p,t-1}\right)\right] + Z_{i,j,kk,o,m,c,t-1}\right\} v_{i,j,kk,k,t-1} \; \forall all \; i,j,o,m,k=1,kk=2$$

(A10). $A_{i,j,k,o,m,t}$

$$= A_{i,j,k,o,m,t-1} - \sum_{c=1}^{2}\left(X_{i,j,k,o,m,c,p=2,t-1} + XCTL_{i,j,k,o=1,m,c,p=2,t-1} + Z_{i,j,k,o,m,c,t-1}\right) + \{A_{i,j,kk,o,m,t-1} - Z_{i,j,kk,o,m,c,t-1}\}v_{i,j,kk,k,t-1} \quad \forall all\ i,j,o,m,k=2,kk=3$$

(A11). $A_{i,j,k,o,m,t} = A_{i,j,k,o,m,t-1} + AR_{i,j,o,m,t-1}\ \forall \text{ all } i,j,o,m,k=3$

(A12). $AR_{i,j,k,o,m,t+n-1} = \sum_{n=1}^{26} R_{i,j,o,m,n,t}u_{i,j,n}\ \ \forall \text{ all } i,j,o,m,n,t,k=2$

(A13). $R_{i,j,o,m,n-t+1,t} = \sum_{c=1}^{2}\sum_{k=1}^{3}\left[\sum_{p=1}^{2}(X_{i,j,k,o,m,c,p,t} + XCTL_{i,j,k,o=1,m,c,p,t})\right] + Z_{i,j,k,o,m,c,t}\ \forall \text{ all } i,j,o,m,n,t$

Conventional demand

Hardwood Sawlogs

(A14). $$\sum_{i=si}\sum_{j=1}^{2}\sum_{m=1}^{2}\sum_{c=1}^{2}\sum_{o=1}^{2}(X_{i,j,k,o,m,c,p,t} + XCTL_{i,j,k,o=1,m,c,p,t})\alpha_{i,j,k,c,t} + 0.375\sum_{i=si}\sum_{j=5}^{5}\sum_{m=1}^{2}\sum_{c=1}^{2}\sum_{o=1}^{2}(X_{i,j,k,o,m,c,p,t} + XCTL_{i,j,k,o=1,m,c,p,t})\alpha_{i,j,k,c,t}$$

$\forall \text{ all } s,t,o,f=1,k=1,p=1$

Softwood Sawlogs

(A15). $\sum_{si\in i}\sum_{j=3}^{4}\sum_{m=1}^{2}\sum_{c=1}^{2}\sum_{o=1}^{2}(X_{i,j,k,o,m,c,p,t} + XCTL_{i,j,k,o=1,m,c,p,t})\alpha_{i,j,k,c,t} +$

0.625 $\sum_{si\in i}\sum_{j=5}^{5}\sum_{m=1}^{2}\sum_{c=1}^{2}\sum_{o=1}^{2}(X_{i,j,k,o,m,c,p,t} + XCTL_{i,j,k,o=1,m,c,p,t})\alpha_{i,j,k,c,t} \geq D_{s,f,k,t}$

$\forall \text{ all } s,t,f=2,k=1,p=1$

Hardwood Pulpwood

(A16). $\sum_{si\in i}\sum_{j=1}^{2}\sum_{m=1}^{2}\sum_{c=1}^{2}\sum_{k=1}^{2}\sum_{o=1}^{2}(X_{i,j,k,o,m,c,p,t} + XCTL_{i,j,k,o=1,m,c,p,t})\alpha_{i,j,k,c,t} +$

0.375 $\sum_{si\in i}\sum_{j=5}^{5}\sum_{m=1}^{2}\sum_{c=1}^{2}\sum_{k=1}^{2}\sum_{o=1}^{2}(X_{i,j,k,o,m,c,p,t} + XCTL_{i,j,k,o=1,m,c,p,t})\alpha_{i,j,k,c,t} \geq D_{s,f,k,t}$

$\forall \text{ all } s,t,f=1,p=2$

Softwood Pulpwood

(A17). $\sum_{si\in i}\sum_{j=3}^{4}\sum_{m=1}^{2}\sum_{c=1}^{2}\sum_{k=1}^{2}\sum_{o=1}^{2}(X_{i,j,k,o,m,c,p,t} + XCTL_{i,j,k,o=1,m,c,p,t})\alpha_{i,j,k,c,t} +$

0.625 $\sum_{si\in i}\sum_{j=5}^{5}\sum_{m=1}^{2}\sum_{c=1}^{2}\sum_{k=1}^{2}\sum_{o=1}^{2}(X_{i,j,k,o,m,c,p,t} + XCTL_{i,j,k,o=1,m,c,p,t})\alpha_{i,j,k,c,t} \geq D_{s,f,k,t}$

$\forall \text{ all } s,t,f=2,p=2$

Woody biomass supply target

(A18). $\sum_{i=1}^{305}\sum_{j=1}^{5}\sum_{k=1}^{2}\sum_{m=1}^{2}\sum_{o=1}^{2}(0.7U_{i,j,k,o,m,c,t}\,\theta_{i,j,k,o,m,t}) + \sum_{i=1}^{305}\sum_{j=1}^{5}\sum_{k=2}^{3}\sum_{m=1}^{2}\sum_{c=1}^{2}\sum_{o=1}^{2} Z_{i,j,o,m,c,t}\beta_i$

$B_t\ [\lambda_t]\ \forall \text{ all } t$

Conventional Wood Volumes Generated by Scenario and Year

Table B-1 | USFPM Projection of Conventional Demand Under Scenario Baseline ML (million dry tons)

	2010	2015	2020	2025	2030	2035	2040
North							
Softwood sawlogs	4.58	5.62	6.18	6.70	7.17	7.37	7.60
Softwood pulpwood	4.02	4.43	4.80	5.02	5.18	5.03	4.51
Softwood sawlogs	10.55	12.56	13.12	13.41	13.86	13.88	13.31
Hardwood pulpwood	13.62	17.08	18.07	18.50	19.01	18.80	18.13
Other industrial roundwood	0.66	0.78	0.84	0.88	0.93	0.94	0.94
Total roundwood harvested	*33.43*	*40.49*	*43.01*	*44.52*	*46.16*	*46.03*	*44.49*
South							
Softwood sawlogs	27.18	37.84	45.46	51.78	57.87	60.63	61.36
Softwood pulpwood	39.90	43.85	46.57	48.22	50.91	53.88	54.20
Softwood sawlogs	14.92	15.31	16.36	17.45	18.61	19.37	19.03
Hardwood pulpwood	11.57	17.71	20.59	21.99	23.45	24.44	24.09
Other industrial roundwood	1.79	2.15	2.50	2.77	3.03	3.19	3.22
Total roundwood harvested	*95.36*	*116.85*	*131.48*	*142.21*	*153.87*	*161.50*	*161.89*
West							
Softwood sawlogs	25.76	36.51	39.80	42.56	45.27	46.25	47.32
Softwood pulpwood	1.25	0.68	0.35	0.18	0.14	0.18	0.26
Softwood sawlogs	1.22	1.31	1.39	1.49	1.60	1.77	1.88
Hardwood pulpwood	0.32	0.27	0.28	0.39	0.74	1.02	1.08
Other industrial roundwood	0.60	0.82	0.90	0.96	1.02	1.05	1.08
Total roundwood Harvested	*29.14*	*39.59*	*42.72*	*45.57*	*48.77*	*50.26*	*51.62*
United States							
Softwood sawlogs	57.52	79.97	91.44	101.04	110.32	114.26	116.28
Softwood pulpwood	45.17	48.96	51.73	53.42	56.24	59.09	58.97
Softwood sawlogs	26.70	29.18	30.87	32.35	34.07	35.02	34.22
Hardwood pulpwood	25.50	35.06	38.94	40.88	43.20	44.26	43.30
Other industrial roundwood	3.04	3.76	4.23	4.61	4.98	5.17	5.23
Total roundwood harvested	*157.93*	*196.93*	*217.20*	*232.30*	*248.80*	*257.79*	*258.00*

Note: Actual projections are in cubic meters; conversion to dry tons used 35.31 cubic feet per cubic meter, 30 dry pounds per cubic foot, and 2,000 pounds per short ton.

Table B-2 | USFPM Projection on Conventional Demand Under Scenario MM (million dry tons)

	2010	2015	2020	2025	2030	2035	2040
North							
Softwood sawlogs	4.58	5.72	6.30	6.86	7.39	7.52	7.71
Softwood pulpwood	4.02	4.43	4.79	4.94	4.99	4.84	4.30
Softwood sawlogs	10.55	12.65	13.48	13.85	14.32	14.18	13.58
Hardwood pulpwood	13.62	17.48	18.86	19.47	20.06	19.46	18.69
Other industrial roundwood	0.66	0.80	0.87	0.92	0.97	0.97	0.96
Total roundwood harvested	*33.43*	*41.09*	*44.30*	*46.04*	*47.74*	*46.97*	*45.23*
South							
Softwood sawlogs	27.18	38.69	46.32	52.92	59.47	61.69	62.22
Softwood pulpwood	39.91	43.20	44.85	45.13	46.32	48.92	49.00
Softwood sawlogs	14.92	15.63	16.55	17.53	18.69	19.35	19.24
Hardwood pulpwood	11.57	17.35	19.79	21.29	22.75	24.06	23.07
Other industrial roundwood	1.79	2.21	2.55	2.82	3.11	3.22	3.25
Total roundwood harvested	*95.37*	*117.08*	*130.06*	*139.69*	*150.33*	*157.25*	*156.78*
West							
Softwood sawlogs	25.76	36.47	39.84	42.59	45.16	46.46	47.60
Softwood pulpwood	1.25	0.63	0.30	0.08	-	0.01	0.07
Softwood sawlogs	1.22	1.34	1.42	1.52	1.64	1.76	1.89
Hardwood pulpwood	0.32	0.26	0.26	0.34	0.61	1.01	1.09
Other industrial roundwood	0.60	0.82	0.90	0.96	1.02	1.05	1.08
Total roundwood Harvested	*29.14*	*39.53*	*42.72*	*45.50*	*48.43*	*50.29*	*51.73*
United States							
Softwood sawlogs	57.52	80.89	92.46	102.38	112.02	115.67	117.52
Softwood pulpwood	45.18	48.26	49.94	50.16	51.31	53.78	53.37
Softwood sawlogs	26.70	29.62	31.46	32.90	34.66	35.28	34.71
Hardwood pulpwood	25.50	35.10	38.91	41.09	43.42	44.53	42.85
Other industrial roundwood	3.04	3.83	4.31	4.71	5.10	5.24	5.29
Total roundwood harvested	*157.94*	*197.70*	*217.09*	*231.24*	*246.50*	*254.51*	*253.75*

Note: Actual projections are in cubic meters; conversion to dry tons used 35.31 cubic feet per cubic meter, 30 dry pounds per cubic foot, and 2,000 pounds per short ton.

Table B-3 | USFPM Projection on Conventional Demand Under Scenario MH (million dry tons)

	2010	2015	2020	2025	2030	2035	2040
North							
Softwoodsawlogs	4.58	5.76	6.40	7.04	7.59	7.53	7.52
Softwoodpulpwood	4.02	4.46	4.84	4.95	4.86	4.57	4.01
Softwoodsawlogs	10.55	12.77	13.94	14.86	15.76	14.92	13.84
Hardwoodpulpwood	13.62	17.78	19.91	21.56	23.00	20.81	19.14
Otherindustrialroundwood	0.66	0.81	0.90	0.98	1.05	1.00	0.95
Totalroundwoodharvested	*33.43*	*41.59*	*46.00*	*49.38*	*52.25*	*48.82*	*45.46*
South							
Softwoodsawlogs	27.18	38.97	47.12	54.02	61.02	62.29	63.50
Softwoodpulpwood	39.91	42.90	42.69	39.84	38.01	42.36	43.14
Softwoodsawlogs	14.92	15.84	17.06	18.48	19.84	19.57	18.72
Hardwoodpulpwood	11.57	16.69	17.78	16.67	15.95	19.80	21.38
Otherindustrialroundwood	1.79	2.23	2.60	2.91	3.22	3.26	3.33
Totalroundwoodharvested	*95.37*	*116.63*	*127.26*	*131.92*	*138.05*	*147.28*	*150.07*
West							
Softwoodsawlogs	25.76	36.46	39.79	42.53	44.89	46.19	47.13
Softwoodpulpwood	1.25	0.61	0.26	0.04	-	-	-
Softwoodsawlogs	1.22	1.35	1.45	1.58	1.72	1.77	1.90
Hardwoodpulpwood	0.32	0.26	0.25	0.31	0.52	1.02	1.09
Otherindustrialroundwood	0.60	0.83	0.91	0.97	1.03	1.05	1.07
TotalroundwoodHarvested	*29.14*	*39.51*	*42.66*	*45.43*	*48.16*	*50.02*	*51.16*
United States							
Softwood sawlogs	57.52	81.19	93.32	103.58	113.50	116.01	118.14
Softwood pulpwood	45.18	47.97	47.79	44.83	42.87	46.93	47.12
Softwood sawlogs	26.70	29.96	32.45	34.92	37.32	36.26	34.45
Hardwood pulpwood	25.50	34.73	37.94	38.53	39.47	41.62	41.62
Other industrial roundwood	3.04	3.87	4.41	4.87	5.31	5.30	5.36
Total roundwood harvested	*157.94*	*197.72*	*215.91*	*226.73*	*238.46*	*246.12*	*246.69*

Note: Actual projections are in cubic meters; conversion to dry tons used 35.31 cubic feet per cubic meter, 30 dry pounds per cubic foot, and 2,000 pounds per short ton.

Table B-4 | USFPM Projection on Conventional Demand Under Scenario HL (million dry tons)

	2010	2015	2020	2025	2030	2035	2040
North							
Softwood sawlogs	4.58	5.62	6.23	6.81	7.33	7.52	7.74
Softwood pulpwood	4.02	4.43	4.77	4.96	5.09	4.96	4.48
Softwood sawlogs	10.55	12.56	13.09	13.32	13.68	13.72	13.36
Hardwood pulpwood	13.62	17.08	18.10	18.47	18.88	18.61	18.08
Other industrial roundwood	0.66	0.78	0.84	0.89	0.93	0.94	0.95
Total roundwood harvested	*33.43*	*40.49*	*43.03*	*44.45*	*45.91*	*45.75*	*44.60*
South							
Softwood sawlogs	27.18	37.84	46.12	53.31	60.35	63.14	64.21
Softwood pulpwood	39.90	43.85	46.50	48.13	50.95	54.14	54.30
Softwood sawlogs	14.92	15.31	16.36	17.44	18.57	19.31	19.11
Hardwood pulpwood	11.57	17.71	20.63	21.98	23.40	24.37	24.18
Other industrial roundwood	1.79	2.15	2.52	2.82	3.11	3.26	3.31
Total roundwood harvested	*95.36*	*116.85*	*132.13*	*143.68*	*156.38*	*164.22*	*165.11*
West							
Softwood sawlogs	25.76	36.51	40.18	43.22	46.27	47.25	48.37
Softwood pulpwood	1.25	0.68	0.35	0.16	0.13	0.18	0.27
Softwood sawlogs	1.22	1.31	1.39	1.48	1.59	1.77	1.89
Hardwood pulpwood	0.32	0.27	0.28	0.40	0.78	1.02	1.09
Other industrial roundwood	0.60	0.82	0.91	0.97	1.04	1.07	1.10
Total roundwood Harvested	*29.14*	*39.59*	*43.11*	*46.24*	*49.81*	*51.28*	*52.72*
United States							
Softwood sawlogs	57.52	79.97	92.53	103.34	113.95	117.91	120.32
Softwood pulpwood	45.17	48.96	51.62	53.25	56.17	59.28	59.05
Softwood sawlogs	26.70	29.18	30.84	32.24	33.84	34.79	34.36
Hardwood pulpwood	25.50	35.06	39.01	40.85	43.06	44.00	43.35
Other industrial roundwood	3.04	3.76	4.27	4.68	5.08	5.27	5.35
Total roundwood harvested	*157.93*	*196.93*	*218.27*	*234.36*	*252.10*	*261.25*	*262.43*

Note: Actual projections are in cubic meters; conversion to dry tons used 35.31 cubic feet per cubic meter, 30 dry pounds per cubic foot, and 2,000 pounds per short ton.

Table B-5 | USFPM Projection on Conventional Demand Under Scenario HM (million dry tons)

	2010	2015	2020	2025	2030	2035	2040
North							
Softwoodsawlogs	4.58	5.72	6.35	6.97	7.56	7.69	7.86
Softwoodpulpwood	4.02	4.43	4.76	4.88	4.90	4.77	4.24
Softwoodsawlogs	10.55	12.65	13.43	13.73	14.11	14.02	13.43
Hardwoodpulpwood	13.62	17.48	18.82	19.34	19.83	19.28	18.54
Otherindustrialroundwood	0.66	0.80	0.87	0.92	0.98	0.97	0.97
Totalroundwoodharvested	*33.43*	*41.09*	*44.23*	*45.85*	*47.37*	*46.74*	*45.03*
South							
Softwoodsawlogs	27.18	38.69	47.01	54.40	62.01	64.32	64.98
Softwoodpulpwood	39.91	43.20	45.09	45.53	46.81	49.42	49.48
Softwoodsawlogs	14.92	15.63	16.49	17.47	18.61	19.32	19.23
Hardwoodpulpwood	11.57	17.35	20.01	21.67	23.09	24.07	22.90
Otherindustrialroundwood	1.79	2.21	2.57	2.87	3.18	3.31	3.35
Totalroundwoodharvested	*95.37*	*117.08*	*131.17*	*141.94*	*153.70*	*160.44*	*159.95*
West							
Softwoodsawlogs	25.76	36.47	40.21	43.32	46.13	47.41	48.51
Softwoodpulpwood	1.25	0.63	0.30	0.08	-	-	-
Softwoodsawlogs	1.22	1.34	1.41	1.51	1.63	1.76	1.89
Hardwoodpulpwood	0.32	0.26	0.26	0.35	0.65	1.01	1.08
Otherindustrialroundwood	0.60	0.82	0.91	0.98	1.04	1.07	1.10
TotalroundwoodHarvested	*29.14*	*39.53*	*43.09*	*46.24*	*49.44*	*51.25*	*52.65*
United States							
Softwood sawlogs	57.52	80.89	93.56	104.70	115.69	119.42	121.35
Softwood pulpwood	45.18	48.26	50.15	50.50	51.71	54.19	53.78
Softwood sawlogs	26.70	29.62	31.34	32.70	34.34	35.10	34.55
Hardwood pulpwood	25.50	35.10	39.09	41.37	43.56	44.37	42.53
Other industrial roundwood	3.04	3.83	4.34	4.77	5.20	5.35	5.41
Total roundwood harvested	*157.94*	*197.70*	*218.48*	*234.03*	*250.51*	*258.43*	*257.63*

Note: Actual projections are in cubic meters; conversion to dry tons used 35.31 cubic feet per cubic meter, 30 dry pounds per cubic foot, and 2,000 pounds per short ton.

Table B-6 | USFPM Projection on Conventional Demand Under Scenario HH (million dry tons)

	2010	2015	2020	2025	2030	2035	2040
North							
Softwood sawlogs	4.58	5.76	6.46	7.14	7.76	7.70	7.67
Softwood pulpwood	4.02	4.46	4.81	4.89	4.76	4.49	3.94
Softwood sawlogs	10.55	12.77	13.93	14.75	15.56	14.78	13.69
Hardwood pulpwood	13.62	17.78	19.91	21.46	22.81	20.64	18.99
Other industrial roundwood	0.66	0.81	0.90	0.99	1.06	1.00	0.96
Total roundwood harvested	*33.43*	*41.59*	*46.02*	*49.22*	*51.95*	*48.61*	*45.25*
South							
Softwood sawlogs	27.18	38.97	47.86	55.62	63.54	65.07	66.44
Softwood pulpwood	39.91	42.90	43.02	40.57	38.46	42.74	43.50
Softwood sawlogs	14.92	15.84	17.02	18.42	19.78	19.55	18.72
Hardwood pulpwood	11.57	16.69	18.07	17.09	16.31	19.88	21.25
Other industrial roundwood	1.79	2.23	2.62	2.96	3.30	3.35	3.43
Total roundwood harvested	*95.37*	*116.63*	*128.59*	*134.66*	*141.39*	*150.59*	*153.35*
West							
Softwood sawlogs	25.76	36.46	40.17	43.23	45.94	47.09	47.99
Softwood pulpwood	1.25	0.61	0.26	0.04	-	-	-
Softwood sawlogs	1.22	1.35	1.45	1.57	1.71	1.77	1.89
Hardwood pulpwood	0.32	0.26	0.25	0.32	0.55	1.02	1.09
Other industrial roundwood	0.60	0.83	0.91	0.99	1.05	1.07	1.09
Total roundwood Harvested	*29.14*	*39.51*	*43.04*	*46.15*	*49.26*	*50.95*	*52.02*
United States							
Softwood sawlogs	57.52	81.19	94.49	105.99	117.24	119.87	122.10
Softwood pulpwood	45.18	47.97	48.09	45.50	43.22	47.23	47.41
Softwood sawlogs	26.70	29.96	32.40	34.74	37.04	36.09	34.30
Hardwood pulpwood	25.50	34.73	38.23	38.86	39.68	41.54	41.33
Other industrial roundwood	3.04	3.87	4.44	4.93	5.41	5.42	5.48
Total roundwood harvested	*157.94*	*197.72*	*217.65*	*230.03*	*242.59*	*250.15*	*250.62*

Note: Actual projections are in cubic meters; conversion to dry tons used 35.31 cubic feet per cubic meter, 30 dry pounds per cubic foot, and 2000 pounds per short ton.

Sampling Error[1]

FIA provides continuous forest estimates of forest area, numbers of trees, tree volume, biomass, growth, removals and mortality. The estimates are based on sampling. The process of sampling (selecting a random subset of a population and calculating estimates from this subset) causes estimates to contain error they would not have if every member of the population (e.g., every tree in the country) had been observed and included in the sample. Under the federal base grid sample, there is only one plot for approximately every six thousand acres. For most of the country, the plot footprint is only 1/6 of an acre. Therefore only about 1 in 24 thousand trees is actually measured on the ground under the federal base grid.

The procedures for statistical estimation outlined in the previous section and described in detail in Bechtold and Patterson (2005) provide the estimates of the population totals and means presented by FIA. Along with every estimate is an associated sampling error that is typically expressed as a percentage of the estimated value (the estimated value plus or minus the sampling error). This sampling error is the primary measure of the reliability of an estimate. FIA reports utilize a sampling error based on one standard error, which means the chances are two in three that, had a 100% inventory been taken using these methods, the results would have been within the limits indicated.

The sampling errors for state-level estimates of forest area and above ground tree biomass on timberland are presented in table B.7. Estimates for classifications smaller than the state totals will have larger sampling errors. To compute an approximate sampling error for an estimate that is smaller than a State total, use the following formula:

$$E = \frac{(SE)\sqrt{(\text{State total estimate})}}{\sqrt{(\text{Smaller estimate})}}$$

where:

E = approximate sampling error for smaller estimate

SE = sampling error for state total estimate (percent)

For example, to compute the error on the area of forest land in Autauga County, Alabama, proceed as follows:

The total forest land area of Autauga County is 305,711 acres.

The total area of all forest land in the State from table B.7 is 23,126,893 acres.

The State total error for forest land area from table B.7 is 0.48 percent.

Using formula (1):

[1] Special appreciation Patrick Miles, Research Forester, Forest Inventory & Analysis, Northern Research Station, U.S. Forest Service for providing this appendix.

Sampling error = $E = \dfrac{(0.48)\sqrt{(23,126,893)}}{\sqrt{(305,711)}}$ = 4.17 percent.

This is just a rough approximation of sampling errors for smaller areas. Individuals seeking more accurate sampling errors should use the FIA estimation tools (fia.fs.fed.us/tools-data/index.php).

The estimators used by FIA are unbiased under the assumptions that the sample plots are a random sample of the total population and the observed value for any plot is the true value for that plot. Deviations from these basic assumptions are not reflected in the computation of sampling errors.

Table B-7 | USFPM Projection on Conventional Demand Under Scenario HH (million dry tons)

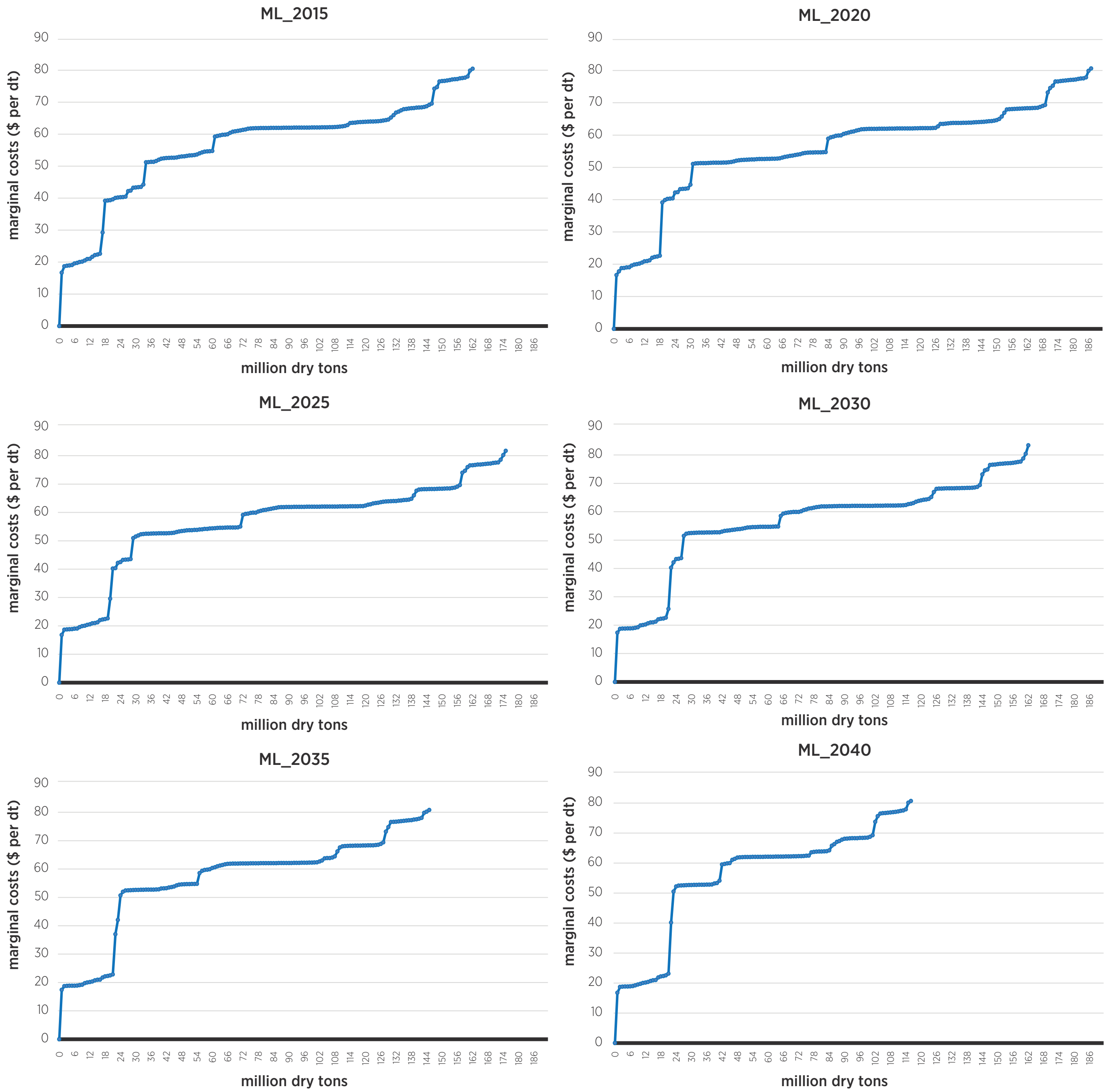
State	Forest land (acres)	Sampling error (%)	Forested plots	Biomass (short tons)	2030 Sampling error (%)	2035 Inventory year
Alabama	23,126,893	0.48	4,275	959,090,501	1.03	2014
Arizona	18,587,490	1.07	3,152	267,728,682	2.17	2013
Arkansas	19,024,429	0.53	3,568	807,091,786	1.06	2014
California	32,101,515	0.63	5,446	2,051,723,218	1.26	2013
Colorado	22,891,282	0.76	3,945	632,036,011	1.53	2013
Connecticut	1,799,342	2.27	320	132,303,437	2.93	2013
Delaware	362,115	3.69	136	25,709,535	5.11	2013
Florida	17,271,795	0.84	3,167	579,123,603	1.75	2013
Georgia	24,744,743	0.55	4,656	1,076,461,100	1.12	2013
Idaho	21,446,207	0.7	3,740	847,983,974	1.64	2013
Illinois	4,974,062	1.61	1,031	251,542,699	2.17	2014
Indiana	4,875,391	1.06	1,809	270,439,967	1.48	2013
Iowa	2,957,321	2.1	634	123,303,581	3.14	2014
Kansas	2,534,899	2.86	604	89,502,870	3.86	2014
Kentucky	12,510,090	0.8	2,469	669,017,945	1.28	2012
Louisiana	14,965,091	0.74	2,736	612,991,064	1.58	2013
Maine	17,636,080	0.4	3,171	693,847,907	0.97	2013
Maryland	2,462,478	2.08	451	185,024,536	3.01	2013
Massachusetts	3,035,792	1.49	545	215,848,770	2.05	2013
Michigan	20,297,434	0.56	4,289	867,096,120	0.98	2014
Minnesota	17,477,313	0.53	6,226	494,337,399	0.91	2014

Table B-7 | *(continued)*

State	Forest land (acres)	Sampling error (%)	Forested plots	Biomass (short tons)	2030 Sampling error (%)	2035 Inventory year
Mississippi	19,430,825	0.56	3,944	830,291,912	1.13	2014
Missouri	15,475,361	0.68	3,182	647,253,400	0.96	2014
Montana	25,702,117	0.68	4,459	787,098,301	1.41	2013
Nebraska	1,559,816	3.96	324	47,750,203	5.77	2014
Nevada	10,577,287	1.37	1,918	109,572,275	2.43	2013
New Hampshire	4,783,480	0.92	951	285,324,910	1.64	2013
New Jersey	2,001,604	2.24	364	117,139,711	3.49	2013
New Mexico	24,839,375	0.97	3,444	318,138,063	1.98	2012
New York	18,950,318	0.57	3,281	1,131,784,873	0.91	2013
North Carolina	18,814,431	0.6	3,672	1,017,871,527	1.12	2014
North Dakota	796,878	5.83	198	19,151,293	8.29	2014
Ohio	8,162,101	0.98	1,664	484,281,536	1.56	2013
Oklahoma	12,362,745	1.54	1,756	279,682,572	2	2013
Oregon	29,684,736	0.47	9,434	2,066,085,416	0.98	2014
Pennsylvania	16,999,249	0.59	3,015	1,085,126,496	0.95	2013
Rhode Island	367,372	3.58	123	24,818,359	4.71	2013
South Carolina	13,043,998	0.75	2,498	620,124,751	1.46	2013
South Dakota	1,943,716	2.73	389	45,260,669	4.2	2014
Tennessee	13,920,504	0.75	2,709	776,151,917	1.23	2012
Texas	62,614,955	0.75	9,004	850,772,597	1.14	2012
Utah	18,303,138	0.96	3,191	296,604,513	1.91	2013
Vermont	4,514,169	0.98	857	279,021,918	1.61	2013
Virginia	15,915,282	0.63	3,048	915,936,069	1.14	2013
Washington	22,195,806	0.54	5,897	1,779,980,873	1.2	2013
West Virginia	12,185,706	0.58	2,033	823,828,883	1.06	2013
Wisconsin	17,092,089	0.43	6,424	649,059,704	0.77	2014
Wyoming	10,455,769	2.37	556	266,018,228	4.34	2013
48 conterminous states	*687,774,585*	*0.14*	*134,705*	*28,406,335,673*	*0.23*	*N/A*

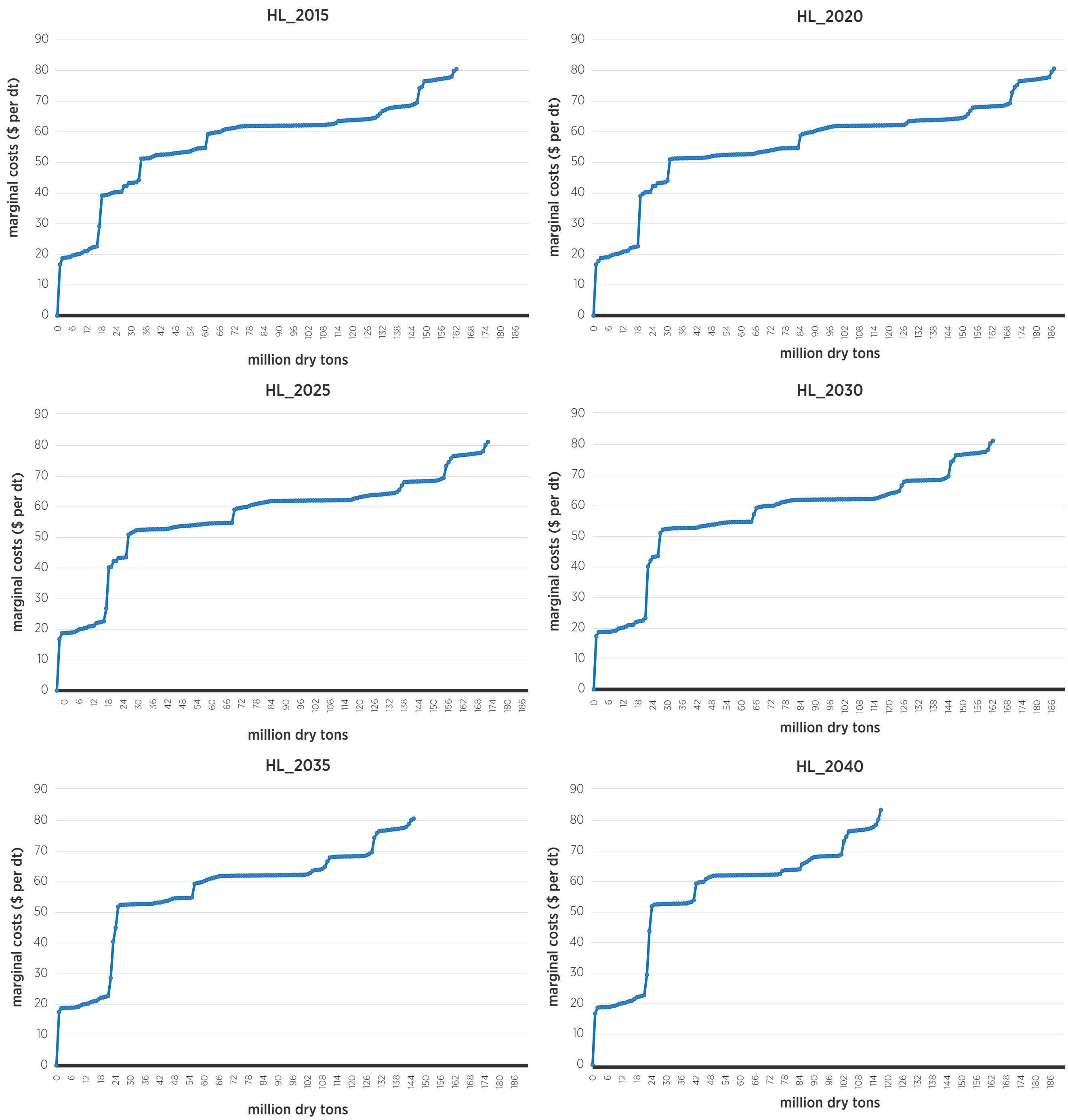
Supply Curves Generated for Each Scenario

Figure B-1 | Baseline_ML supply curves



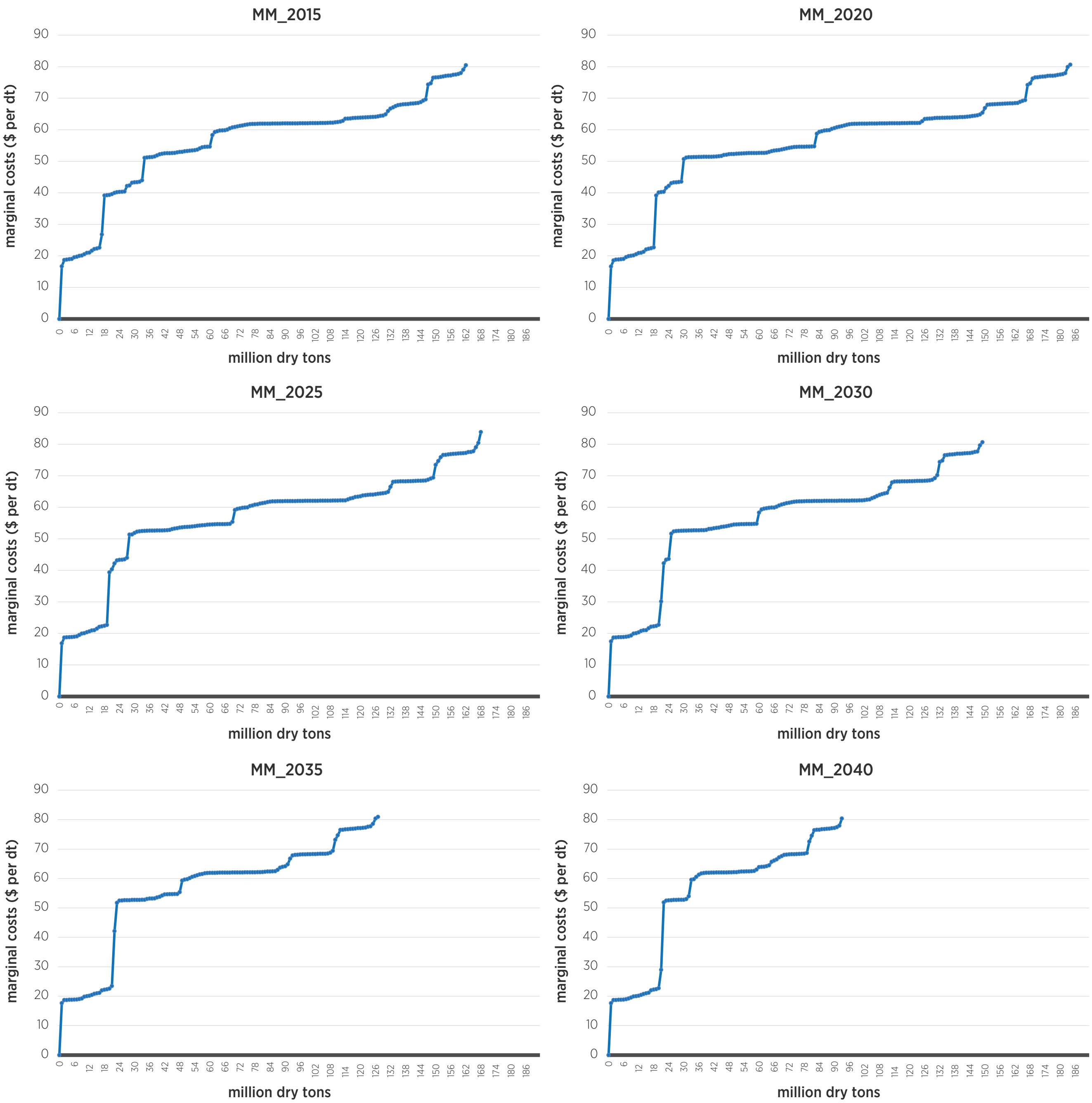
Note: The first letter of the code for the scenarios indicates level of housing starts (high and medium), and the second letter indicates the level of biomass harvested for fuel (high, medium, and low).

Figure B-2 | HL supply curves



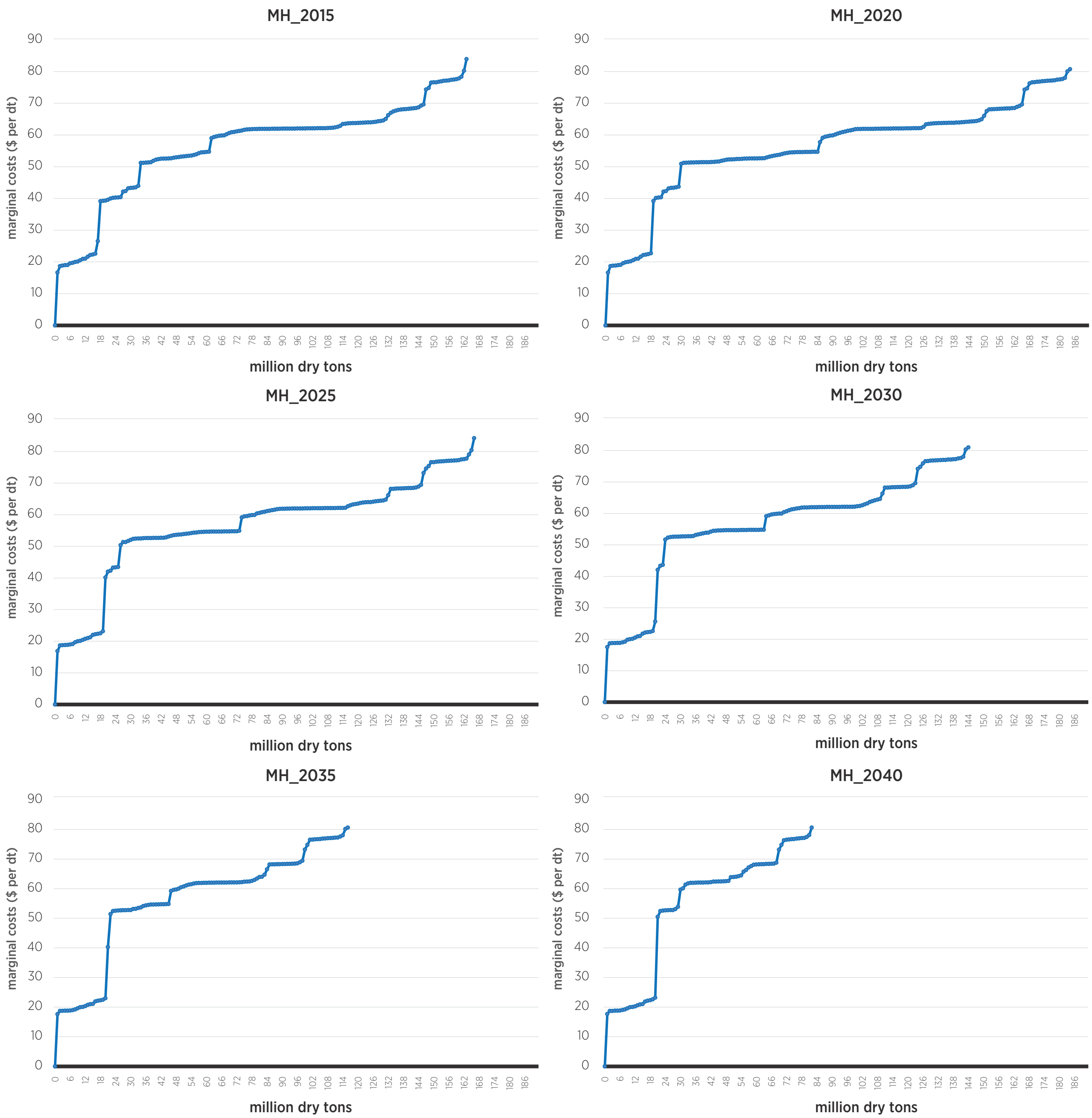
Note: The first letter of the code for the scenarios indicates level of housing starts (high and medium), and the second letter indicates the level of biomass harvested for fuel (high, medium, and low).

Figure B-3 | MM supply curves



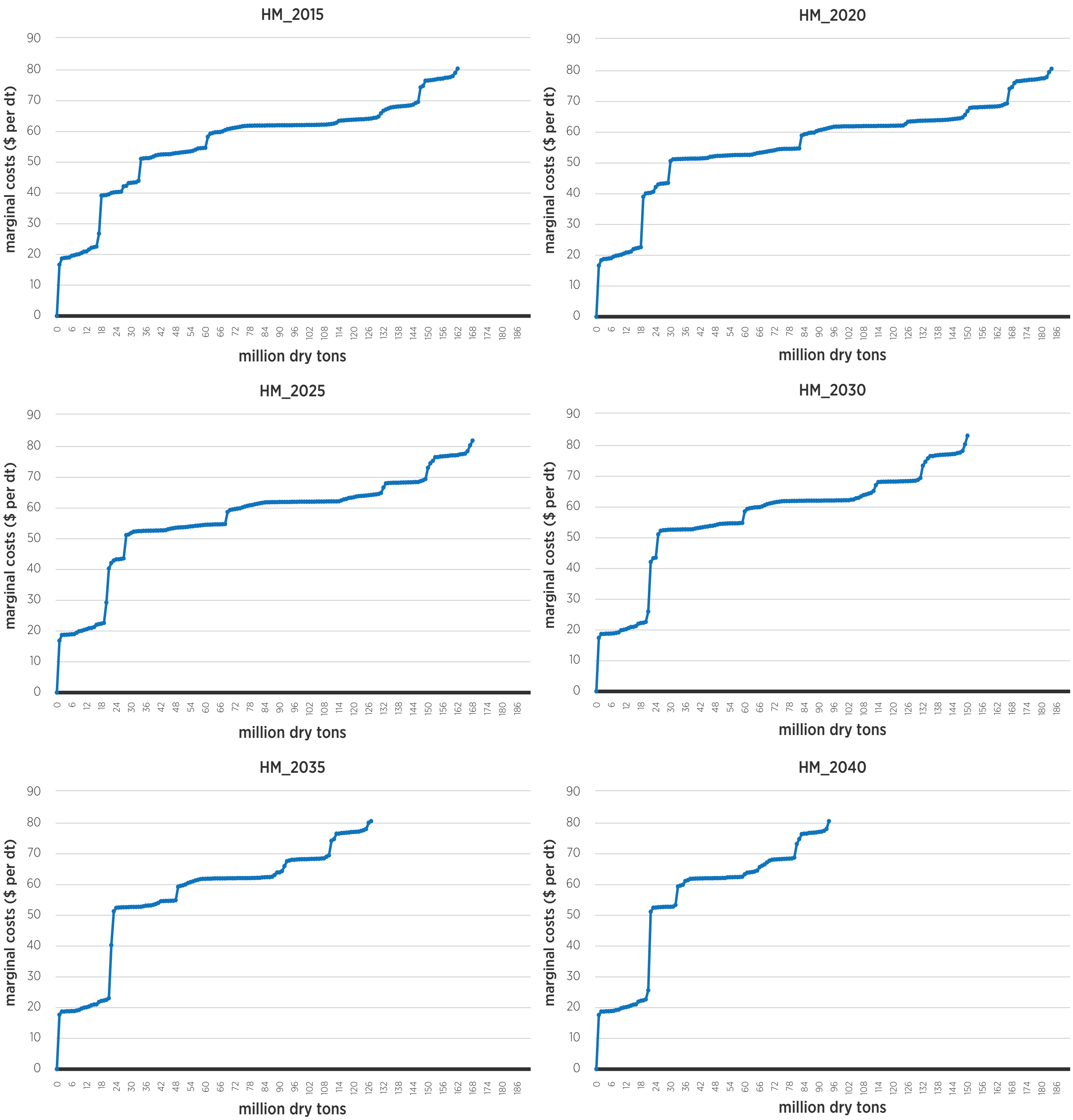
Note: The first letter of the code for the scenarios indicates level of housing starts (high and medium), and the second letter indicates the level of biomass harvested for fuel (high, medium, and low).

Figure B-4 | MH supply curves



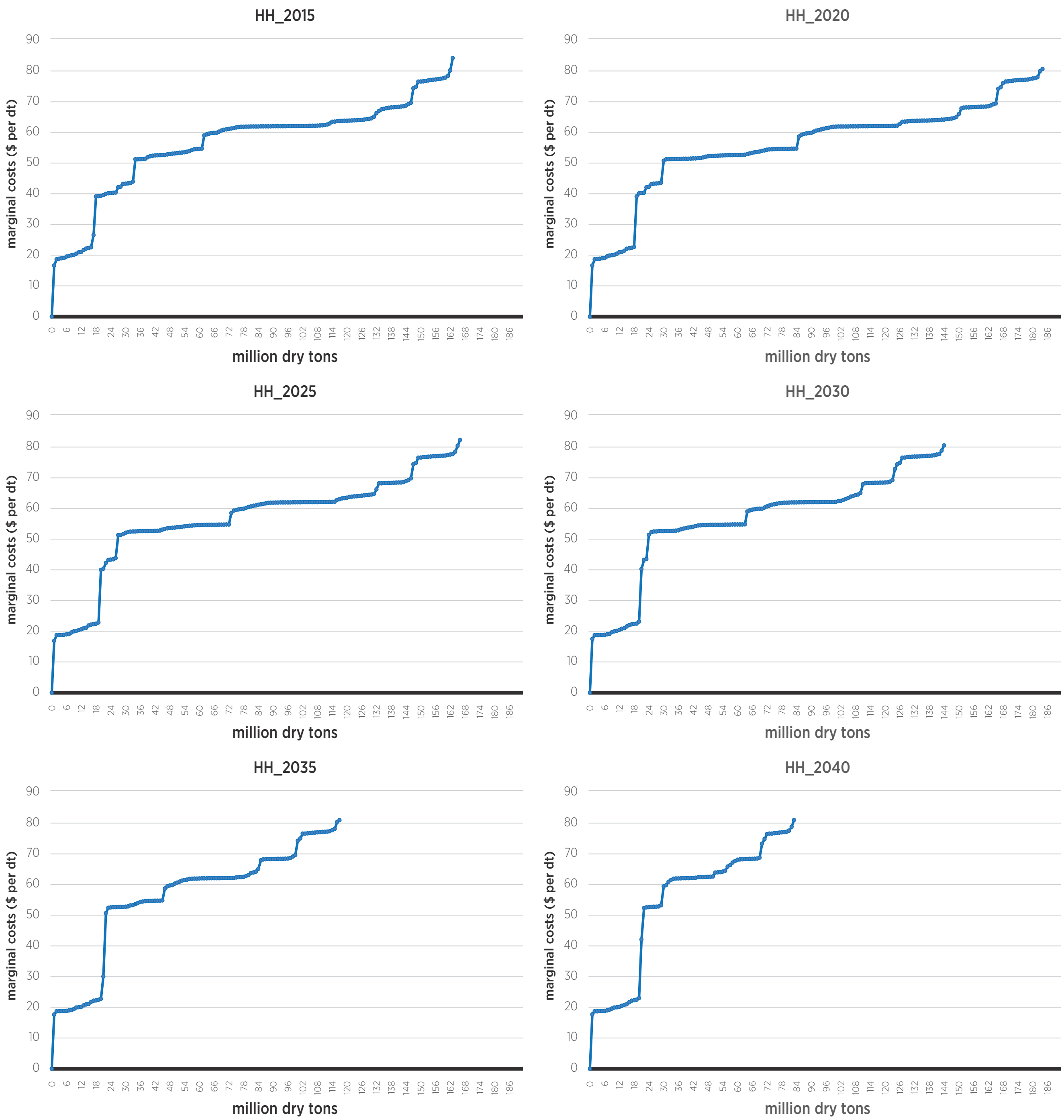
Note: The first letter of the code for the scenarios indicates level of housing starts (high and medium), and the second letter indicates the level of biomass harvested for fuel (high, medium, and low).

Figure B-5 | HM supply curves



Note: The first letter of the code for the scenarios indicates level of housing starts (high and medium), and the second letter indicates the level of biomass harvested for fuel (high, medium, and low).

Figure B-6 | HH supply curves



Note: The first letter of the code for the scenarios indicates level of housing starts (high and medium), and the second letter indicates the level of biomass harvested for fuel (high, medium, and low).

Sensitivity Analysis

Table B-8 | Tons Associated with Sensitivity Cases

Biomass price ($/dry ton)	Baseline (million tons)			HH scenario (million tons)		
	As modeled	Increased Volume case	Increased Volume Plus case	As modeled	Increased Volume case	Increased Volume Plus case
40	22	23	25	22	22	22
60	46	86	88	32	51	53
80	116	200	197	83	135	132

References

Bechtold, W. A. Patterson, P. L., eds. 2005. The Enhanced Forest Inventory and Analysis Program–National Sampling Design and Estimation Procedures. Gen. Tech. Rep. SRS-80. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 85 p.

Appendix C

Appendix to Chapter 4 - At the Farmgate: Agricultural Residues and Biomass Energy Crops

C.1 POLYSYS

At its core, POLYSYS is structured as a system of interdependent modules simulating (a) county-level crop supply for the continental United States; (b) national crop demands and prices; (c) national livestock supply and demand; and (d) agricultural income. Variables that drive the modules include planted and harvested area, production inputs, yields, exports, costs of production, demand by use, commodity price, government program outlays, and net realized income. Crop transitions among agricultural lands based on cropland allocation decisions made by individual farmers are primarily driven by the expected productivity of land, the cost of crop production, the expected economic return on the crop, and market conditions. POLYSYS is used to model the introduction of a biomass market under specified agronomic assumptions and market scenarios. These assumptions are summarized in the following sections and described in more detail in the 2011 *BT2* section 5.2.

1. General Agricultural Land Modeling Assumptions

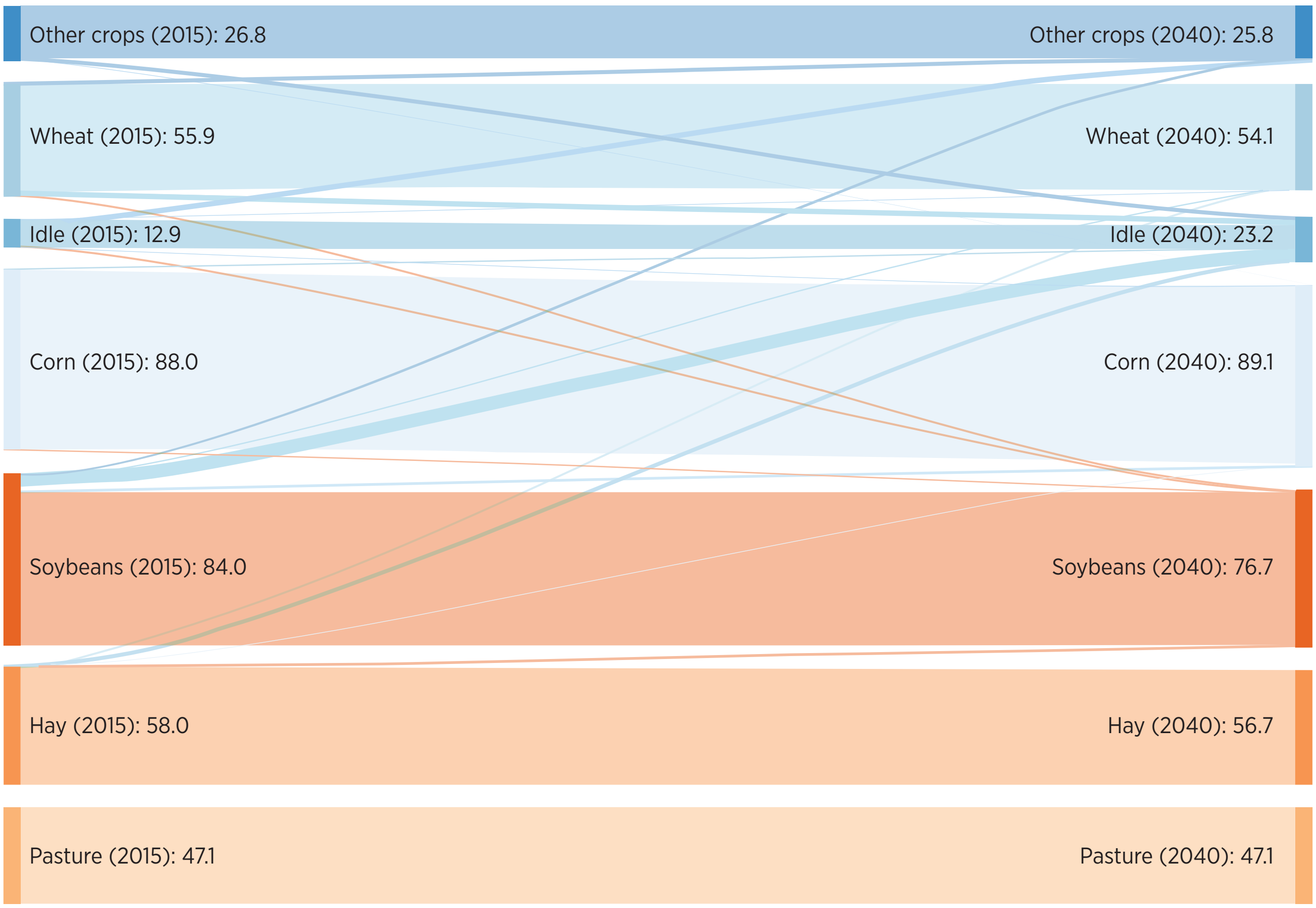
The following are assumptions applicable to all resources simulated in POLYSYS:

Land base: NASS data from USDA are used to generate initial county-level estimates of planted area, harvested area, harvested/planted ratio and yield for the conventional crops modelled in POLYSYS. Data sources include the annual tabular survey data and the geospatial Cropland Data Layers. The survey data are the primary source of county-level estimates of area and yield. However, in some states and for some crops, survey data is only reported at the Agricultural Statistic District (ASD). In those cases where only ASD-level estimates exist, county-level estimates are made by multiplying the ASD planted and harvested areas by the county crop fractions in the ASD which are derived from the Cropland Data Layers. The ASD harvested/planted ratio and yield are assigned to a county in the ASD if the Cropland Data Layers report planted area in the county. Four years of data (2010–2013) are averaged to reduce inter-annual variability, and the averages are provided as input to the county-level version of POLYSYS employed for this study.

- The starting year of simulation in POLYSYS is crop year 2014 (the most current complete year in the 2015 USDA Baseline). For the sake of simplicity, the crop year 2014 denotes the marketing year 2013/2014. For reporting of results, the year 2015 is assumed to be the initial year of simulation.

- It is assumed that all land within the POLYSYS model is fixed throughout the projection period. However, land is allowed to rotate between management regimes, including tillage practices and annual and perennial production, as well as to transition to fallow or idle[2] to satisfy baseline demands.[3] For example, under extension of a baseline scenario (BL0), transition among cropland, pasture and hay occurs, with some reduction in cropland as depicted in figure C.1 and table C. 1.

Figure C-1 | Land base transitions simulated under a baseline scenario (BL0)



Note: Other crops include barley, oats, rice, cotton, grain sorghum.

[2] Idle land or "cropland idle" was reported in the 2012 USDA Agricultural census to include "1. Land used for cover crops or soil improvement but not harvested or grazed. 2. Land in Federal or State conservation programs that was not hayed or grazed in 2012. 3. Land occupied with growing crops for harvest in 2013 or later years but not harvested or summer fallowed in 2012 (except fruit or nuts in an orchard, grove, or vineyard or berries being maintained for production). Examples are acreage planted in winter wheat, strawberries, etc., for harvest in 2013 and no crop was harvested from these acres in 2012" (USDA 2012). Some cropland is idle each year for various physical and economic reasons. Acreage diverted from crops to soil-conserving uses (e.g., if not eligible for and used as cropland pasture) under federal farm programs is included in this component. Cropland enrolled in the Federal Conservation Reserve Program (CRP) is included in idle cropland land base, although these lands are excluded from the land base available for transition to energy crops within POLYSYS.

[3] Total idle land is fixed across all scenarios beginning at 12.3 million acres in 2015 and ending at 23.2 million acres in 2040, following the USDA baseline projection (USDA 2015).

Cropland: Similar to the 2012 USDA Census of Agriculture definition of "total cropland," this land category includes planted and harvested acres of corn, wheat, grain sorghum, barley, soybeans, rice, cotton, barley, and hay. The cumulative land base is assumed equal to the amount needed to satisfy the crop supply and demand estimates of the USDA Baseline projections. County-level distribution is determined by a multi-year average of production from 2010–2013 USDA-NASS surveys of agricultural production.

The land class category excludes cropland used as pasture, permanent pasture, idle land, and land under retirement programs.

- It is assumed to be a total 312.6 million acres in the initial simulation year of agricultural production in 2015.
- Table C.1 provides estimates of land allocated to major crops and hay to satisfy assumed domestic and international demands of traditional crops and crop products.

Table C-1 | Selected Land Allocation of Major Crops and Hay for Selected Years in the Baseline (2014–2025) and Extended Baseline (2026–2040) Periods

Planted acres (millions)	2015	2017	2022	2030	2040
Corn	88	90	89	89.09	89.1
Grain Sorghum	7.5	7.4	7.1	7.01	7.02
Oats	3	2.5	2.5	2.47	2.44
Barley	3.5	3.2	3	2.96	2.9
Wheat	56	52.5	52	52.58	54.07
Soybeans	84	78	79	78.37	76.87
Cotton	9.8	9.8	10.2	10.38	10.53
Rice	2.94	2.94	3.03	3.06	3.06
Hay	57.9	57.24	56.65	56.65	56.65
Total All Crops	**312.6**	**303.58**	**302.48**	**302.57**	**302.64**

Pastureland, all: A category not explicitly defined in the 2012 USDA Census of Agriculture, but estimated as the reported composite category of cropland used as pasture, permanent pasture, woodland pasture, irrigated pastureland, rangeland and wasteland in the 2012 UDSA Census of Agriculture.

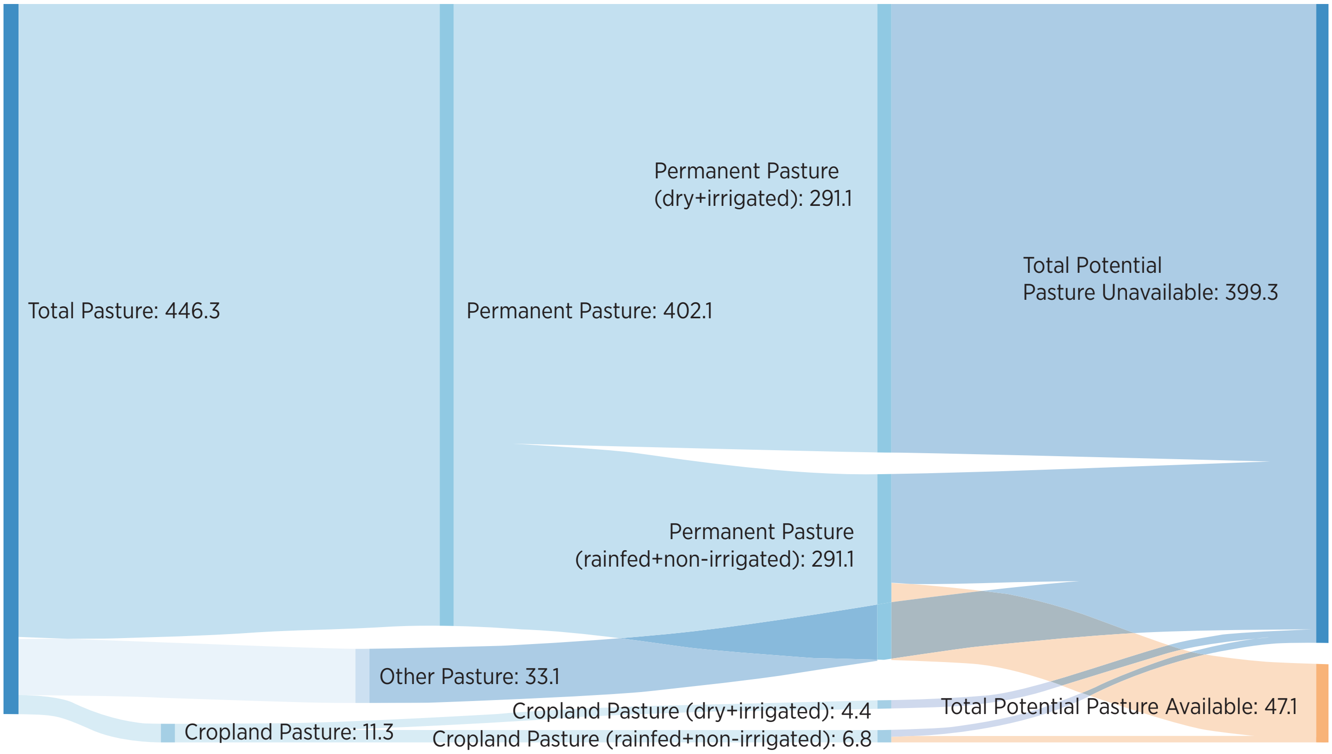
- It is assumed to be a total 446.3 million acres across the projection period.
- The following classes of pastureland are utilized in estimating the pastureland base for bioenergy crop production:
  - "Cropland pasture" or cropland used for pasture or grazing: Assumed to be a total 11.2 million acres across the projection period.
    - Permanent pasture:[6] Assumed to be a total 402.1 million acres across the projection period, of which irrigated pasture[7] is assumed to be 97.3 million acres across the projection period.

- Woodland and other pasture (including rangeland and wasteland): 33.1 million acres (estimated by subtraction, reported county-level acreage for woodland pasture equaled 24.3 million acres [USDA 2012]).

Land base transition constraints: Annual transition is limited to 5% of permanent pasture, 20% of cropland pasture, and 10% of cropland. Cumulative transition is limited to 40% of permanent pasture, 40% of cropland pasture, and 10% of cropland for most energy crops (except for biomass sorghum, which is constrained to USDA land capability classes I & II).

Additionally, in order to ensure successful establishment of energy crops and minimize impacts to existing grazing markets, it is assumed that pastureland must meet the following criteria to be available land for energy crop production: (1) be non-irrigated and (2) be in a county with a 30-year normal precipitation of 25 inches per year or more a (for transition from pastureland to energy crops or MiG). The resulting land availability after applied constraints totals 47.1 million acres of pastureland, as depicted in figure C.1 and figure C.2.

Figure C-2 | Sankey diagram of pastureland by type and criteria available and unavailable for bioenergy crop production



[6] "Permanent pasture," or rangeland, other than cropland and woodland pastured: Defined in the 2012 USDA Census of Agriculture, appendix B, as a land category that "encompasses grazable land that does not qualify as woodland pasture or cropland pasture. It may be irrigated or dry land. In some areas, it can be a high quality pasture that could not be cropped without improvements. In other areas, it is barely able to be grazed and is only marginally better than wasteland" (USDA 2012).

[7] Irrigated pasture is defined to be any pasture land that falls under the "irrigated land" land class defined by USDA to include "all land watered by any artificial or controlled means, such as sprinklers, flooding, furrows or ditches, subirrigation, and spreader dikes. Included are supplemental, partial, and preplant irrigation" (USDA 2012).

Land uses: POLYSYS is calibrated to county-level major crops (corn, grain sorghum, oats, barley, wheat, soybeans, cotton, rice, and hay) based on a four-year average of the 2010 to 2013 USDA NASS annual survey data (USDA 2012).

Food, feed, fiber, and corn ethanol demands: POLYSYS prioritizes future demands for food, feed, fiber, and corn ethanol demands as specified in the 2015 USDA Baseline Projection (USDA 2015) before responding to simulated cellulosic biomass markets. As stated earlier, the potential supply estimates from agriculture are anchored to the USDA Long-Term Forecast (extended to 2040) such that all projected demands for food, feed, fiber, fuel, and exports are satisfied before biomass crops are planted. POLYSYS simultaneously balances available supply and sector demands via adjustments to commodity prices using known economic relationships. Food, feed, and industrial demands are adjusted by using crop "own-" and "cross-" price elasticities. Through these relationships, quantities of commodity demands can change from baseline via changes in available supply and price levels. Corn grain demand for ethanol remains fixed in all scenarios, and therefore does not change in quantity as corn price may change (see Ray et al. 1998).

Crop budgets: Both traditional crops and energy crop budgets are estimated at the county level through a spatial interpolation method of regional-level enterprise budgets. More information on budgets is described below.

Cellulosic biomass markets: Markets for biomass feedstocks are introduced as specified farmgate prices offered (≤$30–≤$100/dry ton in $5 increments) in specified-price simulations.[8] These prices (2014$) are adjusted for inflation using the Producer Price Index for Crude and Raw Materials (PPICRM)[9] and are applied to all counties for all years in the simulation period. Figure C.2 shows the index applied in each year. For example, when applying a ≤$60 real feedstock price ($/dry ton, base-2014) in a specified-price simulation, the offered price in 2040 has an index of 1.495. Therefore, the offered nominal feedstock price ($/dry ton) is ≤$89.7, rounded to ≤$90 in that year.

Table C-2 | Inflation Index Applied to Real Feedstock Price to Calculate Nominal Prices in Specified-Price Simulations

Year	2014	2015	2016	2017	2018	2019	2020			
Index	1.000	0.977	0.977	0.982	0.992	1.007	1.026			
Year	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Index	1.045	1.065	1.0852	1.106	1.127	1.148	1.170	1.192	1.215	1.238
Year	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**	**2040**
Index	1.262	1.286	1.310	1.335	1.3603	1.386	1.412	1.439	1.467	1.495

[9] The PPICRM is a price index specifically for crude goods that "have not been manufactured or fabricated but will undergo some processing before becoming intermediate or finished goods." (Bureau of Labor Statistics, 2012).

Fixed and Variable Costs of Production: Following prior analysis using POLYSYS (BT2 and De La Torre Ugarte et al. 2003), it is assumed that crop costs of production in the supply curve estimation scenarios are restricted to variable costs, such as land preparation, planting, maintenance, and crop harvest. Land rent is assumed to be a sunk cost and is excluded from crop costs budgets and planting decisions. This may differ from enterprise or business model approaches to costing, which include a broader characterization of costs. An exception to this is the estimation of the biomass cost curve generated from the ≤$60/dry ton base-case (1%) scenario represented in the delivered supply analysis. In this approach, it was assumed that profit was equal to 10% of variable costs of production. This approach also resolves the issue of backward-bending supply curves that occur when energy crops compete for land differently at each simulated price (see text box 4.2). The accounting of production and opportunity cost using a single estimate along the supply curve creates a monotonic supply curve (increasing in quantity supplied as price increases).

2. Agricultural Residue Modeling Assumptions

There are many harvest options for residues,[10] but for each crop, this study models and costs a crop-specific machinery complement.

For corn stover, the stover collection operations assumed are the following:

- Turn off spreader behind combine
- Shred
- Bale with large rectangular baler
- Move bales to roadside with automated bale wagon.

For wheat straw, the collection operations are the following:

- Turn off the spreader behind the combine,
- Bale with large rectangular baler
- Move bales to the roadside with automated bale wagon.

It is assumed that the removed nutrients (e.g., nitrogen, phosphorus, and potassium) need to be replaced, except for potassium in regions where potassium fertilizer is not added (western half of the United States). Table C.3 details assumptions about the crop characteristics used to estimate residues. These challenges and opportunities are described in more detail in chapter 8. In addition, sustainability and operational efficient restraints are imposed on agricultural residues and are discussed in chapter 4. They are represented in figure C.3.

Table C-3 | Assumptions about Crop Characteristics Used in Estimating Residues

Crop	Weight	Moisture	Dry weight	Residue-to-grain weight ratio	Residue
	lb/bu	%	lb/bua		dry tons/bu
Corn	56	15.5	47.32	1.0	0.0237
Sorghum	56	14.0	48.16	1.0	0.0241
Barley	48	14.5	41.04	1.5	0.0308
Oats	32	14.0	27.52	2.0	0.0275
Winter wheat	60	13.5	51.09	1.7	0.0441
Spring wheat	60	13.5	51.09	1.3	0.0337

abu = bushels

[10] Crop residues modeled in POLYSYS include corn stover and wheat, barely, oats, and sorghum straw. Example of other residues not included are rice field residue (straw), cotton field residue, and sugarcane residues (trash-leaves, tops, and remaining stalk after primary harvest of the stalk).

Tillage flexibility: Tillage production distribution (CTIC 2007) is grouped into three categories of management: no-till production, reduced tillage, conventional tillage. A flexibility constraint is included in POLYSYS to control switching between these tillage classes among each individual crop. The methodology to control this constraint employs a +/- 10% annual change constraint,[11] which is multiplied by the following variable: additional change = 1.0 + absolute value (% change in net present value [NPV] between simulation NPV and baseline NPV) * index (tillflex). Where tillflex is equal to 3, a 0.75 index is used; where tillflex is equal to 2, a 0.50 index is used; and where tillflex is equal to 1, a 0.30 if index is used. This means that at all index levels, as the percent change in NPV between simulation and baseline becomes greater, more land is allowed to transition up to a maximum of 100% of tillage acreage. The difference between the index levels is simply one of intensity, with a value of 3 increasing the percentage allowed to transition more rapidly than a value of 1. See also chapter 4 sensitivity analysis section on tillage flexibility.

3. Energy Crop Modeling Assumptions

Energy crop yields: New in this analysis, energy crop yields are empirically modeled. Energy crop yields were derived from modeling of crop yields based on data from the Sun Grant Regional Feedstock Partnership in coordination with the Oregon State University PRISM modeling group. Following six crop-specific workshops, data from more than 110 field trails was used to estimate county-specific per-acre yields based on 30-year historic weather data (see chapter 4, text box 4.1).

Table C-4 | Regional Absolute Average and Range Yield Assumptions, in Dry Tons at Maturity (or mean annual increment at harvest) of Energy Crops in POLYSYS, Averaged Across All Counties with Simulated Production in 2040 (at ≤$60 per ton)

Farm production region	Switchgrass	Poplar	Willow	Biomass sorghum	Miscanthus	Energy cane
Appalachia	7.5 (5.7–9.3)	5.3 (4.4–6.8)	6.2 (3.7–7.9)	10.7 (9.7–11.4)	8.5 (6.8–10.9)	N/A
Corn Belt	7.6 (5.5–8.7)	5.6 (4.6–6.7)	6.7 (3.9–8.2)	11 (10.4–11.6)	10.2 (7.9–11.2)	N/A
Delta States	8.3 (6.1 - 9.5)	5.3 (4.7 - 6.5)	5.2 (4.8 - 5.6)	11.5 (10.3 - 12.3)	8.2 (7.2–10.3)	10.9 (8.8–12.1)
Lake States	3 (2.7–3.3)	4.7 (3.7–5.8)	5.3 (3.7–7.1)	N/A	7.7 (5.3–10.5)	N/A
Mountain	2.3 (1.5–3.2)	n/a	3.1 (2.9–3.2)	N/A	4 (3.9–4)	N/A
Northeast	6.4 (4.6–7.3)	5.1 (4.4–5.9)	6 (3.8–7.3)	N/A	8.1 (6.4–9.1)	N/A
Northern Plains	4.3 (2–8)	5.4 (5.3–5.6)	4.8 (2.8–6.2)	10.9 (10.3–11.5)	8.1 (4.4–11.2)	N/A
Pacific	2.3 (1.6–2.8)	3.9 (3.3–4.4)	3.8 (3.8–3.8)	N/A	N/A	N/A
Southeast	7 (4.7–9.3)	4.8 (4–6.6)	5.6 (3.8–7.5)	10.5 (9.2–11.8)	7.5 (5.8–8.6)	10.7 (8.1–13.3)
Southern Plains	5.3 (1.7 - 8.9)	4 (2.6 - 4.8)	2.8 (1.4 - 3.2)	10.2 (8.6 - 11.7)	5.9 (3.8–9.2)	N/A

[11] "Additional change" is constrained to a maximum value of 10.0.

Table C-5 | Regional Average and Range Crop Suitability, as an Index (0 = unsuitable, 1 = highly suitable) of Energy Crops as Inputs to POLYSYS, Averaged Across All Counties with Simulated Production in 2040 (at ≤$60 per ton)

Farm production region	Switchgrass (0.75 lowland, 0.43 upland)	Poplar (0.70)	Willow (0.56)	Biomass sorghum (0.79)	Miscanthus (0.47)	Energy cane (0.96)
Appalachia	0.8 (0.6–1)	0.7 (0.6–0.9)	0.8 (0.4–1)	0.9 (0.8–0.9)	0.8 (0.6–1)	N/A
Corn Belt	0.8 (0.6–0.9)	0.7 (0.6–0.9)	0.8 (0.5–1)	0.9 (0.8–0.9)	0.9 (0.7–1)	N/A
Delta States	0.9 (0.6–1)	0.7 (0.6–0.9)	0.6 (0.6–0.7)	0.9 (0.8–1)	0.7 (0.6–0.9)	0.8 (0.7–0.9)
Lake States	0.3 (0.3–0.4)	0.6 (0.5–0.8)	0.6 (0.5–0.9)	N/A	0.7 (0.5–0.9)	N/A
Mountain	0.2 (0.2–0.3)	N/A	0.4 (0.3–0.4)	N/A	0.4 (0.3–0.4)	N/A
Northeast	0.7 (0.5–0.8)	0.7 (0.6–0.8)	0.7 (0.5–0.9)	N/A	0.7 (0.6–0.8)	N/A
Northern Plains	0.4 (0.2–0.8)	0.7 (0.7-0.7)	0.6 (0.3–0.8)	0.9 (0.8–0.9)	0.7 (0.4–1)	N/A
Pacific	0.2 (0.2–0.3)	0.5 (0.4–0.6)	0.5 (0.5–0.5)	N/A	N/A	N/A
Southeast	0.7 (0.5–1)	0.6 (0.5–0.9)	0.7 (0.5–0.9)	0.9 (0.7–1)	0.7 (0.5–0.8)	0.8 (0.6–1)
Southern Plains	0.6 (0.2–0.9)	0.5 (0.3–0.6)	0.3 (0.2–0.4)	0.8 (0.7–0.9)	0.5 (0.3–0.8)	N/A

Note: Under each crop name is included the R2 for the modeled yield and sampled field trial yield to develop the absolute yield transformation function.

4. Energy Crop Feedstock-Specific Assumptions

Switchgrass production: Switchgrass grows in every region, although it has been shown to be more productive and sustainable on rain-fed marginal land east of the 100th Meridian (see BT2 and Mitchell et al. 2010). The stand life is 10 years. POLYSYS allows for a 50% harvest in year 1, a 75% harvest in year 2, and a 100% harvest in years 3–10. It is assumed to be established with no-till. Seeding rate is 6 lb/acre and 10% is reseeded in year 2. Varieties planted include Alamo, Kanlow, Trailblazer, Cave-in-Rock, and Liberty. In year 1, limestone is applied in regions where it is needed at 1 ton/acre; phosphate (P_2O_5) at 40 lb/acre; and, in regions where it is needed, potassium (K_2O) at 80 lb/acre. In years 2 through 10 fertilizers are applied are: nitrogen 13 lb/dry ton harvested, phosphorus (as P_2O_5) 4 lb/dry ton harvested, and K_2O 14 lb per dry ton harvested. Herbicide treatments in year 1 are quinclorac, Atrazine, and 2,4-D; and in years 2, 5, and 8, herbicide treatment is 2,4-D. Switchgrass is harvested after a killing frost with equipment consisting of a mower-conditioner, large rectangular baler, and automatic bale wagon. For all baling operations, twine costs are assumed to be 2.56/dry ton (Klein et al. 2015).[12]

[12] Klein et al. (2015, 7) show a twine cost for a large rectangular bale of $1.23/bale. To calculate a per ton twine cost we assume a bale of biomass would be 1000 dry lb, and thus use a twine cost of $2.56/dry ton.

Miscanthus production: Miscanthus is planted with conventional tillage. Rhizomes are used and planted at 8,750 per acre at a cost of 0.10/rhizome. Stand life is assumed to be 15 years. POLYSYS allows for 0% harvest in year 1, 50% in year 2, and 100% in years 3–15. Tillage is a chisel plow followed by two diskings at establishment. Herbicide treatments occur in the first year using 2,4-D and Harness Xtra and in the second year using 2,4-D. First-year fertilizer applications are 62 lb/acre of P_2O_5 and, in regions where potassium is needed, 50 lb/acre of K_2O. Fertilization takes place in years 2 through 15 with nitrogen at 9 lb/dry ton harvested, P_2O_5 at 1.5 lb/dry ton harvested, and K_2O (in regions where needed) at 8 lb/dry ton harvested. Harvesting is done after senescence and before regrowth starts (late winter/early spring), at which point miscanthus has dried and translocated much of its nutrients back into the roots. Harvesting equipment consists of a mower-conditioner, large rectangular baler, and automatic bale wagon.

Energy cane production: Energy cane is limited to the southern rim of the United States, but it is grown in a larger area than where sugar cane grows. Stand life is assumed to be 7 years with harvest once a year. POLYSYS allows for a harvest of 75% in year 1, and 100% in years 2–7. For establishment, conventional tillage is assumed with a chisel plow and an offset disk twice over. Cultured seed cane is hand planted in the same fashion as cultured sugar cane. Herbicide treatments are extensive. In year 1, Roundup, Sencor, and pendimethalin are applied. In years 2 to 7 pendimethalin, atrazine, and 2,4-D are applied. Establishment year fertilization is 62 lb/acre and 50 lb/acre of P_2O_5 and K_2O, respectively. In subsequent years, nitrogen, P_2O_5, and K_2O are applied at rates of 9, 1.5, and 8 lb per dry ton of energy cane harvested, respectively. Harvesting is done with a sugar cane billet harvester and three high-dump sugar cane wagons.

Biomass sorghum production: Biomass sorghum is an annual crop, similar to forage sorghum. Establishment is assumed to use conventional tillage with a chisel plow and an offset disk. Planting uses a row crop planter. Fertilization is limestone (in regions where needed), nitrogen, P_2O_5, and K_2O (in regions where needed). Herbicide treatments are Bicep II/Magnum and 2,4-D. Harvest is with a self-propelled forage harvester and two high-dump forage wagons. Sorghum is restricted to a “1 in 4 year rotation” (i.e. it can only come into production on 1/4 of available land) based on the land capability classes I&II (source: USDA NRCS Map ID m6175; data source: 1997 National Resources Inventory, revisited December 2000). The annual yield increase for biomass sorghum is consistent with other energy crops in the BC1 scenario, but is as follows in the high yield scenarios: 1.5% in the 2% yield increase scenario (HH2), 1.75% in the 3% yield increase scenario (HH3), and 2% in the 4% yield increase scenario (HH4).

Hybrid poplar: Hybrid poplar is modeled as growing on an 8-year rotation schedule in most of the eastern United States and Pacific Northwest. Establishment uses conventional tillage: moldboard plow followed by an offset disk. Fertilization is limestone (2 tons/acre except in the Pacific Northwest) and K_2O (18 to 60 lb/acre, depending on the region) in the establishment year; nitrogen (90 lb/acre as a combination of urea and diammonium phosphate) and phosphorus (15 to 30 lb/acre, depending on the region as diammonium phosphate in year 3; and nitrogen (90 lb/acre as urea) in year 6. Herbicide treatments in the establishment year are glyphosate (Roundup) and pendimethalin, and in years 2 and 3, glyphosate. An insecticide is applied in year 4. Harvest is done in year 8. It is modeled in this study as a single-stem 8-year rotation for simplicity, but it is potentially coppiced at variable rotations. Harvest is costed as a custom operation with a fixed cost per dry ton, consisting of a feller buncher, skidder, chipper and chip van.

Southern pine: Pine is established using conventional tillage with a moldboard plow and offset disk. Seedlings are planted at 762 per acre. In the establishment year, limestone (2,000 tons/acre) and K_2O (48.2 lb/acre) are applied; in years 2, 4, and 6, nitrogen (at 90 lb/acre as urea) is applied; and in year 3, P_2O_5 (91.7 lb/acre as diammonium phosphate) is applied. Herbicide treatments in the establishment year are glyphosate and pendimethalin and in years 2 and 3, glyphosate. Harvest is done in year 8. Harvest is costed as a custom operation with a fixed cost per dry ton, consisting of: feller buncher, skidder, chipper and chip van.

Eucalyptus: Eucalyptus can be grown in the southeastern United States. Stands are harvested every 4 years with one coppice, for a stand life of 8 years. After the first harvest of all acres (year 4), an additional 15% boost in yield occurs for all additional harvests through the end of the rotation period. Eucalyptus is established using conventional tillage with a moldboard plow and offset disk. Containerized seedlings are planted at 1,575 per acre. Herbicide treatments in the establishment year are glyphosate and sulfmetruon methyl. In years 2 and 6, glyphosate is applied. Fertilizer is ground applied in year 1 as limestone (2,000 lb/acre); in years 1, 6, 11, 16, and 21 as P_2O_5 (114.6 lb/acre as triple superphosphate); in years 1, 6, 11, 16, and 21 as K_2O (40 lb/acre); and in year 6, 11, 16, and 21 as nitrogen and diammonium phosphate. Fertilizer is aerially applied as urea and diammonium phosphate at rates of 150 lb/acre of nitrogen and 115 lb/acre of P_2O_5. Harvest, at year 5, is costed as a custom operation with a fixed cost per dry ton, consisting of: feller buncher, skidder, chipper and chip van.

Willow: Willow budgets are based on the EcoWillow model from State University of New York College of Environmental Science and Forestry. Willow is modeled as a coppiced crop over a 32 year period, with harvest every 4 years. After the first harvest (year 4), an additional 15% boost in yield occurs for all additional harvests through the end of the rotation period. In the fall before planting, establishment uses brush hogging, plowing, and disking; and a cover crop is planted. In year 1, the cover crop is killed, willow cuttings are planted at 5,500 per acre, a preemergent herbicide is applied after planting, and additional weed control occurs. The herbicide treatments used in this establishment year are two applications of glyphosate (1.5 pt/acre each), oxyfluorfen (Goal) (2.5 pt/ac; see Abrahamson et al. [2010]), and pendimethalin (Prowl) (2.4 pt/acre). In year 2, the willows are cut down but not harvested, and additional weed control occurs. Fertilization occurs after the initial cutting in year 2 and after each harvest (except the final one) at a cost of approximately $65 per acre (nitrogen, P_2O_5, and K_2O at rates of 45, 20, and 45 lb/acre, respectively) mechanical weed control using a rototiller also occurs in year 2. Harvest is costed as a custom operation with a fixed cost per dry ton: self-propelled forage harvester equipped with a willow cutting head that cuts and chips the stems. The chips are blown into forage wagons transported to the road side. At the roadside, the chips are transferred to a chip van.

C.2 Enhancements and Modifications from BT2

Although this analysis follows the same general methodology for estimating farmgate supplies as was reported in the 2011 BT2, several changes have been made in this analysis. The changes include updating input data (see section C.3), adjusting for inflation, harmonizing with current and projected operational technology, and minor corrections in the modeling framework. Prominent updates and modifications of the modeling assumptions are as follows. See also table C.5.

- The simulation period is advanced from 2010–2030 in the 2011 BT2 to 2015–2040 in this report.
- POLYSYS is anchored in the USDA Baseline Projection from 2015 to 2025, extended linearly to 2040.

- Currently available resources are reported as 2015 unless otherwise specified.
- *BT2* reported flat nominal prices. Farmgate prices are reported as 2015 dollars, adjusted for inflation based on the PPICRM. In this report, inflation of operational costs over time was also harmonized across all crops consistent with the USDA Baseline Projection.
- Residue removal is allowed on conventionally tilled acres as long as residues remaining after harvest meet constraints described in chapter 4. This change reflects examples from extant cellulosic biofuels products.
- Operationally available residues are limited to 50% of total residues starting in 2015, increasing linearly to 90% of available residues in 2040 (see section 1.2, Agricultural Residue Modeling Assumptions). The operational constraint is a function of total stover yield. The total amount of "harvestable yield" is constrained by both "operational yield" and "sustainable removable yield" (whichever is more constraining). The harvestable residue is subsequently selected as economically harvestable at the county level in POLYSYS if and where the price offered for biomass exceeds the cost of production. The generalized work flow is illustrated in figure C.3.

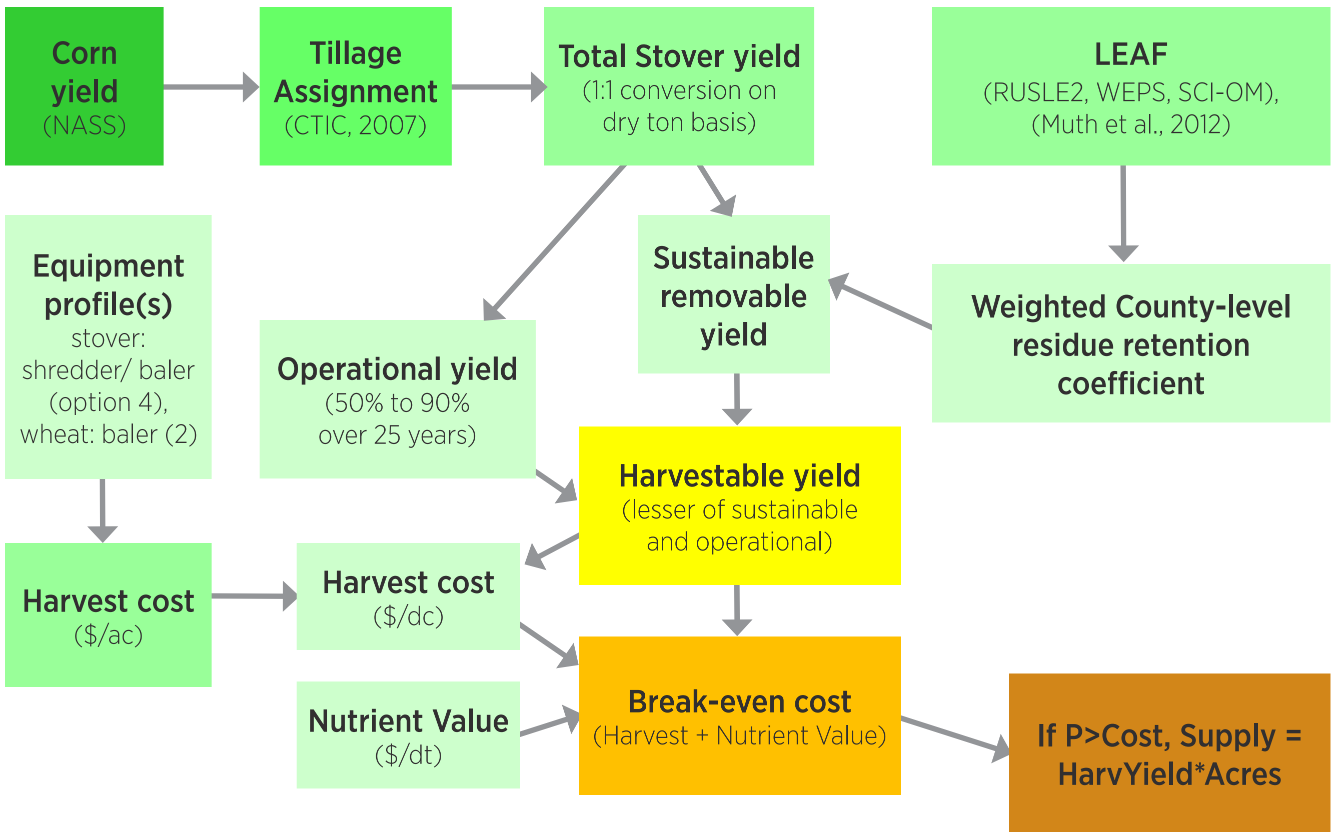
Table C-6 | Summary of Enhancements and Modifications in Agricultural Land Resource Modeling

Scope	2011 *BT2*	*BT16*
USDA Baseline	2010 USDA Baseline assumed, extrapolated from 2020 to 2030	2015 USDA Baseline assumed, extrapolated from 2025 to 2040
Energy crop types	Perennial herbaceous, annual herbaceous, coppice SRWC, non-coppice SRWC	Switchgrass, miscanthus, energy cane, biomass sorghum, non-coppice (poplar, loblolly pine), and coppice (willow and eucalyptus)
Energy crop yields	Regionally assigned yields based on literature	Modeled yields based on Regional Feedstock Partnership PRISM results (see chapter 4)
Pasture intensification	One acre of management-intensive grazing assumed capable of replacing forage production displaced by one acre of pasture converted to energy crops	1.5 acres of management-intensive grazing assumed capable of replacing forage production displaced by one acre of pasture converted to energy crops
Energy crop yield improvements	Base-case (1%) and high-yield (2%, 3%, and 4%)	Scenario-specific yield improvements (see chapter 4, table 4.1). Specified-price simulation scenario descriptions) at 1%, 2%, 3%, and 4% for most energy crops (see chapter 4, section 4.3.1)
Farmgate prices	Flat nominal prices	Flat real (inflation-adjusted) prices based on the Producer Price Index for Crude Materials for Further Processing

Table C-6 *(continued)*

Scope	2011 *BT2*	*BT16*
Operational constraints	All crop residues available after sustainability retention coefficients are met are assumed operationally available	Operational availability is assumed 50% in 2014 increasing linearly to 90% in 2040, not exceeding sustainability retention coefficients
Geographic range of energy crops on pasture land	East of the 100th Meridian	To account for precipitation, pasture-land values from the 2012 USDA census were considered to constrain the transition of pastureland to energy crops in counties where the 30 year average annual precipitation is 25 in. or less
Nutrient replacement costs	Costs of nutrients for 1 dry ton/acre of energy crops included	Costs of nutrients for energy crops applied on a per dry ton basis
Adjustments to USDA baseline	Calculations made on harvest rather than production	Annuity with a 30-year planning horizon now used to calculate total net returns for all biomass crops
Grower payment	$10/dry ton additional grower payment reported to be included	No additional grower payment has been added
SRWC plantings	Averaged plantings over rotation cycle	Implemented a staggered planting, where 1/4 (coppice) or 1/8 (non-coppice) of the acres converted to SRWCs are planted every year.
SRWC price premium	No premium added	A $5/dry ton and $10/dry ton price premium is now offered for coppice (willow and eucalyptus) and non-coppice (pine and poplar) woody crops, respectively.
Tillage flexibility constraint	Exogenously determined tillage adoption rates for baseline and high-yield scenario	Tillage responsiveness allowed to vary based upon residue price at 4 levels (0, 1, 2, & 3; see section 1.2, Agricultural Residue Modeling Assumptions).

Table C-3 | Work-flow diagram illustrating calculation of sustainably available biomass



C.3 Production Budgets: Energy and Conventional Crops

Conventional crop yields and budgets were updated based on the 2015 USDA Baseline. Harvest costs of primary agricultural residues were revised to reflect the latest available information for specified residue harvest operations. We also summarize energy crop input costs:

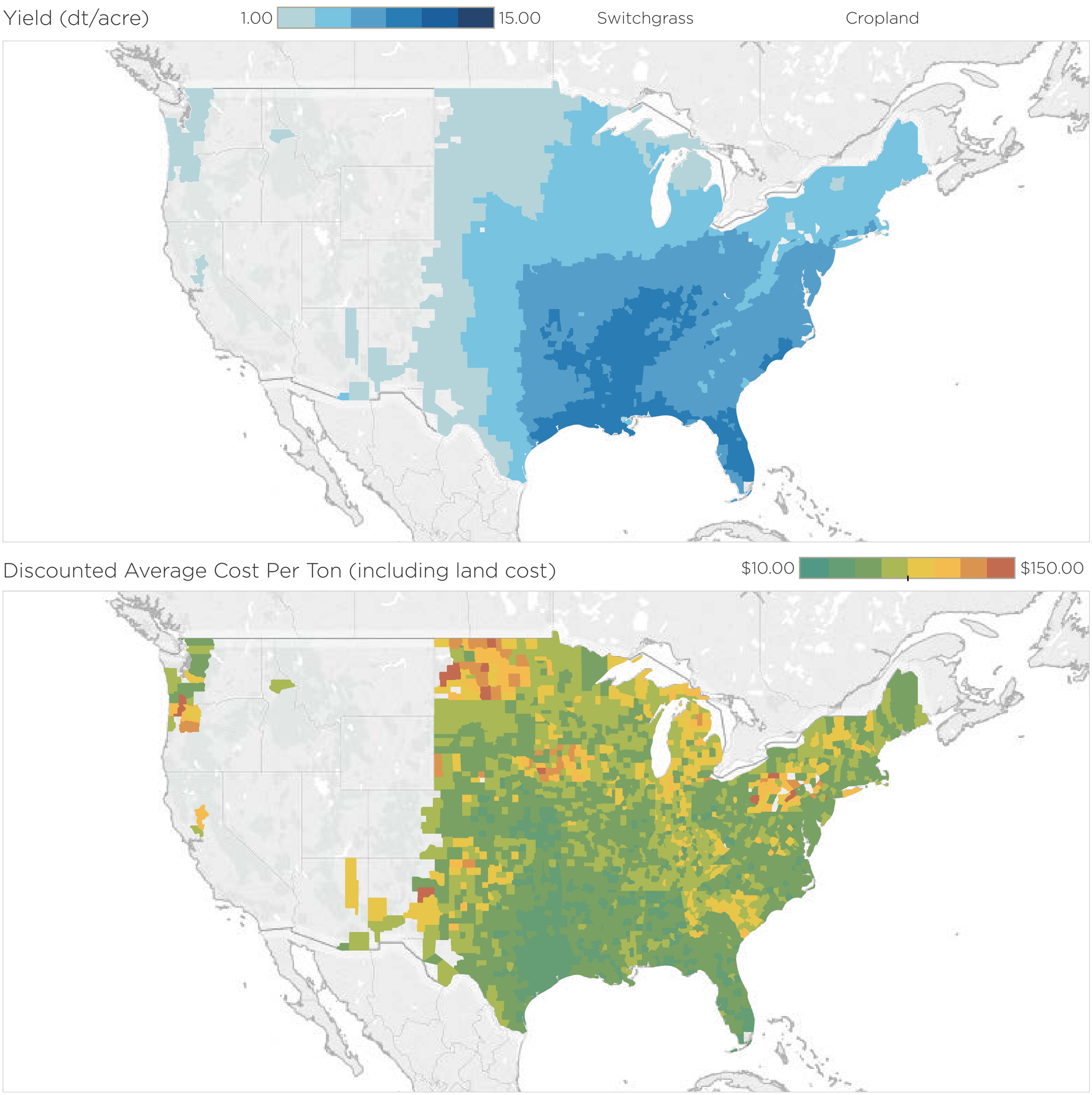
1. Spatial Interpolation of Crop Budgets

We create spatially explicit budgets by starting with detailed crop budgets for large regions and then using a spatial interpolation method to average across boundaries to create per acre production costs at the ASD Agricultural Statistic District (ASD) level. Larger regional budgets for all crops are developed using the Agricultural Policy Aanalysis Center Budgeting System (Slinsky and Tiller 1999). This system generates detailed field operation schedules and associates per-hectare crop production costs for all production systems considered. The method used is consistent with those used by USDA and recommended by the American Agricultural Economics Association (American Agricultural Economics Association 2000). The budgets were calculated using 2014 input costs and energy prices and are used in the model as "enterprise" budgets, in which each crop's costs used individually and not in rotation. We then use spatial interpolation to refine the budgets to smaller geographic regions. Spatial interpolation is the process of using points with known values to estimate values at other points in spatial data environments in which a few points are known, but values in between the known points are not known. Spatial interpolation is a process of filling in values between the sample regions and resolves previous challenges with large cost transitions between political and agricultural regions. More detail on the interpolation methods used by POLYSYS to estimate geographically specific budgets can be found in the document (Hellwinckel et al. 2015).

2. Costs ($/dry ton) and Yield (dry tons/acre) Associated with Individual Energy Crops

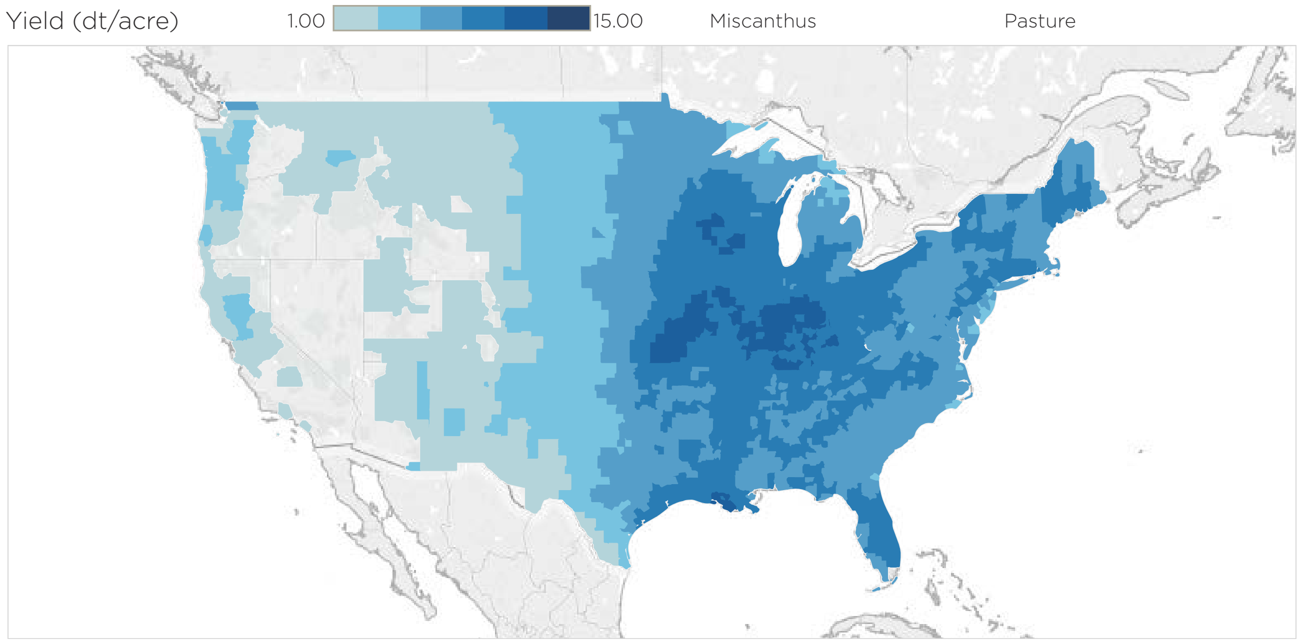
The following figures depict yields by feedstock. We summarize the input cost for herbaceous and woody energy crops in tables C.6 and C.7.

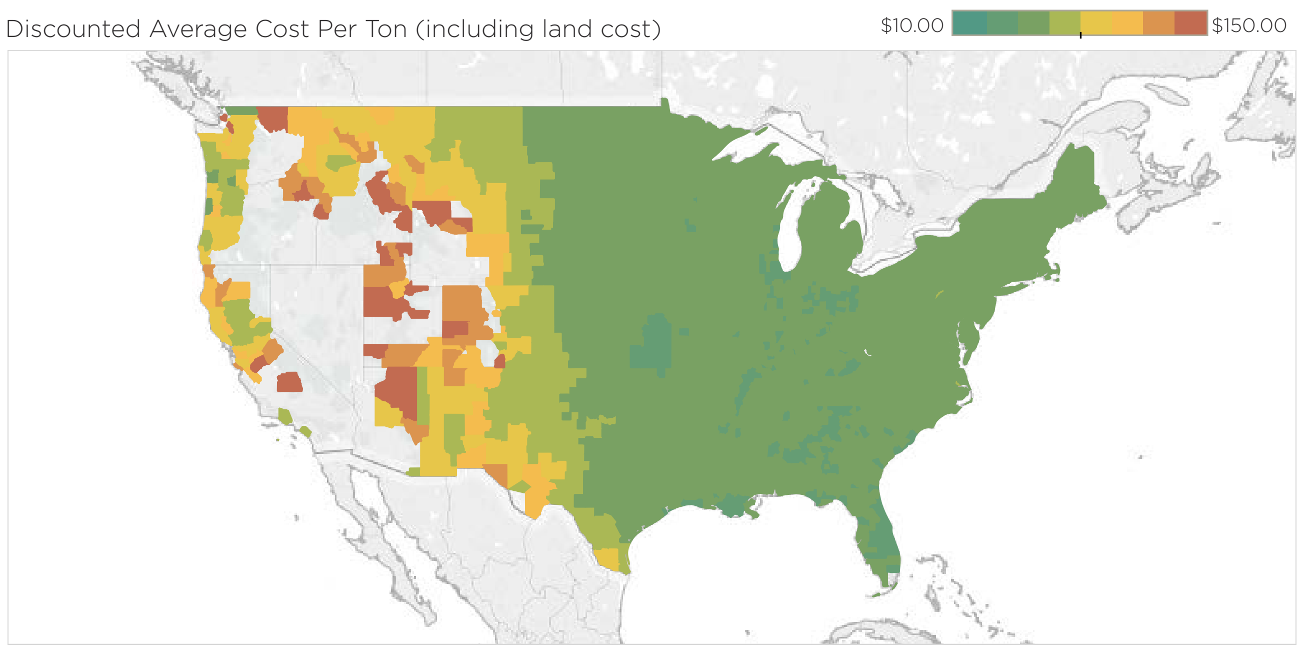
Figure C-4 | Yield (dry tons per acre) for switchgrass[13]



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

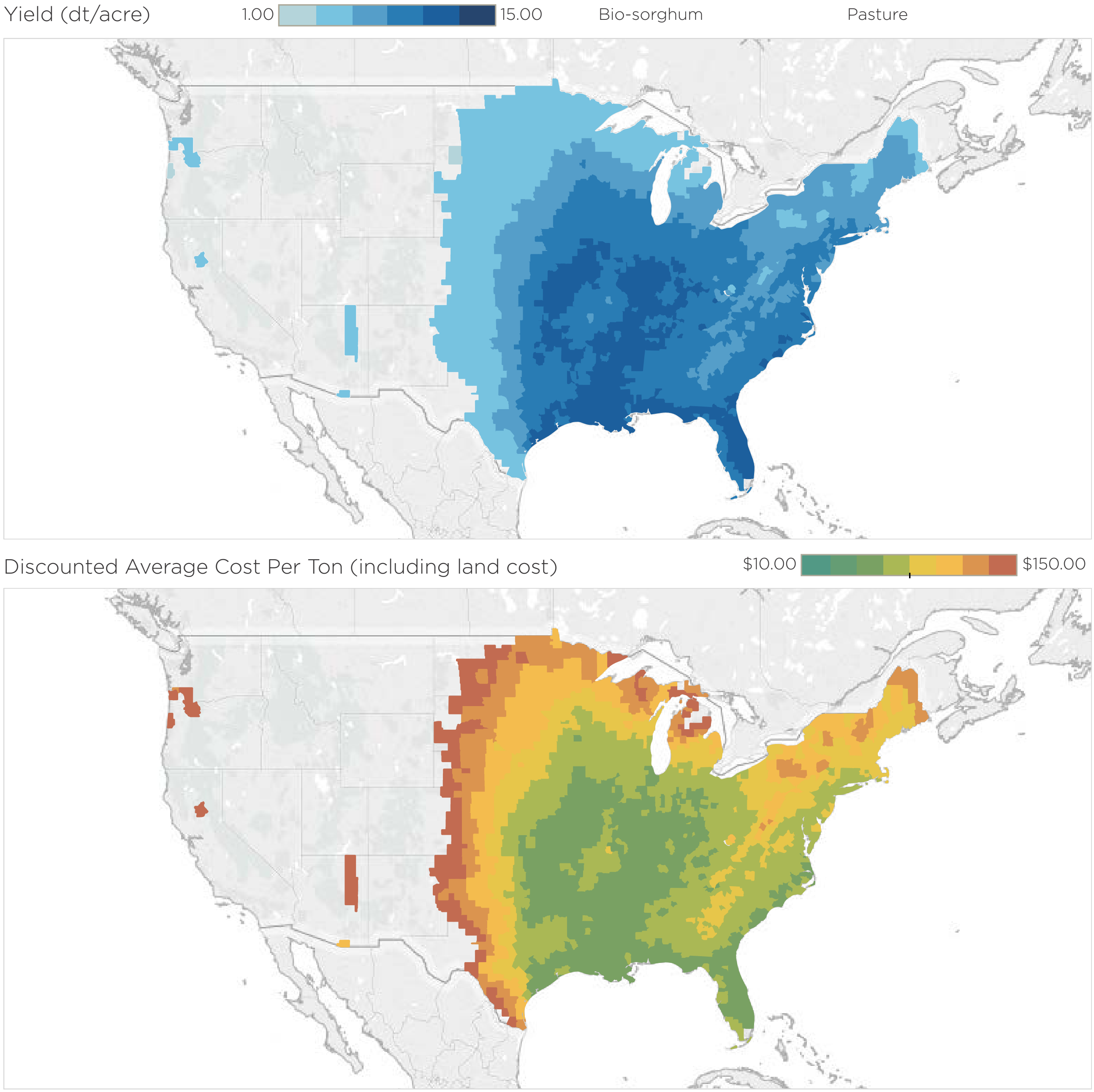
Figure C-5 | Yield (dry tons per acre) for miscanthus[14]





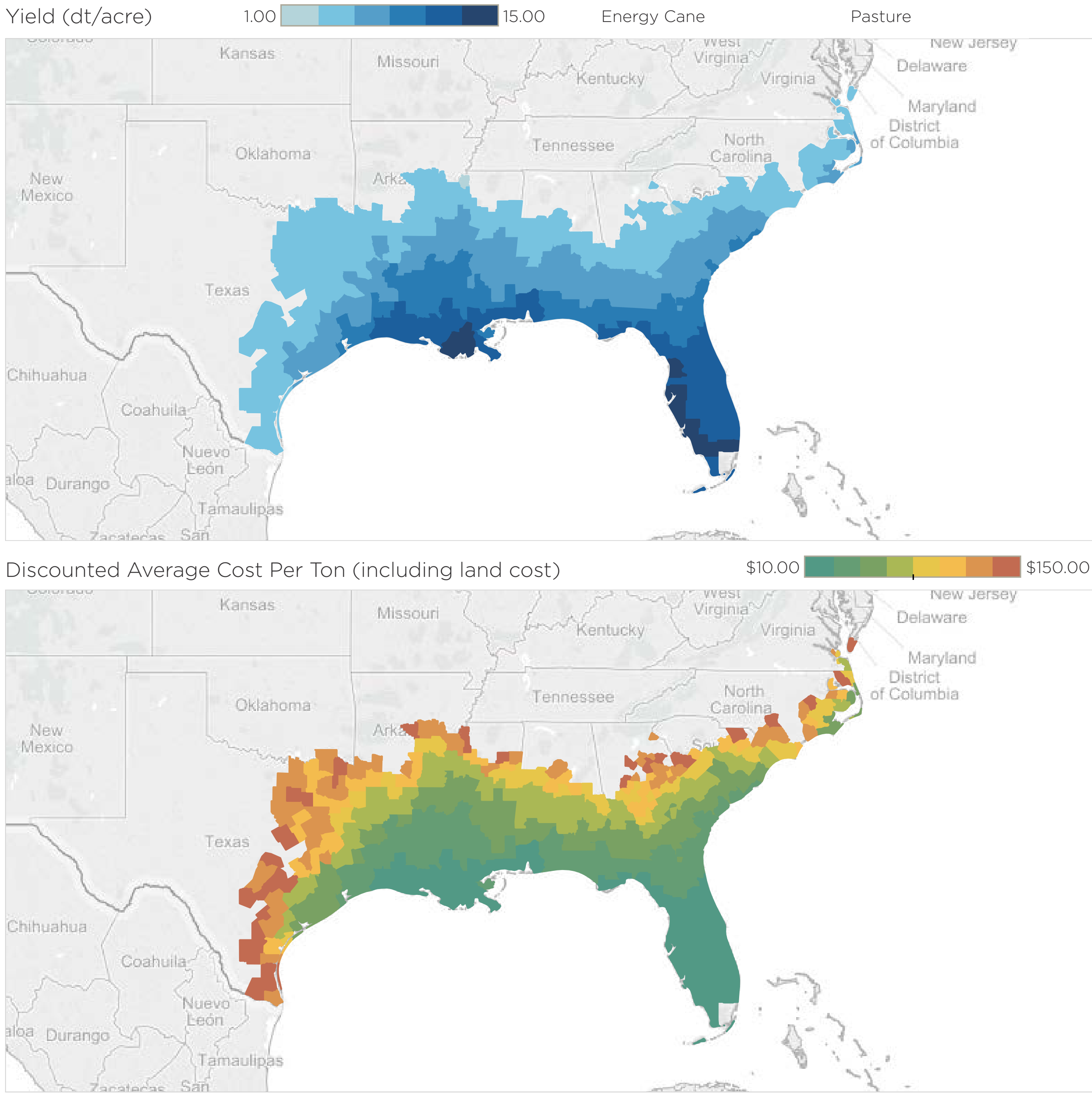
[14] Interactive visualization: https://bioenergykdf.net/billionton2016/4/4/tableau

Figure C-6 | Yield (dry tons per acre) for biomass sorghum[15]



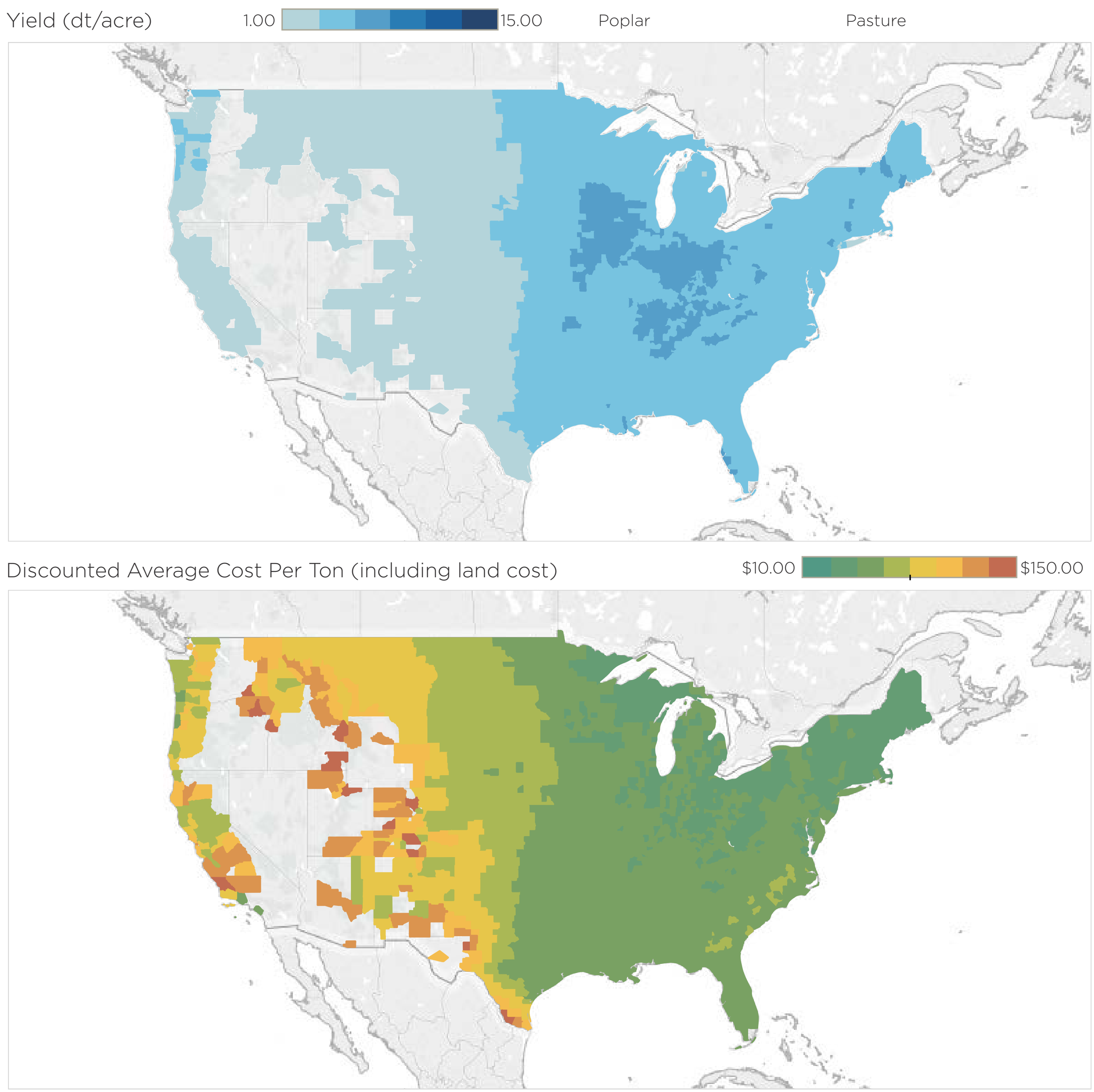
[15] Interactive visualization: https://bioenergykdf.net/billionton2016/4/4/tableau

Figure C-7 | Yield (dry tons per acre) for energy cane[16]



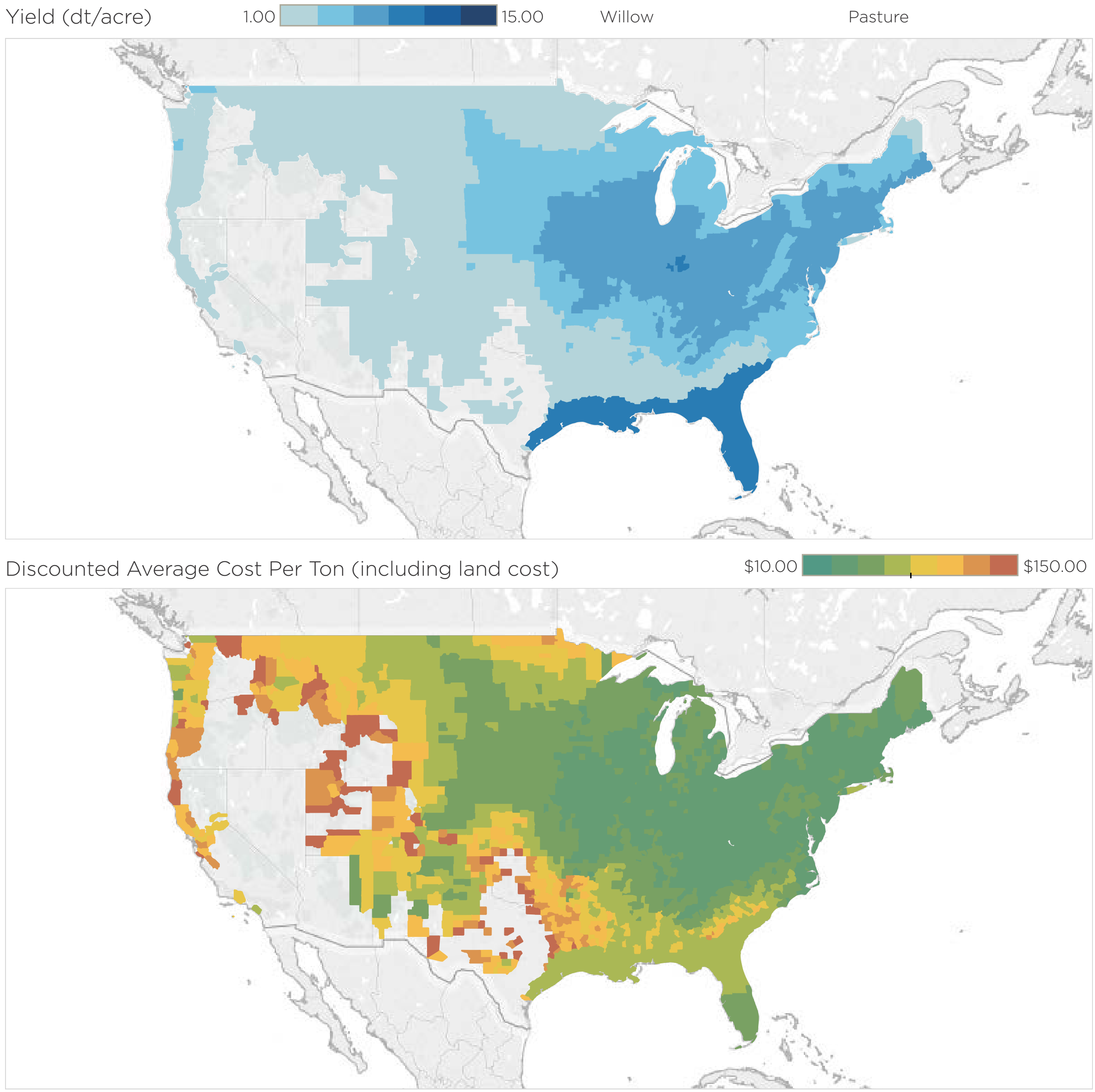
[16] Interactive visualization: https://bioenergykdf.net/billionton2016/4/4/tableau

Figure C-8 | Yield (dry tons per acre) for non-coppice woody crops: poplar and pine[17]



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

Figure C-9 | Yield (dry tons per acre) for coppice woody crops: willow and eucalyptus[18]



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

Table C-7 | Summary of Production Inputs and Costs for Herbaceous Energy Crops

Item	Units	Perennial			Annual		
		Switch-grass	Miscanthus	Energy cane	Biomass sorghum	Corn stover	Wheat straw
Stand life	years	10	15	7	1	N/A	N/A
Seed	\$/lb	4.75–14.49	N/A	N/A	2.46	N/A	N/A
Seed	\$/rhizome	N/A	0.10	N/A	N/A	N/A	N/A
Seed	\$/acre	N/A	N/A	467	N/A	N/A	N/A
Planting rate	lb/acre	6	N/A	N/A	5	N/A	N/A
Planting rate	rhizome / acre	N/A	8750	N/A	N/A	N/A	N/A
Replanting rate	%	10	0	0	0	N/A	N/A
Planting equipment	N/A	No-till drill	Miscanthus planter	Hand planting, opener, cover, flat roller	Row crop planter 8 row	N/A	N/A
Herbicide treatments	number, passes	3,3	2,2	3,3	2,2	N/A	N/A
Mechanical weeding	passes	0	0	0	1	N/A	N/A
Nitrogen (establish-ment)	lb N/acre	0	0	0	150	N/A	N/A
Phosphorus	lb P_2O_5/ acre	40	62	62	60	N/A	N/A
Potassium[19]	lb K_2O/ acre	80	50	50	120	N/A	N/A
Limestone[24]	tons/acre	1.0	1.0	1.0	1.0	N/A	N/A
Total establishment costs	\$/acre	215–410	985–1,140	910–970	175–360	N/A	N/A
Reseeding	year	2	None	None	N/A		
Herbicide treatments[25]	Number passes by year	1 in years 2,5,8	1 in year 2	4,2	N/A		
Nitrogen (mainte-nance)	lb N/dt	10	9	9	N/A	14.8	11.0
Phosphorus	lb P_2O_5/ dt	4	1.5	1.5	N/A	5.1	2.8
Potassium	lb K_2O/ dt	14	8	8	N/A	27.2	24.7
Year 1	\$/acre	N/A	N/A	120–225	30.90–32.90	10.10–28.45	7.30–23.00

[19] None in Great Plains and West

Table C-7 *(continued)*

Item	Units	Perennial			Annual		
		Switch-grass	Miscanthus	Energy cane	Biomass sorghum	Corn stover	Wheat straw
Year 2	$/acre	N/A	17.50–18.40	N/A		N/A	
Years 2,5,8	$/acre	11.70–12.75	N/A	N/A		N/A	
Year 2–7	$/acre	N/A	N/A	85–210		N/A	
Years 3,4,6,7,9,10	$/acre	2.90–3.45	N/A	N/A		N/A	
Years 2–15	$/dt	N/A	6.70–11.80	N/A		N/A	
Years 3–15	$/acre	N/A	2.90–3.30	N/A		N/A	
All years	$/dt	8.50–17.15	N/A	N/A		N/A	
Harvest method		Mower-conditioner, large rectan-gular baler, bale wagon	Mower-conditioner, large rectan-gular baler, bale wagon	Billet harvester, 3 sugar cane high-dump wagons	Forage harvester, 2 high-dump forage wagons	Shredder, large rectan-gular baler, bale wagon	Large rectan-gular baler, bale wagon
Harvest costs	$/acre	41-46	41–45	285	240–250	36–40	28–30
Harvest costs	$/dt	2.90	2.90	N/A	N/A	2.90	2.90

Table C-8 | Summary of Production Inputs and Costs for Woody Energy Crops

Item	Units	Hybrid poplar	Pine	Eucalyptus	Willow
Rotation	years	8	8	8 years (2 har-vests at years 4 and 8); model assumes replant-ing for up to 32 years	32 years (8 har-vests, occurring every 4 years)
Spacing	square feet	60	60	28	7.9
Spacing	trees/acre	726	762	1,575	5,500
Establishment – year 1					
Cuttings	$/tree	0.12	0.065	0.60	0.12
Planting	$/tree	0.09	0.12	0.118	822/acre
Replants	%	0.05	0.05	0	0
Bushog	frequency	N/A	N/A	N/A	1 time
Moldboard plow	frequency	1 time	1 time	1 time	1 time
Disk	frequency	1 time	1 time	1 time	1 time
Plant cover crop	frequency	N/A	N/A	N/A	1- 50/acre

Table C-8 *(continued)*

Item	Units	Hybrid poplar	Pine	Eucalyptus	Willow
Kill cover crop	frequency	N/A	N/A	N/A	1- 30/acre
Cultivate	frequency	2 times	2 times	2 times	1-weed control 15/acre
Herbicide	herbicide name quantity	1-Roundup 4S 0.375 gal/acre	1-Roundup 4S 0.375 gal/acre	1-Roundup 4S 0.375 gal/acre	2-Roundup (1.5 pt/acre each), Goal (2.5 pt/ac), Prowl (2.4 pt/acre)
Herbicide	herbicide name quantity	1-Prowl 0.21 gal/acre	1-Lorox 0.75 lb/acre	1-SFM 0.1406 lb/acre	1-preemergent after planting 45/acre
Nitrogen	lb N/acre	N/A	N/A	150	N/A
Phosphorous	lb P_2O_5/acre	N/A	40	50	N/A
Potassium	lb K_2O/acre	18–60	N/A	48	N/A
Limestone	tons/acre	1	1	1	N/A
Coppice	cut back/acre	N/A	N/A	N/A	1- 10/acre
Establishment costs	$/acre	295–435	425–490	1,565–1,620	N/A
Maintenance years					
Cultivate—year 2		2 times	2 times	0	N/A
Cultivate—year 3		1 time	1 time	0	N/A
Herbicide	years	2,3	2,3	2,6	N/A
	herbicide name quantity	1-Roundup 4S 0.375 gal/acre	1-Roundup 4S 0.375 gal/acre	1-Roundup 4S 0.375 gal/acre	N/A
Nitrogen	years	3,6	2,4,6	6,11,16,21	2,4,8,16,20,24,28,32
	lb N/acre	90	90	150	45
Phosphorous	years	3	3	6,11,16,21	2,4,8,16,20,24,28,32
	lb P_2O_5/acre	15–30	92 (includes 36 lb N/acre)	115	20
Potassium	years	N/A	N/A	6,11,16,21	2,4,8,16,20,24,28,32
	lb K_2O/acre	N/A	N/A	40	45
Insecticide	years	4	N/A	2,6	N/A
	Name	Poplar insecticide	N/A	N/A	N/A
	lb/acre	1	N/A	N/A	N/A
Maintenance costs					
Year 2	$/acre	22.55–25.70	77.40–85.10	10.40–10.80	N/A
Year 3	$/acre	110–135	100–105	170–180	N/A

Table C-8 *(continued)*

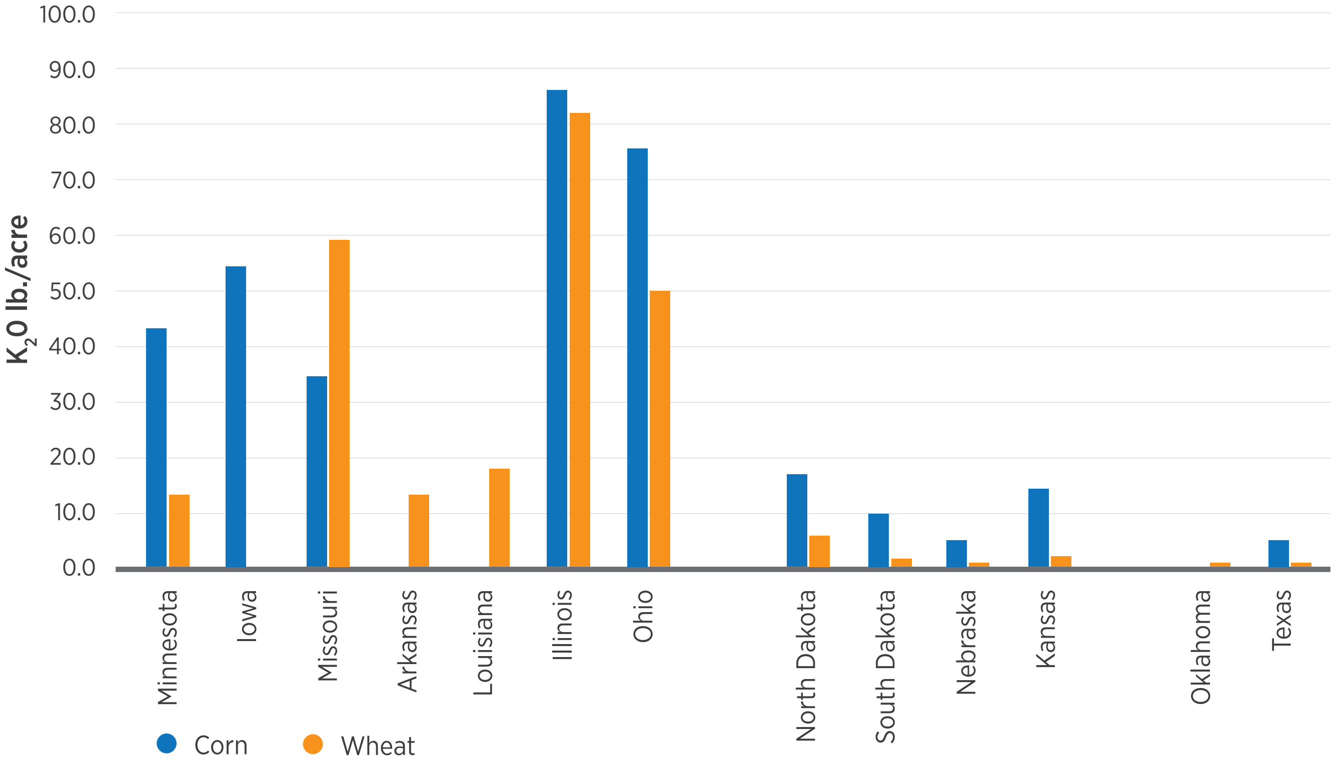
Item	Units	Hybrid poplar	Pine	Eucalyptus	Willow
Year 4	$/acre	22.20	71.95–73.70		N/A
Year 6	$/acre	71.20–82.90	71.95–73.70	190	N/A
Years 8,13,18,23	$/acre			185–190	N/A
Years 11,16,21	$/acre			180	N/A
Remove stumps		N/A	N/A	N/A	Year 22: 400/acre
Harvest					
Harvest method		feller buncher, skidder, chipper and chip van.	feller buncher, skidder, chipper and chip van	feller buncher, skidder, chipper and chip van	Self-propelled forage harvester equipped with a willow cutting head that cuts and chips the stems; the chips are blown into forage wagons transported to the road side; at the roadside, the chips are transferred to a chip van
Harvest costs	$/dt	23.00–24.70	24.50	24.50	N/A

3. Nutrient Costs and How the Inclusion or Exclusion of K_2O Affects Residues and Herbaceous Energy Crops

Biomass production budgets nutrients (nitrogen, phosphorus, and potassium) are removed in crop residues. Data from Nielsen (1995), Lang (2002), Gallagher et al. (2003), Schechinger and Hettenhaus (2004), and Fixen (2007) were used to estimate an average nutrient composition of removed corn stover. Nutrient values used were 14.8 pounds nitrogen per dry ton, 5.1 pounds P_2O_5 (phosphate) per dry ton, and 27.2 pounds K_2O per dry ton. Data from Larson et al. (1978), Jurgens (1978), and Gallagher et al. (2003) were used to estimate average nutrient composition of removed wheat straw. Nutrient values used were 11.0 pounds nitrogen per dry ton, 2.8 pounds P_2O_5 per dry ton, and 24.7 pounds K_2O per dry ton.

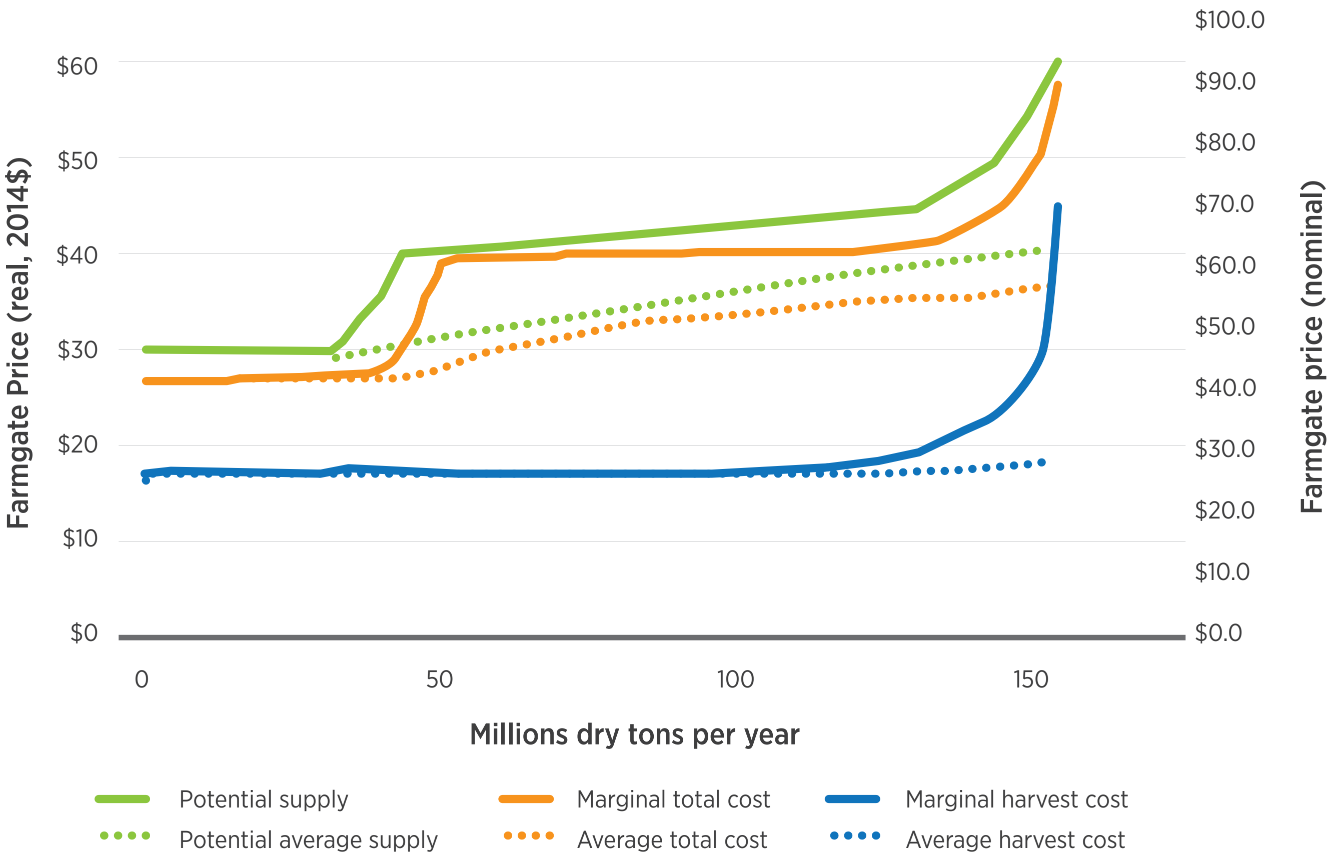
In regions in the western half of the United States potassium is only applied at very low rates (potassium is applied to less of the crop acres and at lower rates) compared to the eastern half of the United States, as shown in figure C.10 for corn and wheat. It is assumed that in calculating grower payments in regions including North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, and Texas and further west (i.e., west of Minnesota, Iowa, Missouri, Arkansas, and Louisiana), potassium would not be costed as part of the grower payment reflecting the fact that potassium is applied at low rates.

Figure C-10 | Potassium application rates for corn and wheat for selected states



Using a national average price of $0.513 per lb of K_2O, for corn stover and wheat straw the exclusion of potassium replacement from the grower payment results in a $13.95 per dry ton of stover and straw lower payment, respectively. Corn stover and wheat straw from regions in the western United States have a cost advantage at equal yields over stover and straw from regions in the eastern United States. In addition, because switchgrass and miscanthus translocate nutrients into their roots and have lower nutrient replacement requirements, they have lower nutrient replacement costs, $10 (4) and $15 (6) per dry ton than corn stover when potassium is included (excluded) from the nutrient replacement cost.

Figure C-11 | Harvest and nutrient costs and potential supply curves for corn stover



4. Costs Associated with Management-Intensive Grazing and Pasture Transition

Displacement of livestock grazing occurs when energy crops are established on permanent pasture and cropland used as pasture. In order for stocking rates to be maintained throughout the projection period, this externality is internalized to the bioenergy crop producer by implementation of management intensive grazing of remaining pastureland acreage. This report assumes yield increases of up to 50% from baseline pastureland yields defined in Hellwinckel et al. (2016).

The costs to intensify pastureland for improved forage yields while maintaining same stocking rates include additional fencing, watering, and labor at following rates:

- **Permanent Pasture:** $100/acre in initial intensification year, $15/acre per year for maintenance
- **Cropland Used as Pasture:** $100/acre in initial intensification year, $10/acre per year for maintenance.

Table C-9 | Economic Impacts of the Extended USDA Baseline and *BT16* Base-Case Scenarios (at $60 per dry ton)

Crop	Extended USDA baseline				*BT16* base case			
Crop prices ($/bu)	2017	2022	2030	2040	2017	2022	2030	2040
Corn	3.5	3.65	3.7	3.7	3.49	3.74	3.83	4.03
Grain sorghum	3.4	3.55	3.68	3.73	3.41	3.87	4.22	4.94
Oats	2.28	2.4	2.4	2.34	2.27	2.59	2.55	2.75
Barley	4.08	4.06	4.02	3.94	4.1	4.29	4.22	4.32
Wheat	4.75	4.85	5.01	5.28	4.72	5.35	5.68	6.48
Soybeans	8.8	9.4	9.36	9.17	8.83	9.86	10.08	10.97
Cotton ($/lb)	0.62	0.69	0.724	0.752	0.621	0.746	0.782	0.826
Rice ($/cwt)	14.9	15.8	16.69	18.29	14.9	15.82	16.86	18.94
Crop acres (millions)								
Corn	90	89	89.09	89.1	89.85	87.6	86.92	84.76
Grain sorghum	7.4	7.1	7.01	7.02	7.39	6.77	6.57	6.16
Oats	2.5	2.5	2.47	2.44	2.5	2.26	2.16	2.09
Barley	3.2	3	2.96	2.9	3.16	2.91	2.92	2.83
Wheat	52.5	52	52.58	54.07	52.74	47.78	47.43	45.83
Soybeans	78	79	78.37	76.87	77.97	75.63	72.85	66.12
Cotton	9.8	10.2	10.38	10.53	9.79	8.91	8.88	8.63
Rice	2.94	3.03	3.06	3.06	2.94	3.02	3.03	2.97
Crop net returns (% relative to 2015)								
Corn	24%	43%	39%	10%	23%	58%	63%	71%
Grain sorghum	16%	-25%	-135%	-333%	18%	103%	91%	111%
Oats	4%	13%	37%	76%	4%	-9%	9%	35%
Barley	-56%	-78%	-124%	-194%	-54%	-55%	-101%	-146%
Wheat	-20%	-26%	-46%	-77%	-21%	22%	23%	42%
Soybeans	3%	21%	14%	-5%	4%	30%	28%	29%
Cotton	8%	23%	66%	148%	8%	-29%	2%	56%
Rice	3%	18%	21%	26%	3%	18%	23%	36%
Livestock								
Total production (million lbs)	22607	25417	26023	26025	22601	25409	26016	25998
Price ($/cwt)	163	156	156	156	163	151	156	157
Inventory (1,000 head)	88,281	93,634	112,981	132,168	88,316	93,581	112,928	132,000
Total crop net returns (% relative to 2015)	8%	24%	15%	-13%	8%	42%	41%	44%
Total livestock net returns (% relative to 2015)	-2%	-2%	11%	11%	-2%	-2%	11%	11%
Total agriculture net returns (% relative to 2015)	1%	5%	12%	5%	1%	9%	19%	19%

Table C-10 | Economic Impacts of Extended USDA Baseline and *BT16* High-Yield Scenarios (at $60 per dry ton)

Crop	Extended USDA baseline				*BT16* base case			
Crop prices ($/bu)	**2017**	**2022**	**2030**	**2040**	**2017**	**2022**	**2030**	**2040**
Corn	3.5	3.65	3.7	3.7	3.33	3.34	3.03	2.86
Grain sorghum	3.4	3.55	3.68	3.73	3.42	3.97	4.38	5.19
Oats	2.28	2.4	2.4	2.34	2.25	2.46	2.35	2.28
Barley	4.08	4.06	4.02	3.94	4.1	4.08	3.98	3.9
Wheat	4.75	4.85	5.01	5.28	4.68	5.32	5.75	7.27
Soybeans	8.8	9.4	9.36	9.17	8.91	9.79	10.29	12.24
Cotton ($/lb)	0.62	0.69	0.724	0.752	0.621	0.764	0.817	0.864
Rice ($/cwt)	14.9	15.8	16.69	18.29	14.9	15.87	16.9	20.39
Crop acres (millions)								
Corn	90	89	89.09	89.1	90.36	84.55	79.67	74.33
Grain sorghum	7.4	7.1	7.01	7.02	7.37	6.63	6.27	5.81
Oats	2.5	2.5	2.47	2.44	2.49	2.21	2.04	1.94
Barley	3.2	3	2.96	2.9	3.15	2.88	2.78	2.69
Wheat	52.5	52	52.58	54.07	52.86	47	45.26	42.04
Soybeans	78	79	78.37	76.87	77.39	75.68	71.06	59.85
Cotton	9.8	10.2	10.38	10.53	9.78	8.49	8.07	7.74
Rice	2.94	3.03	3.06	3.06	2.94	3.01	3.02	2.81
Crop net returns (% relative to 2015)								
Corn	24%	43%	39%	10%	9%	32%	15%	2%
Grain sorghum	16%	-25%	-135%	-333%	23%	162%	213%	272%
Oats	4%	13%	37%	76%	5%	-3%	11%	41%
Barley	-56%	-78%	-124%	-194%	-55%	-77%	-125%	-193%
Wheat	-20%	-26%	-46%	-77%	-22%	27%	41%	117%
Soybeans	3%	21%	14%	-5%	5%	30%	33%	47%
Cotton	8%	23%	66%	148%	8%	-47%	-33%	11%
Rice	3%	18%	21%	26%	3%	19%	24%	56%
Livestock								
Total production (million lbs)	22,607	25,417	26,023	26,025	22,605	25,409	26,016	25,998
Price ($/cwt)	163	156	156	156	163	150	155	155
Inventory (1,000 head)	88,281	93,634	112,981	132,168	88,307	93,814	113,392	132,779
Total crop net returns (% relative to 2015)	8%	24%	15%	-13%	3%	33%	29%	37%
Total livestock net returns (% relative to 2015)	-2%	-2%	11%	11%	-2%	-2%	11%	11%
Total agriculture net returns (% relative to 2015)	1%	5%	12%	5%	-1%	7%	15%	18%

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Appendix D

Appendix to Chapter 7 - Microalgae

D.1 Calculation of Gas Flow Rate

For practical pipeline purposes, in this analysis, we use Eq. (D.1) (SPE 2015) to calculate gas flow rate:

$$P_1^2 - P_2^2 = 25.2\left[\frac{SQ_g^2 ZTfL}{d^5}\right] \quad \text{(D.1)}$$

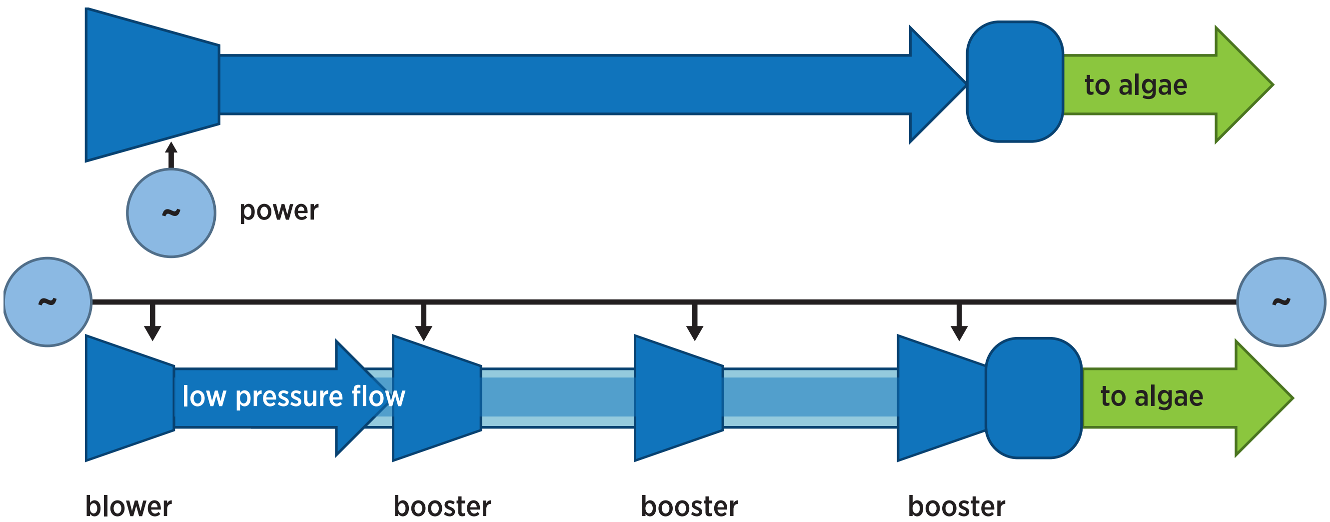
where:

P_1 = upstream pressure (psia)
P_2 = downstream pressure (psia)
S = specific gravity of gas
Q_g = gas flow rate, MMscf/day,
Z = compressibility factor for gas (dimensionless)
T = flowing temperature (°R)
f = Moody friction factor (dimensionless)
d = pipe ID (inches)
L = length (feet)

The Moody friction factor is a function of Reynolds number.

Two configurations were considered: (1) a high-pressure compressor (>100 psig) at the source and (2) low-pressure (20 psig) boost compressors at intervals along the pipe (figure D.1). For the case of intermediate boost compressors, there is a trade-off between the spacing of the compressors and the diameter of the pipeline to optimize the pressure drop. This in turn leads to a trade-off between the cost of compressors and the cost of piping.

Figure D-1 | Alternative configurations for pipeline transport of CO_2 or flue gas



A review of Eq. (D.1) shows that the required pipe diameter for a given pressure drop does not scale linearly with mass flow rate. Furthermore, the cost of piping does not scale linearly with diameter. Consequently, the ideal resource for algae would be a modest-sized facility using pure CO_2 from a relatively close site.

D.2 Description of Growth Model in the Biomass Assessment Tool from Wigmosta et al. (2011)

The growth model of Wigmosta et al. (2011) is used to describe key components in the conversion of solar energy to algal biomass, with the rate of biomass production (P_{mass} in mass per unit area per unit time) given by

$$P_{mass} = \left(\tau_p C_{PAR} E_s\right)\left[\frac{E_c \varepsilon_b}{E_a Q_r E_p}\right]\left(\varepsilon_s \varepsilon_t\right) \qquad \text{(D.2)}$$

The first term on the right-hand side of Eq. (D.1) represents the amount of photosynthetically active radiation (PAR) available, where E_s is the full-spectrum solar energy at the land surface (MJ/m^2), C_{PAR} is the fraction of PAR, and τ_p is the transmission efficiency of incident solar radiation to the pond microalgae. The middle term on the right-hand side is a strain-specific term representing the conversion of PAR to biomass under optimal light and water temperature, where E_a is the energy content per unit biomass (MJ/kg), the photon energy (E_p) (MJ/mol) converts PAR as energy to the number of photons, and $\mathcal{E}_p$ accounts for reductions in photon absorption due to suboptimal light and water temperature. The quantum requirement (Q) is the number of photons required to liberate one mol of O_2 and, together with the carbohydrate energy content (E_c), represents the conversion of light energy to chemical energy through photosynthesis (Weyer et al. 2010). The biomass-accumulation efficiency ($\mathcal{E}_b$) is a poorly understood function of species, water temperature, and other growing conditions accounting for energy required for cell functions that do not produce biomass (e.g., respiration). The final term in Eq. (D.2) represents a reduction in photon absorption from suboptimal light ($\mathcal{E}_s$) and/or water temperature ($\mathcal{E}_t$).

The light utilization efficiency ($\mathcal{E}_s$), including light saturation and photo inhibition, was modeled using the Bush equation (Huesemann et al. 2009):

with E_s and the light saturation constant (E_s) expressed in µmoles/m²•sec.

$$\varepsilon_s = \frac{S_o}{E_s}\left(\ln\left(\frac{E_s}{S_o}\right)+1\right) \qquad \text{(D.3)}$$

The correction for water temperature ($\mathcal{E}_t$) in Eq. (D.2) is given by

$$\begin{array}{l} 0 \text{ for } T < T_{\min} \\ (T - T_{\min}) / (T_{opt\_low} - T_{\min}) \text{ for } T_{\min} \le T \le T_{opt\_low} \\ \varepsilon_t = 1.0 \text{ for } T_{opt\_low} \le T \le T_{opt\_high} \\ (T_{\max} - T) / (T_{\max} - T_{opt\_high}) \text{ for } T_{opt\_high} \le T \le T_{\max} \\ 0 \text{ for } T > T_{\max} \end{array} \qquad \text{(D.4)}$$

where T is the minimum water temperature for zero productivity (°C), T_{opt_low} is the lower water temperature for optimal productivity (°C), T_{opt_high} is the upper water temperature for optimal productivity (°C), and T_{max} is the maximum water temperature for zero productivity (°C).

Growth model parameters for the two selected algal strains are shown in Table D.1.

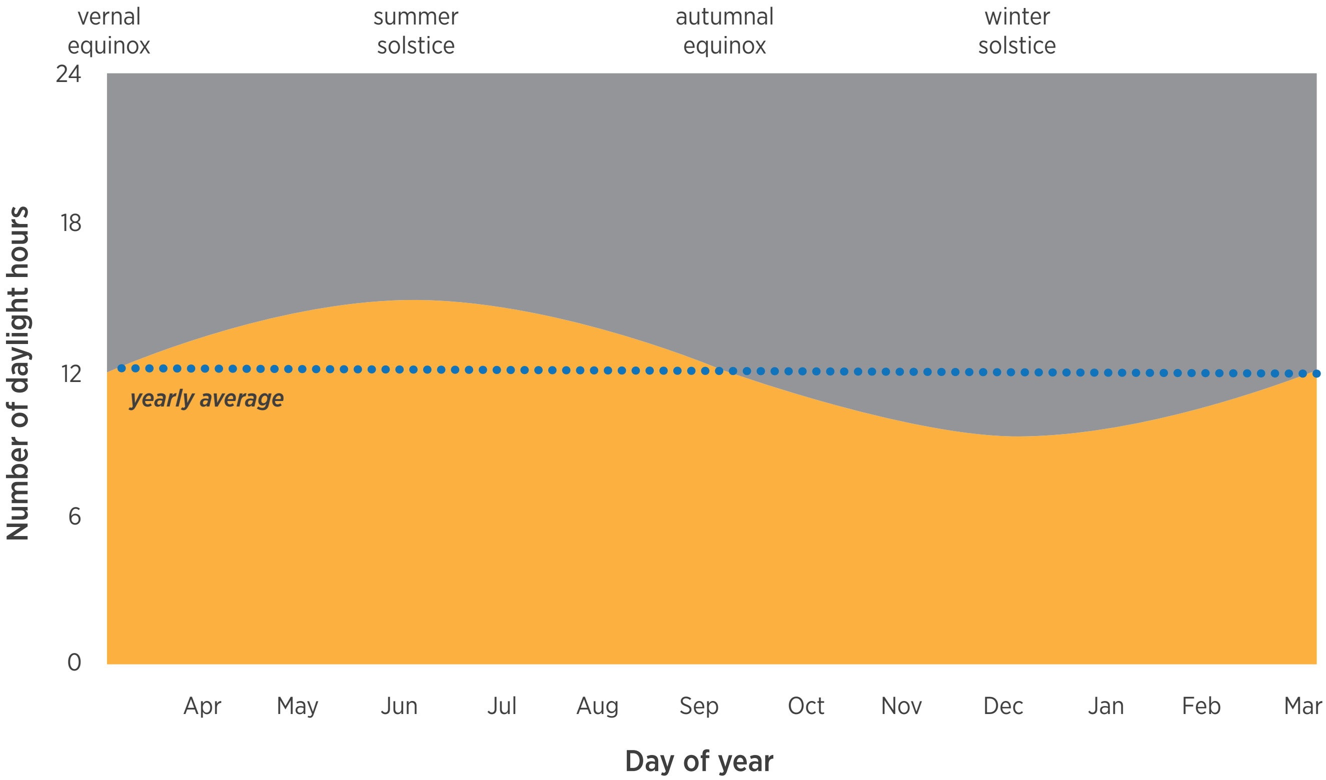
Table D-1 | Growth Model Parameters for Two Selected Algal Strains

	Freshwater-brackish	Saline
	Chlorella sorokiniana	*Nannochloropsis salina*
S_o	250 µmoles/m²•sec	250 µmoles/m²•sec
$\mathcal{E}_b$	0.61^0	0.21
T_{min}	12.8°C	11°C
T_{opt_low}	36.0°C	26.3°C
T_{opt_high}	36.2°C	28°C
T_{max}	45.0°C	36°C

D.3 Hours of Daylight

A 12-hour daylight day is assumed for CO_2 demand and delivery based on the geographic center latitude of the conterminous United States, at 39.82°N.

Figure D-2 | Monthly and annual average daylight available at the geographic center latitude for the conterminous United States



D.4 Cost of Transporting CO_2 from Co-Located Industrial Facilities to Algae Production Facilities

D.4.1 Coal-Fired Power Plants

Cost of Transport of CO_2 to Algae Growth Facilities

Delivering flue gas from a coal-fired power plant to feed a 1,000-acre algae facility (open pond) was modeled assuming two identical transport systems of compressor, pipeline, and small buffer storage. The capital cost was calculated for this equipment. The operating cost consists primarily of purchasing electricity to run the compressors. A trade-off between capital and operating cost is possible by selecting a larger- or smaller-diameter pipe. The larger pipe is more expensive but requires less compressor power.

The results of the cost analysis for transporting flue gas from a coal-fired power plant to feed a 1,000-acre algae facility (open pond) are shown in figures D.3 and D.4. The results are shown to highlight the effect of distance (pipeline length) from the co-located source. This information is then used in the Pacific Northwest National Laboratory Biomass Assessment Tool analysis to search for potential algae growth sites.

The distinction between the two figures is as follows: in figure D.3, the analysis is carried out to minimize the energy requirement; whereas in figure D.4, the analysis is carried out to minimize the capital cost. In both figures, an estimate of the annual electricity cost plus an annualized capital cost (labeled "sum") is compared with the annual cost of the required CO_2 at both \$30/ton and \$40/ton. The economic analysis for the CO_2 transport assumes a 20-year life for the capital equipment and a 10% cost of money.

Figure D-3 | Equipment and electricity costs for coal flue gas transport system, including two parallel sets of pipelines and blowers. The system supports a 1,000-acre open pond and is designed to minimize energy requirements for the blowers.

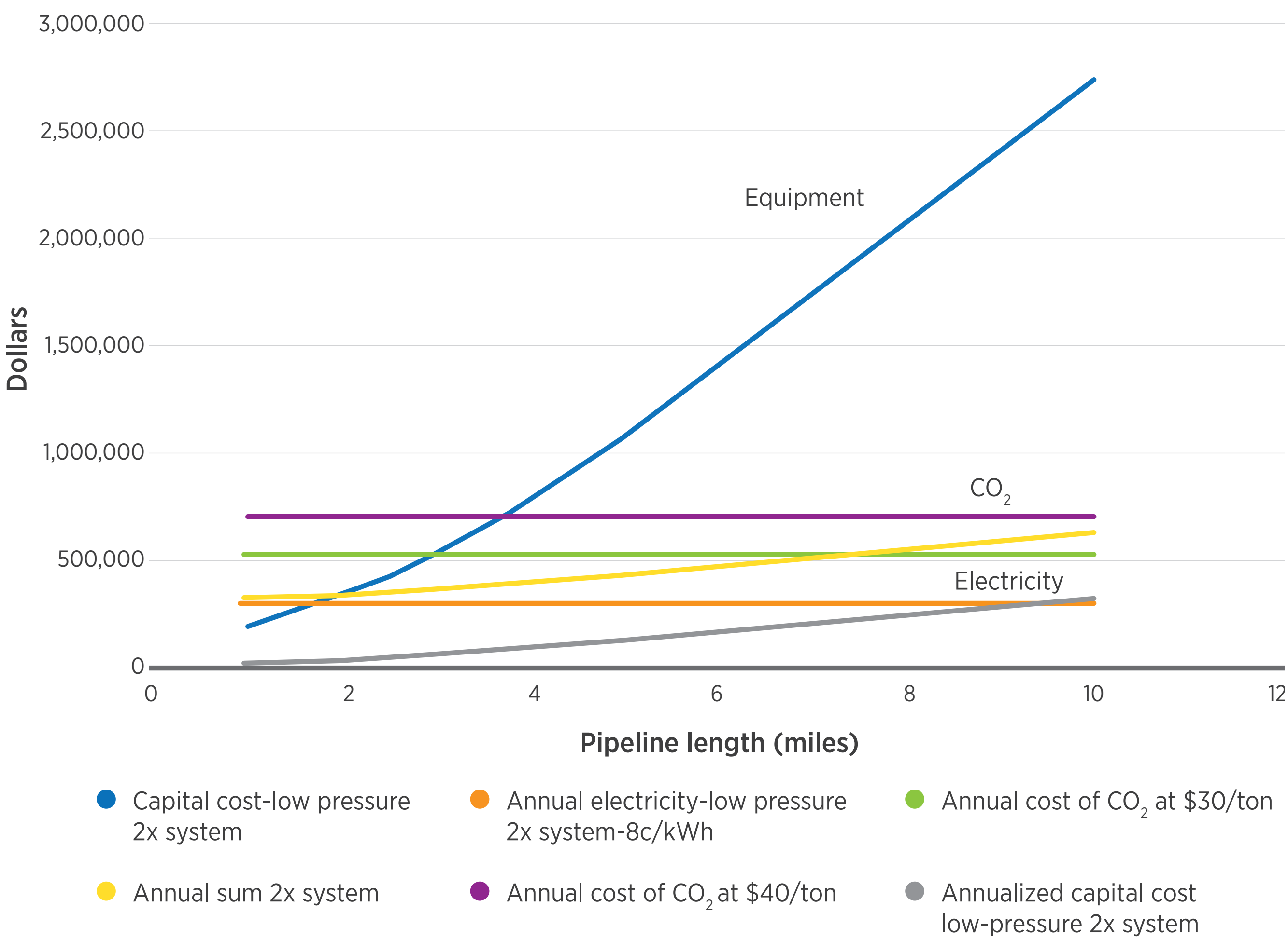
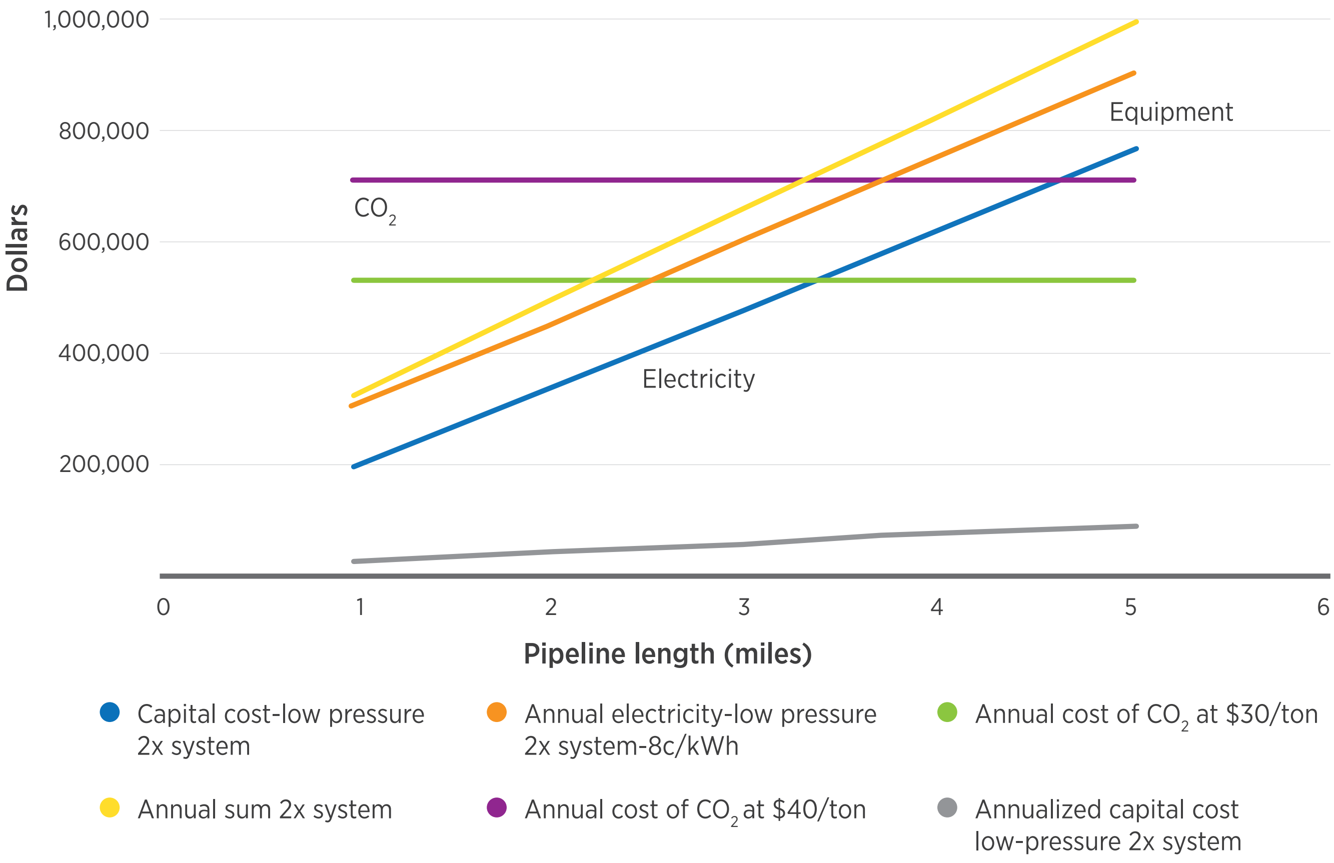


Figure D-4 | Equipment and electricity costs for coal flue gas transport system, including two parallel sets of pipelines and blowers. The system supports a 1,000-acre open pond and is designed to minimize cost.



Cost-Effective Distance

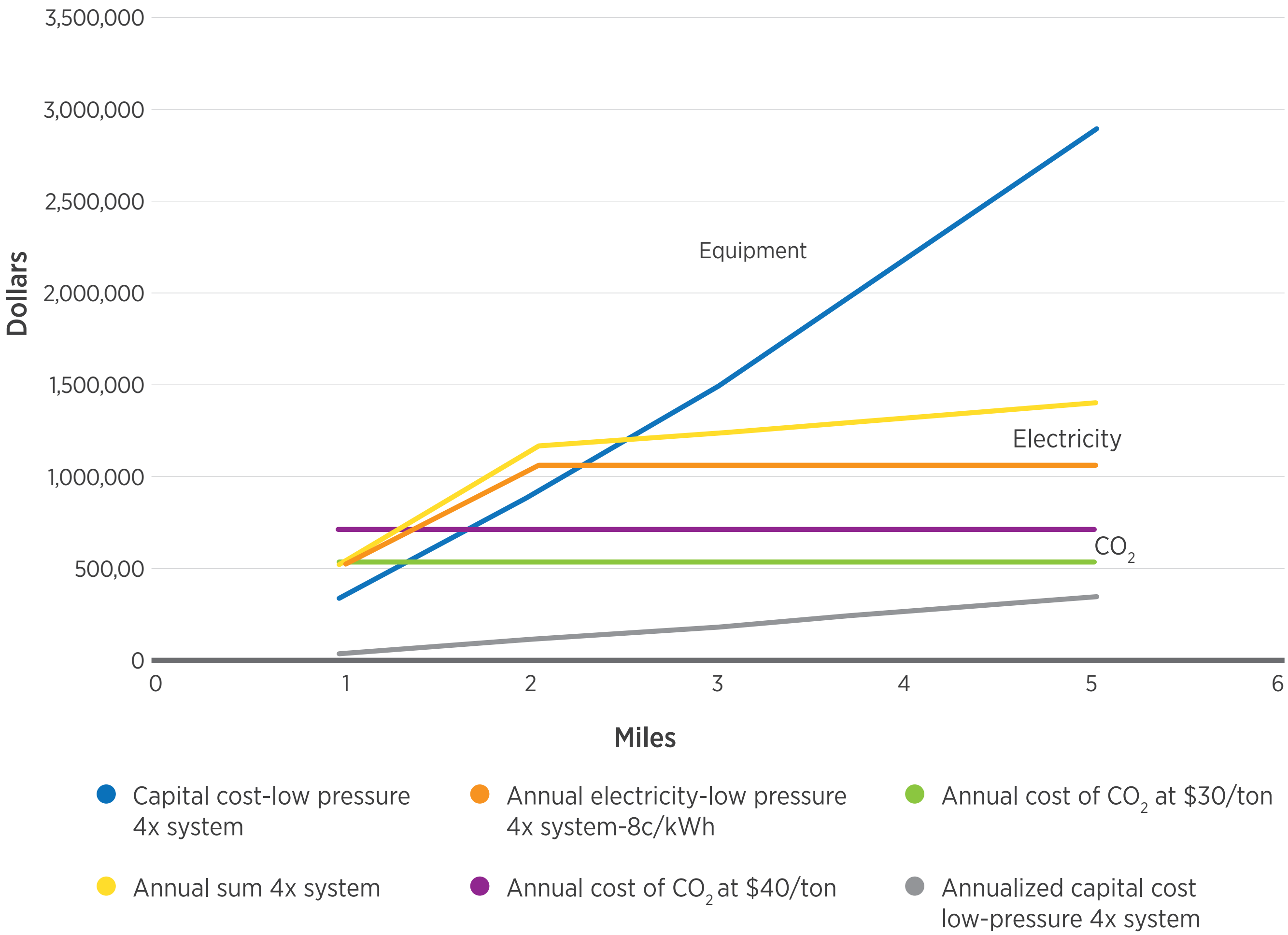
The cost-effective distance is less than about 7 miles to minimize blower energy. The cost-effective distance is less than about 3 miles to minimize capital cost. These results are subject to the assumptions of farm size and the various cost and economic factors. They suggest that the algae facility would need to be very close to the power plant.

D.4.2 Natural Gas–Fired Plants

Cost of Transport of CO_2 to Algae Growth Facilities

Similar to the scenario for coal-fired plant flue gas, the case for using flue gas from a natural gas-fired power plant requires large pipes to move the gas to the algae. This case is even more difficult because the CO_2 is more dilute in the emission stream of a natural gas-fired plant. For a 1,000-acre algae farm, a four-pipe system was assumed. In this case, the system must be designed to minimize compressor power, or else there is no other opportunity to reduce operating costs than to simply purchase CO_2. The results of the cost analysis are shown in figure D.5.

Figure D-5 | Equipment and electricity costs for a natural gas–fired power plant flue gas transport system include (4x) pipeline and blower; 1,000-acre open pond. For transport more than 1 mile, only one blower per pipeline is needed.



Cost-Effective Distance

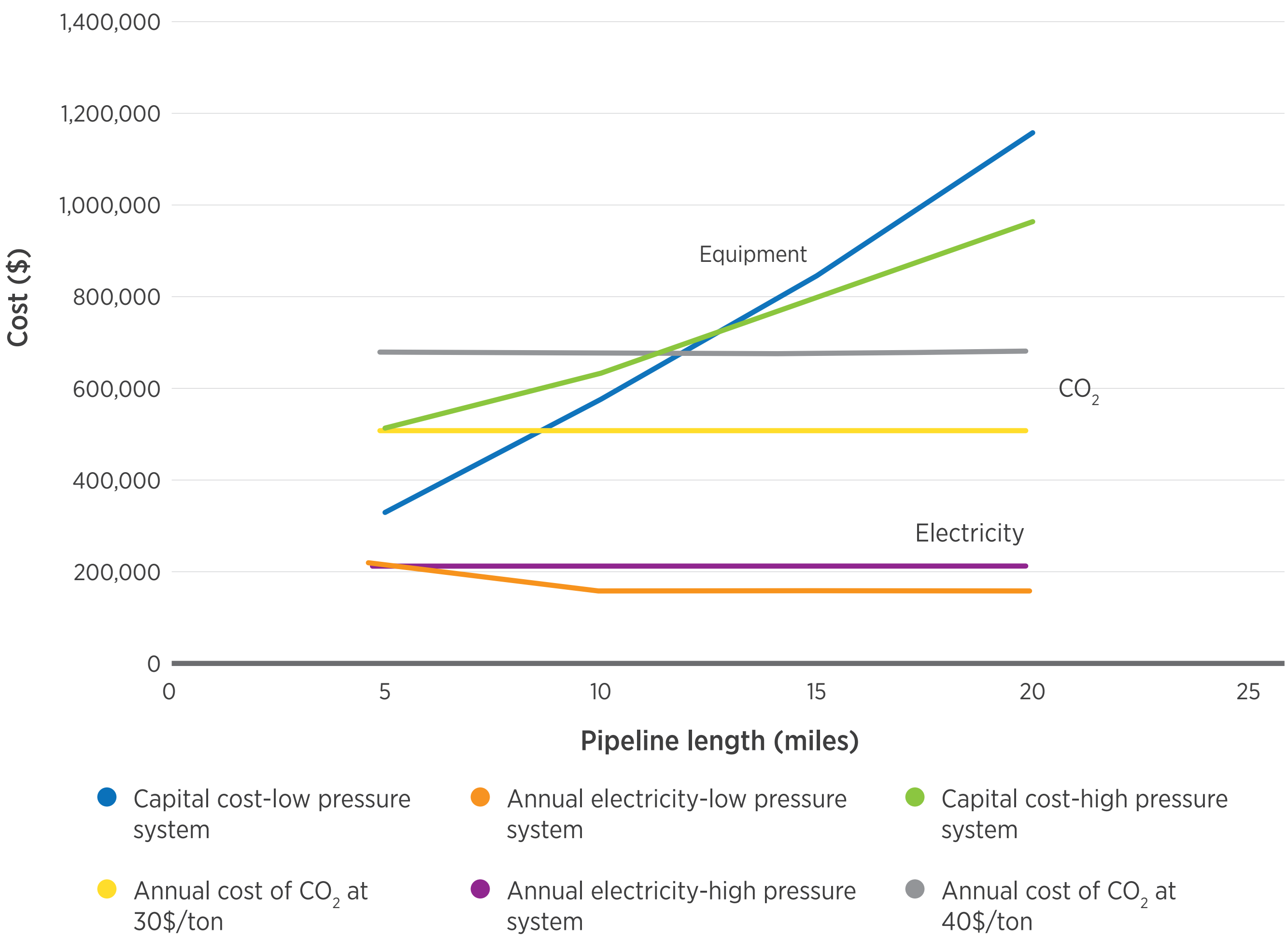
The cost-effective distance for co-location of an algae facility with a natural gas–fired power plant is less than 2 miles. The cost of a pipeline, plus the power to move the very dilute gas, suggests that the algae facility must be located at the same site as the power plant.

D.4.3 Corn Ethanol Plants

Cost of Transport of CO_2 to Algae Growth Facilities

The transport of the gas stream from a corn ethanol plant is much simpler than transport from a power plant because the output gas is more than 99% pure. The pipes can be smaller in diameter and the blowers can be lower in power and less expensive. The results of the cost analysis for equipment and electricity for transporting CO_2 to a 1,000-acre algae facility (open pond) are shown in figure D.6.

Figure D-6 | Equipment and electricity costs for a CO_2 transport system from a corn ethanol plant to an open pond facility include pipeline, compression, and storage



Cost-Effective Distance

For the base ethanol case, the results suggest it is easily cost-effective to pipe CO_2 from a corn ethanol plant to an algae facility up to 20 miles away. This makes it easier to find suitable land for the algae farm that does not compete with land for growing the corn.

D.5 Detailed Scenario Results from Biophysically Based Production Estimates

The tables provided in this appendix provide Biomass Assessment Tool (BAT) model analysis results for site-specific biomass production supported by CO_2-based co-location constrained by available supply and transport economics. In total, 12 scenarios are evaluated. Both current and future productivities are modeled for both *Chlorella sorokiniana* and *Nannochloropsis salina*, each considering three CO_2 co-location options (i.e., ethanol, coal electric generating unit [EGU], natural gas EGU). A summary table of these results is provided in section 7.6.3, Biophysically Based Production Estimates.

Ethanol Production Plant Co-Location: Freshwater Open-Pond Scenario (*Chlorella sorokiniana*)—Current Productivity

Table D-2 | Ethanol Plant Co-Location Results Under Chlorella sorokiniana Freshwater Scenario

Description	Value	Units
Total U.S. ethanol CO_2 supply	151.3	million tons/year
Total CO_2 potentially available for co-location	76.77	million tons/year
Percentage of total ethanol CO_2 stream available		
for co-location	50.7%	
Total CO_2 available during daylight hours	38.38	million tons/year
Percentage of daylight supply used in co-location	25.4%	
Total CO_2 used in co-location scenario (transport to production sites $\leq$\$40/ton and/or sufficient pond areas/biomass production to support available CO_2 supply)	29.21	million tons/year
Percentage of supply used in co-location	19.3%	
Largest single plant CO_2 output	5.47	million tons/year
Average plant CO_2 output	1.40	million tons/year
Number of ethanol CO_2 plants sourced for co-location	117	
Number of algae production sites	904	unit farm (1,000 acres)
Total algae production area	904,699	acres
Average distance from CO_2 source to algae facility	15.2	miles
Total biomass produced with available co-located CO_2	11.88	million tons/year
Percentage of sites favoring low-pressure system	82.7%	
Percentage of sites favoring high-pressure system	17.3%	
Average cost of co-located CO_2 (CapEx and OpEx)	$10.67	$/ton of CO_2
Total cost per year of all co-located CO_2	$239.88	total million $
Average site cost per year of co-located CO_2	$265.35	total thousand $
Average site cost of commercially purchased CO_2 ($40/ton) for same co-located biomass amount	$1.17	total million $

Table D-2 ***(continued)***

Description	Value	Units
Co-located cost savings	$907.15	total thousand $
Percentage of co-located cost savings	77.4%	

CapEx = capital expense; OpEx = operating expense.

Coal EGU Co-Location: Freshwater Open-Pond Scenario (*Chlorella sorokiniana*)—Current Productivity

Table D-3 | Coal EGU Plant Co-Location Results Under *Chlorella sorokiniana* Freshwater Scenario

Description	Value	Units
Total U.S. coal CO_2 supply	2.725	billion tons/year
Total CO_2 potentially available for co-location	671.61	million tons/year
Percentage of coal CO_2 stream available for co-location	24.7%	
Total CO_2 available during daylight hours	201.48	million tons/year
Percentage of daylight supply used in co-location	7.4%	
Total CO_2 used in co-location scenario (transport to production sites ≤$40/ton and/or sufficient pond areas/biomass production to support available CO_2 supply)	45.61	million tons/year
Percentage of supply used in co-location	1.7%	
Largest single plant CO_2 output	17.52	million tons/year
Average plant CO_2 output	2.08	million tons/year
Number of coal CO_2 plants sourced for co-location	189	
Number of algae production sites	1,256	unit farm (1,000 acres)
Total algae production area	1,256,971	acres
Average distance from CO_2 source to algae facility	6.2	miles
Total biomass produced with available co-located CO_2	18.54	million tons/year
Average cost of co-located CO_2 (CapEx and OpEx)	$19.48	$/ton of CO_2
Total cost per year of all co-located CO_2	$612.91	total million $
Average site cost per year of co-located CO_2	$487.9	total thousand $
Average site cost of commercially purchased CO_2 ($40/ton) for same co-located biomass amount	$1.32	total million $
Co-located cost savings	$829.6	total thousand $
Percentage of co-located cost savings	63.0%	
Percentage of sites ≤2 miles	4.4%	
Percentage of sites >2 miles	95.6%	

CapEx = capital expense; OpEx = operating expense.

Natural Gas EGU Co-Location: Freshwater Open-Pond Scenario (*Chlorella sorokiniana*)—Current Productivity

Table D-4 | Natural Gas EGU Plant Co-Location Results Under *Chlorella sorokiniana* Freshwater Scenario

Description	Value	Units
Total U.S. natural gas CO_2 supply	414.54	million tons/year
Total CO_2 potentially available for co-location	240.42	million tons/year
Percentage of coal CO_2 stream available for co-location	58.0%	
Total CO_2 available during daylight hours	96.17	million tons/year
Percentage of daylight supply used in co-location	23.2%	
Total CO_2 used in co-location scenario (transport to production sites ≤$40/ton and/or sufficient pond areas/biomass production to support available CO_2 supply)	36.87	million tons/year
Percentage of supply used in co-location	8.9%	
Largest single plant CO_2 output	740.1	K tons/year
Average plant CO_2 output	96.4	K tons/year
Number of CO_2 plants sourced for co-location	176	
Number of algae production sites	789	unit farm (1,000 acres)
Total algae production area	789,610	acres
Average distance from CO_2 source to algae facility	4.8	miles
Total biomass produced with available co-located CO_2	14.99	million tons/year
Average cost of co-located CO_2 (CapEx and OpEx)	$31.58	$/ton of CO_2
Total cost per year of all co-located CO_2	$781.91	total million $
Average site cost per year of co-located CO_2	$991.01	total thousand $
Average site cost of commercially purchased CO_2 ($40/ton) for same co-located biomass amount	$1.70	total million $
Co-located cost savings	$704.69	total thousand $
Percentage of co-located cost savings	41.6%	
Percentage of sites ≤1 mile	3.9%	
Percentage of sites >1 mile	96.1%	

CapEx = capital expense; OpEx = operating expense.

Ethanol Production Plant Co-Location: Saline Water Open-Pond Scenario (*Nannochloropsis salina*)—Current Productivity

Table D-5 | Ethanol Plant Co-Location Results Under *Nannochloropsis salina* Saline Water Scenario

Description	Value	Units
Total U.S. ethanol CO_2 supply	151.33	million tons/year
Total CO_2 potentially available for co-location	76.77	million tons/year
Percentage of total ethanol CO_2 stream available for co-location	50.7%	
Total CO_2 available during daylight hours	38.38	million tons/year
Percentage of daylight supply used in co-location	25.4%	
Total CO_2 used in co-location scenario (transport to production sites $\leq$ $40/ton and/or sufficient pond areas/biomass production to support available CO_2 supply)	25.45	million tons/year
Percentage of supply used in co-location	16.8%	
Largest single plant CO_2 output	5.47	million tons/year
Average plant CO_2 output	1.38	million tons/year
Number of ethanol CO_2 plants sourced for co-location	134	
Number of algae production sites	792	unit farm (1,000 acres)
Total algae production area	792,612	acres
Average distance from CO_2 source to algae facility	16.0	miles
Total biomass produced with available co-located CO_2	10.35	million tons/year
Percentage of sites favoring low-pressure system	80.3%	
Percentage of sites favoring high-pressure system	19.7%	
Average cost of co-located CO_2 (CapEx and OpEx)	$10.92	$/ton of CO_2
Total cost per year of all co-located CO_2	$213.26	total million $
Average site cost per year of co-located CO_2	$269.3	total thousand $
Average site cost of commercially purchased CO_2 ($40/ton) for same co-located biomass amount	$1.17	total million $
Co-located cost savings	$896.6	total thousand $
Percentage of co-located cost savings	76.9%	

CapEx = capital expense; OpEx = operating expense.

Coal EGU Co-Location: Saline Water Open-Pond Scenario (*Nannochloropsis salina*)—Current Productivity

Table D-6 | Coal EGU Plant Co-Location Results Using *Nannochloropsis salina* Saline Water Strain

Description	Value	Units
Total U.S. coal CO_2 supply	2.725	billion tons/year
Total CO_2 potentially available for co-location	912.33	million tons/year
Percentage of coal CO_2 stream available for co-location	33.5%	
Total CO_2 available during daylight hours	273.70	million tons/year
Percentage of daylight supply used in co-location	10.1%	
Total CO_2 used in co-location scenario (transport to production sites ≤ \$40/ton and/or sufficient pond areas/biomass production to support available CO_2 supply)	133.80	million tons/year
Percentage of supply used in co-location	4.91%	
Largest single plant CO_2 output	22.7	million tons/year
Average plant CO_2 output	6.77	million tons/year
Number of coal CO_2 plants sourced for co-location	246	
Number of algae production sites	3,346	unit farm (1,000 acres)
Total algae production area	3,348,586	acres
Average distance from CO_2 source to algae facility	8.9	miles
Total biomass produced with available co-located CO_2	54.40	million tons/year
Average cost of co-located CO_2 (CapEx and OpEx)	\$21.67	\$/ton of CO_2
Total cost per year of all co-located CO_2	\$2.765	total billion \$
Average site cost per year of co-located CO_2	\$826.4	total 100 thousand \$
Average site cost of commercially purchased CO_2 (\$40/ton) for same co-located biomass amount	\$1.45	total million \$
Co-located cost savings	\$624.7	total thousand \$
Percentage of co-located cost savings	43.0%	
Percentage of sites ≤2 miles	1.2%	
Percentage of sites >2 miles	98.8%	

CapEx = capital expense; OpEx = operating expense.

Natural Gas EGU Co-Location: Saline Water Open-Pond Scenario (*Nannochloropsis salina*)—Current Productivity

Table D-7 | Natural Gas EGU Plant Co-Location Results Under *Nannochloropsis salina* Saline Water Scenario

Description	Value	Units
Total U.S. natural gas CO_2 supply	414.54	million tons/year
Total CO_2 potentially available for co-location	218.67	million tons/year
Percentage of coal CO_2 stream available for co-location	52.8%	
Total CO_2 available during daylight hours	87.47	million tons/year
Percentage of daylight supply used in co-location	12.6%	
Total CO_2 used in co-location scenario (transport to production sites $\leq$ \$40/ton and/or sufficient pond areas/biomass production to support available CO_2 supply)	52.23	million tons/year
Percentage of supply used in co-location	12.6%	
Largest single plant CO_2 output	740.1	K tons/year
Average plant CO_2 output	64.2	K tons/year
Number of CO_2 plants sourced for co-location	151	
Number of algae production sites	1,095	unit farm (1,000 acres)
Total algae production area	1,095,846	acres
Average distance from CO_2 source to algae facility	6.7	miles
Total biomass produced with available co-located CO_2	21.24	million tons/year
Average cost of co-located CO_2 (CapEx and OpEx)	$34.43	$/ton of CO_2
Total cost per year of all co-located CO_2	$1.246	total billion $
Average site cost per year of co-located CO_2	$1.14	total million $
Average site cost of commercially purchased CO_2 ($40/ton) for same co-located biomass amount	$1.73	total million $
Co-located cost savings	$592.5	total thousand $
Percentage of co-located cost savings	34.2%	
Percentage of sites $\leq$1 mile	2.28%	
Percentage of sites >1 mile	97.72%	

CapEx = capital expense; OpEx = operating expense.

Ethanol Production Plant Co-Location: Freshwater Open-Pond Scenario (*Chlorella sorokiniana*)—Future Productivity

Table D-8 | Ethanol Plant Co-Location Results Using *Chlorella sorokiniana* Fresh Water Strain Under Future Productivity Conditions

Description	Value	Units
Total U.S. ethanol CO_2 supply	151.32	million tons/year
Total CO_2 potentially available for co-location	76.77	million tons/year
Percentage of total ethanol CO_2 stream available for co-location	50.7%	
Total CO_2 available during daylight hours	38.38	million tons/year
Percentage of daylight supply used in co-location	25.4%	
Total CO_2 used in co-location scenario (transport to production sites ≤$40/ton and/or sufficient pond areas/biomass production to support available CO_2 supply)	32.24	million tons/year
Percentage of supply used in co-location	21.3%	
Largest single plant CO_2 output	5.47	million tons/year
Average plant CO_2 output	1.48	million tons/year
Number of ethanol CO_2 plants sourced for co-location	141	
Number of algae production sites	508	unit farm (1,000 acres)
Total algae production area	508,393	acres
Average distance from CO_2 source to algae facility	14.5	miles
Total biomass produced with available co-located CO_2	13.11	million tons/year
Percentage of sites favoring low-pressure system	82.7%	
Percentage of sites favoring high-pressure system	17.3%	
Average cost of co-located CO_2 (CapEx and OpEx)	$7.79	$/ton of CO_2
Total cost per year of all co-located CO_2	$185.97	total million $
Average site cost per year of co-located CO_2	$366.1	total $100 thousand
Average site cost of commercially purchased CO_2 ($40/ton) for same co-located biomass amount	$2.30	total million $
Co-located cost savings	$1.94	total million $
Percentage of co-located cost savings	84.1%	

CapEx = capital expense; OpEx = operating expense.

Coal EGU Co-Location: Freshwater Open-Pond Scenario (*Chlorella sorokiniana*)—Future Productivity

Table D-9 | Coal EGU Plant Co-Location Results Using *Chlorella sorokiniana* Freshwater Strain Under Future Productivity Conditions

Description	Value	Units
Total U.S. coal CO_2 supply	2.725	billion tons/year
Total CO_2 potentially available for co-location	671.61	million tons /year
Percentage of coal CO_2 stream available for co-location	24.7%	
Total CO_2 available during daylight hours	201.48	million tons/year
Percentage of daylight supply used in co-location	7.4%	
Total CO_2 used in co-location scenario (transport to production sites ≤ $40/ton and/or sufficient pond areas/biomass production to support available CO_2 supply)	24.66	million tons/year
Percentage of supply used in co-location	0.9%	
Largest single plant CO_2 output	2.68	million tons/year
Average plant CO_2 output	7.63	million tons/year
Number of coal CO_2 plants sourced for co-location	68	
Number of algae production sites	257	unit farm (1,000 acres)
Total algae production area	257,199	acres
Average distance from CO_2 source to algae facility	3.8	miles
Total biomass produced with available co-located CO_2	10.03	million tons/year
Average cost of co-located CO_2 (CapEx and OpEx)	$24.04	$/ton of CO_2
Total cost per year of all co-located CO_2	$1.390	total billion $
Average site cost per year of co-located CO_2	$2.70	total million $
Average site cost of commercially purchased CO_2 ($40/ton) for same co-located biomass amount	$3.48	total million $
Co-located cost savings	$782.8	total thousand $
Percentage of co-located cost savings	22.5%	
Percentage of sites ≤4 miles	41.4%	
Percentage of sites >4 miles	58.6%	

CapEx = capital expense; OpEx = operating expense.

Ethanol Production Plant Co-Location: Saline Water Open-Pond Scenario (*Nannochloropsis salina*)—Future Productivity

Table D-10 | Ethanol Plant Co-Location Results Using *Nannochloropsis salina* Saline Water Strain Under Future Productivity Conditions

Description	Value	Units
Total U.S. ethanol CO_2 supply	151.33	million tons/year
Total CO_2 potentially available for co-location	63.55	million tons/year
Percentage of total ethanol CO_2 stream available for co-location	42.0%	
Total CO_2 available during daylight hours	31.77	million tons/year
Percentage of daylight supply used in co-location	21.0%	
Total CO_2 used in co-location scenario (transport to production sites ≤$40/ton and/or sufficient pond areas/biomass production to support available CO_2 supply)	27.91	million tons/year
Percentage of supply used in co-location	18.5%	
Largest single plant CO_2 output	5.47	million tons/year
Average plant CO_2 output	1.42	million tons/year
Number of ethanol CO_2 plants sourced for co-location	127	
Number of algae production sites	435	unit farm (1,000acres)
Total algae production area	435,336	acres
Average distance from CO_2 source to algae facility	14.6	miles
Total biomass produced with available co-located CO_2	11.35	million tons/year
Percentage of sites favoring low-pressure system	72.2%	
Percentage of sites favoring high-pressure system	27.8%	
Average cost of co-located CO_2 (CapEx and OpEx)	$8.01	$/ton of CO_2
Total cost per year of all co-located CO_2	$159.39	total million $
Average site cost per year of co-located CO_2	$366.4	total thousand $
Average site cost of commercially purchased CO_2 ($40/ton) for same co-located biomass amount	$2.33	total million $
Co-located cost savings	$1.96	total million $
Percentage of co-located cost savings	84.3%	

CapEx = capital expense; OpEx = operating expense.

Coal EGU Co-location: Saline Water Open-Pond Scenario (*Nannochloropsis salina*)—Future Productivity

Table D-11 | Coal EGU Plant Co-Location Results Using *Nannochloropsis salina* Saline Water Strain Under Future Productivity Conditions

Description	Value	Units
Total U.S. coal CO_2 supply	2.725	billion tons/year
Total CO_2 potentially available for co-location	912.33	million tons/year
Percentage of coal CO_2 stream available for co-location	33.5%	
Total CO_2 available during daylight hours	273.70	million tons/year
Percentage of daylight supply used in co-location	10.1%	
Total CO_2 used in co-location scenario (transport to production sites ≤$40/ton and/or sufficient pond areas/biomass production to support available CO_2 supply)	30.38	million tons/year
Percentage of supply used in co-location	1.1%	
Largest single plant CO_2 output	22.68	million tons/year
Average plant CO_2 output	8.12	million tons/year
Number of coal CO_2 plants sourced for co-location	70	
Number of algae production sites	299	unit farm (1,000 acres)
Total algae production area	299,231	acres
Average distance from CO_2 source to algae facility	4.4	miles
Total biomass produced with available co-located CO_2	12.35	million tons/year
Average cost of co-located CO_2 (CapEx and OpEx)	$33.43	$/ton of CO_2
Total cost per year of all co-located CO_2	$1.869	total billion $
Average site cost per year of co-located CO_2	$1.10	total million $
Average site cost of commercially purchased CO_2 ($40/ton) for same co-located biomass amount	$3.69	total million $
Co-located cost savings	$2.59	total million $
Percentage of co-located cost savings	70.2%	
Percentage of sites ≤4 miles	10.7%	
Percentage of sites >4 miles	89.3%	

CapEx = capital expense; OpEx = operating expense.

D.6 Productivities Associated with Costs

Table D-12 | Productivities (g/m^2/d) of *Chlorella sorokiniana* (freshwater media) and *Nannochloropsis salina* (saline media) associated with minimum, median, and maximum costs for each scenario. The 5-digit FIPs code (county identifier) associated with the productivity is given in each cell, following the productivity.

Scenario—time	Scenario—culture medium	Source of CO_2	Productivities (g/m^2/d); FIPs code		
			Minimum	Median	Maximum
Present productivity	Freshwater media	Coal	15.87; 12099	11.63; 22011	3.21; 55003
		Natural gas	16.77; 12071	13.63; 48201	7.17; 35029
		Ethanol	14.46; 48057	11.54; 48401	3.25; 55099
	Saline media	Coal	17.23; 12011	11.07; 01091	3.49; 32013
		Natural gas	16.77; 12071	13.30; 48361	4.64; 32019
		Ethanol	14.46; 48057	11.31; 22067	3.23; 41057
Future productivity	Freshwater media	Coal	29.81; 12009	27.66; 12107	6.88; 32013
		Ethanol	28.49; 48057	22.74; 48401	6.36; 41057
	Saline media	Coal	31.02; 12009	21.19; 12017	7.16; 32013
		Ethanol	29.31; 22057	28.67; 31121	5.30; 36063

D.7 References

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Glossary of Key Terms

Glossary of Key Terms

advanced supply system – Feedstock supply system with advanced preprocessing to transform raw biomass into a tradeable commodity. In this analysis, advanced systems feature preprocessing depots to convert biomass bales or wood chips into pellets, which can then be blended and accepted by any biorefinery.

AFDW – ash-free dry weight

ASD – Agricultural Statistic District

algal biofuels – Utilization of primarily microalgae to produce high quantities of biomass per unit land area. The lipids in the microalgae can be used to produce biodiesel.

bcf – billion cubic feet

BGY – billion gallons per year

BT2 – Billion-Ton Update – *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry* (2011); the second of the Billion-Ton reports; expanded and updated analyses of the 2005 *Billion-Ton Study* to provide a more comprehensive assessment of U.S. biomass resources; evaluated the potential economic availability of biomass feedstocks under a range of offered prices and yield scenarios between 2012 and 2030.

BT16 – Billion-Ton Report—*U.S. Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy* (2016); the third of the Billion-Ton reports; provides the most recent estimates of potential biomass that could be available for biorefining and consists of two volumes: volume 1 (this report), focusing on biomass potentially available at specified prices, and volume 2, changes in environmental sustainability indicators associated with select production scenarios in volume 1.

BTS – Billion-Ton Study—B*iomass as a Feedstock for Bioenergy and Bioproducts: The Feasibility of a Billion Ton Annual Supply* (2005); the first of the Billion-Ton reports; a national-level, strategic assessment of the potential biophysical availability of biomass; identified more than one billion tons of biomass resources in the United States from agricultural land and forestland.

biobased product – The term biobased product, as defined by the Farm Security and Rural Investment Act of 2002 (FSRIA), means a product determined by the U.S. Secretary of Agriculture to be a commercial or industrial product (other than food or feed) that is composed, in whole or in significant part, of biological products or renewable domestic agricultural materials (including plant, animal, and marine materials) or forestry materials.

biodiesel – Fuel derived from vegetable oils or animal fats. It is produced when a vegetable oil or animal fat is chemically reacted with an alcohol, typically methanol. It is mixed with petroleum-based diesel.

BAT – Biomass Assessment Tool

bioenergy – Energy derived from biomass.

bioenergy equivalent – Conversion estimate for the quantity of raw biomass on a dry ton basis, assuming a particular heating content and thermal conversion efficiency. For example, wood biopower for electric generation is assumed to be 13 million Btu per bone dry ton and municipal solid waste (MSW)-derived biopower is assumed to be 8 million Btu per bone dry ton.

biofuels – Fuels made from biomass resources, or their processing and conversion derivatives. Biofuels include ethanol, biodiesel, and methanol.

biomass – Any organic matter that is available on a renewable or recurring basis, including agricultural crops and trees, wood and wood residues, plants, algae, grasses, animal manure, municipal residues, and other residue materials.

biomass resource analysis – The quantification of a supply of biomass that under specified conditions (e.g., availability of land, water, and fertilizer; spatial resolution and extent; timeframe) can be used to generate biofuel or biopower.

biopower – The use of biomass feedstock to produce electric power or heat through direct combustion of the feedstock, through gasification and then combustion of the resultant gas, or through other thermal conversion processes. Power is generated with engines, turbines, fuel cells, or other equipment.

biorefinery – A facility that processes and converts biomass into value-added products (e.g., renewable fuels, power, chemical products, and intermediates). The biorefinery concept is analogous to a petroleum refinery, which produces a slate of multiple fuels, intermediates, and products from a petroleum feedstock.

black liquor – Solution of lignin residue and the pulping chemicals used to extract lignin during the manufacture of paper.

Btu – British Thermal Unit – A unit of energy equal to approximately 1,055 Joules. It is the amount of energy required to heat 1 pound (0.454 kg) of water from 39˚ to 40˚ F.

Bu – bushels

C&D – Construction and demolition materials – Wood waste generated during the construction of new buildings and structures, the repair and remodeling of existing buildings and structures, and the demolition of existing buildings and structures.

CHP – combined heat and power

CNG – compressed natural gas

CONUS – conterminous United States

CORRIM – Consortium for Research on Renewable Industrial Materials

conventional supply system – Feedstock supply system using traditional agricultural and forestry systems to deliver biomass bales or wood chips to the refinery. In this analysis, conventional systems have little to no active quality control and biorefineries can only accept one feedstock type.

conventionally sourced wood – Wood that has commercial uses other than fuel (e.g. pulpwood) but is used for energy because of market conditions. This would probably only include smaller diameter pulpwood-sized trees.

coppice – To regrow from a (tree) stump after harvest.

cotton gin trash – Residue available at a processing site, including seeds, leaves, and other material.

cotton residue – Cotton stalks available for collection after cotton harvest.

CRM – component ratio method – A method introduced in 2009 used to estimate non-merchantable volumes from merchantable trees by the USDA Forest Service.

CRP – Conservation Reserve Program – A land conservation program administered by the Farm Service Agency (FSA) that pays a yearly rental payment in exchange for farmers removing environmentally sensitive land from agricultural production and planting species that will improve environmental quality (Definition from U.S. Department of Agriculture Farm Service Agency Conservation Programs).

crop residues – The portion of a crop remaining after the primary product is harvested.

cropland – Similar to the 2012 USDA Census of Agriculture definition of "total cropland," this land category includes planted and harvested acres of corn, wheat, grain sorghum, barley, soybeans, rice, cotton, barley and hay (see Natural Resources Conservation Service definition of cropland and appendix C for more details).

cropland pasture, or cropland used for pasture or grazing – Defined in the 2012 USDA Census of Agriculture Appendix B as "land used only for pasture or grazing that could have been used for crops without additional improvement. Also included are acres of crops hogged or grazed but not harvested prior to grazing" (Adapted from the U.S. Department of Agriculture; see appendix C for more details).

cull tree – A live tree, 5.0 inches dbh or larger that is non-merchantable for saw logs, now or prospectively, because of rot, roughness, or species.

CTL – cut-to-length

delivered cost – An estimate of all costs—including production, harvest, storage, handling, preprocessing, and transportation—to deliver biomass feedstocks to the reactor throat.

dbh – diameter at breast height – The common measure of wood volume approximated by the diameter of trees measured at approximately breast height from the ground.

DOE – United States Department of Energy

EGU – electric generating unit

EISA – The Energy Independence and Security Act of 2007

EPA – United States Environmental Protection Agency

ethanol – Also known as ethyl alcohol or grain alcohol, this volatile, flammable, and colorless liquid with the chemical formula C_2H_6O is produced by the fermentation of sugars.

EU – European Union

feedstock – A product used as the basis for manufacture of another product.

FIA – Forest Inventory and Analysis – A program of the U.S. Forest Service of the U.S. Department of Agriculture that collects, analyzes, and reports information on the status and trends of America's forests: how much forest exists, where it exists, who owns it, and how it is changing. It has been in continuous operations since 1928. The latest technologies are used to acquire a consistent core set of ecological data about forests through remote sensing and field measurements. The data in this report are summarized from more than 100,000 permanent field plots in the United States.

fiber products – Products derived from fibers of herbaceous and woody plant materials. Examples include pulp, composition board products, and wood chips for export.

forest land – Land at least 10% stocked by forest trees of any size, including land that formerly had such tree cover and that will be naturally or artificially regenerated. (Adapted from the U.S. Forest Service of the U.S. Department of Agriculture)

ForSEAM – Forest Sustainable and Economic Analysis Model

FRCS – Fuel Reduction Cost Simulator – A forest harvesting costing model utilized in this report to estimate the cost of harvesting small diameter trees for biomass.

fuelwood – Wood used for conversion to some form of energy, primarily for residential use.

GDP – gross domestic product

GFPM – Global Forest Products Module

GHG – greenhouse gas – Natural or anthropogenic gas that can absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the earth's surface, the atmosphere, and the clouds. Water vapor (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and ozone (O_3) are the primary greenhouse gases in the Earth's atmosphere. (Adapted from the Intergovernmental Panel on Climate Change and the International Organization for Standardization 13065 sustainability criteria for bioenergy)

growing stock – A classification of timber inventory that includes live trees of commercial species meeting specified standards of quality or vigor. Cull trees are excluded. When associated with volume, growing stock includes only trees 5.0 inches dbh and larger.

HI – harvest index – For conventional crops, the ratio of residue to grain.

idle land – A land class defined as cropland used for cover crops or soil improvement, but not harvested and not pastured or grazed (Adapted from the U.S. Department of Agriculture; see also appendix C for more details).

IMPLAN – Impact analysis for planning

industrial wood – All commercial roundwood products except fuelwood.

irrigated pasture – Irrigated pasture is defined to be any pasture land that falls under the "irrigated land" land class defined by the U.S. Department of Agriculture (USDA 2012; see also appendix C for more details).

KDF – Bioenergy Knowledge Discovery Framework – Online collection of bioenergy-related research, data sets, applications, and maps for bioenergy researchers, policymakers, and industry; hosts U.S. Billion-Ton Report interactive data and visualizations

kwh – kilowatt hour

LHW – lowland hardwood

LNG – liquefied natural gas

logging residues – The unused portions of growing-stock and non-growing-stock trees cut or killed by logging and left in the woods.

MGD – million gallons per day

MiG – management-intensive grazing – Management of grazing land that can increase the carrying capacity, whereby animal nutrient demand through the grazing season is balanced with forage supply based on animal requirements (Adapted from *Management-Intensive Grazing* by Jim Gerrish, 2004).

mill residues – Bark and woody materials that are generated in primary wood-using mills when roundwood products are converted to other products. Examples are slabs, edgings, trimmings, sawdust, shavings, veneer cores and clippings, and pulp screenings. Includes bark residues and wood residues (both coarse and fine materials) but excludes logging residues. May include both primary and secondary mills.

MSW – municipal solid waste – Wastes (garbage) collected from municipalities consisting mainly of yard trimmings and paper products.

MW – megawatt

nonforest land – Land that has never supported forests and lands formerly forested where use of timber management is precluded by development for other uses. Nonforest land includes area used for crops, improved pasture, residential areas, city parks, improved roads of any width and adjoining clearings, powerline clearings of any width, and 1- to 4.5-acre areas of water classified by the Bureau of the Census as land. If intermingled in forest areas, unimproved roads and nonforest strips must be more than 120 feet wide, and clearings, etc., must be more than 1 acre in area to qualify as nonforest land.

other forestland – Forest land other than timberland and reserved forest land. It includes available forest land, which is incapable of annually producing 20 cubic feet per acre of industrial wood under natural conditions because of adverse site conditions such as sterile soils, dry climate, poor drainage, high elevation, steepness, or rockiness.

other removals and residues – Unutilized wood volume from cut or otherwise killed growing stock, from cultural operations such as precommercial thinnings, or from timberland clearing for other uses (i.e., cropland, pastureland, roads, urban settlement). It does not include volume removed from inventory through reclassification of timberland to productive reserved forest land.

PBR – photobioreactor

perennial – A crop that lives for more than two years. Well-established perennial crops have a good root system and provide cover that reduces erosion potential. They generally have reduced fertilizer and herbicide requirements compared to annual crops.

permanent pastureland, or rangeland, other than cropland and woodland pastured – Defined in the 2012 USDA Census of Agriculture Appendix B as a land category which “encompasses grazable land that does not qualify as woodland pasture or cropland pasture. It may be irrigated or dry land. In some areas, it can be a high quality pasture that could not be cropped without improvements. In other areas, it is barely able to be grazed and is only marginally better than wasteland.” (USDA 2012; see also appendix C for more details).

POLYSYS – Policy Analysis System – An agricultural policy modeling system of U.S. agriculture, including both crops and livestock. It is based at the University of Tennessee Institute of Agriculture, Agricultural Policy Analysis Center.

PVC – polyvinyl chloride

primary agricultural resources – Resources included within this category include energy feedstocks (annual energy crops, coppice and non-coppice woody crops, perennial grasses), crop residues (barely straw, corn stover, oat straw, sorghum stubble, wheat straw), and conventional crops (barley, born, cotton, hay, oats, rice, sorghum, soybeans, wheat). The projections included for this category of feedstocks are two baseline scenarios (one with no energy crops—e.g., feedstock price of zero—and another including energy crops) and four high-yield scenarios with estimated biomass prices ranging between $30 and $100.

primary wood-using mill – A mill that converts roundwood products into other wood products. Common examples are sawmills that convert saw logs into lumber and pulp mills that convert pulpwood roundwood into wood pulp.

PS – planted softwood

psig – pounds per square inch gauge

PSU – practical salinity units

pulpwood – Roundwood, whole-tree chips, or wood residues that are used for the production of wood pulp (also referred to as conventional wood within the database).

renewable fuel – liquid fuels (e.g., ethanol or biodiesel as a replacement for gasoline, jet fuel, kerosene, or diesel) or other fuels (e.g., pellets as a substitute for fossil based power production). Note: the generation of renewable fuels can also produce valuable biomass based products or chemicals.

RFS – Renewable Fuel Standard – The RFS was established by the Energy Policy Act of 2005. It required 7.5 billion gallons of renewable-based fuel (which was primarily ethanol) to be blended into gasoline by 2012. This original RFS (referred to sometimes as RFS1) was expanded upon (RFS2) by the Energy Independence and Security Act of 2007 (EISA) to include diesel in addition to gasoline as well as to increase the volume of renewable fuel to be blended into fossil-based fuel to 9 billion and ultimately 36 billion gallons by 2022. RFS2 established life-cycle greenhouse gas requirements (less than fossil fuels they replace) for renewable fuels.

RIN – Renewable Identification Number

roundwood products – Logs and other round timber generated from harvesting trees for industrial or consumer use.

RPA – Resources Planning Act – The Forest and Rangeland Renewable Resources Planning Act of 1974 requires periodic assessments and reports the status and trends of the nation's renewable resources on all forest and rangelands.

RPS – renewable portfolio standard – A standard or regulation that requires electricity utilities and other retail electricity suppliers to obtain a certain percent of their electricity from certified renewable sources.

RUSLE2 – Revised Universal Soil Loss Equation – A computer program that estimates erosion and sediment delivery for conservation planning in crop production.

RVO – renewable volume obligation

SCM – Supply Characterization Model

SRTS – Subregional Timber Supply

Soil Conditioning Index – An index indicating the impact of crop management activities on soil organic matter.

starch – A carbohydrate consisting of many glucose units. It is the most common carbohydrate in the human diet.

stumpage value – The sale value of the products that can be obtained from a stand of trees. This is the value of the wood products at a processing or end use facility minus transport and harvest costs and a profit for the harvester.

SUNY – State University of New York

sustainability – Aspirational concept denoting the capacity to meet current needs while maintaining options for future generations to meet their needs. To make the concept of sustainability operational, consistent approaches are required that facilitate comparable, science-based assessments using measurable indicators of environmental, economic, and social processes (Hecht et al. 2009; McBride et al. 2011; Dale et al. 2015). Notes: Conceptual sustainability and sustainable development goals are described in the Brundtland Report (1987) and the National Environmental Policy Act (U.S. Government 1969), the latter of which committed "to create and maintain conditions under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic and other requirements of present and future generations." Sustainability does not imply a steady state or an absolute value, but instead is a relative and comparative term that must have a defined context, based on clear objectives (Efroymson et al. 2013).

thinnings (other forestland treatment thinnings) – The practice of reducing the number of plants in an area of the quantity of vegetative or reproductive structures on individual plants. Thinnings can come from operations to reduce fuel load (i.e., removal of small trees to reduce the fire danger) and from composite integrated operations on forestland (activities to harvest merchantable commercial wood and low-quality wood for bioenergy applications simultaneously). Thinnings can also come from pre-commercial operations and from other forestland to improve forest health.

timberland – Forest land that is producing or is capable of producing crops of industrial wood, and that is not withdrawn from timber utilization by statute or administrative regulation. Areas qualifying as timberland are capable of producing more than 20 cubic feet per acre per year of industrial wood in natural stands. Currently inaccessible and inoperable areas are included.

TPO – Timber Product Output Database Retrieval System – System that acts as an interface to a standard set of consistently coded TPO data for each state and county in the country; developed in support of the 1997 Resources Planning Act (RPA) Assessment. This set of national TPO data consists of 11 data variables that describe for each county the roundwood products harvested, the logging residues left behind, the timber otherwise removed, and the wood and bark residues generated by its primary wood-using mills.

urban wood wastes – Wastes coming from municipal solid waste (MSW) and construction and demolition (C&D) debris. In the MSW portion, there is a wood component in containers, packaging, and discarded durable goods (e.g., furniture) and yard and tree trimmings.

UK – United Kingdom

UHW – upland hardwood

USDA – United States Department of Agriculture

USFPM – U.S. Forest Products Module

WWTP – wastewater treatment plants

WEF – Water Environment Federation

wheat dust – Portion of wheat left after processing, known as dust and chaff.

yield – The volume of feedstock on a designated land unit at a specific point in time.

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