U.S. DEPARTMENT OF ENERGY
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

2023 Billion-Ton Report:

An Assessment of U.S. Renewable Carbon Resources

March 2024

Disclaimer

Availability

This report and supporting documentation, data, and analysis tools are available online:

- Report landing page: https://www.energy.gov/eere/bioenergy/2023-billion-ton-report-assessment-us-renewable-carbon-resources
- Data portal: https://bioenergykdf.ornl.gov/bt23-data-portal

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Foreword

March 14, 2024

On behalf of the U.S. Department of Energy Bioenergy Technologies Office and the numerous authors and contributors to this document, I am pleased to present the *2023 Billion-Ton Report: An Assessment of U.S. Renewable Carbon Resources* (BT23). The challenge of decarbonizing our nation's economy will require rethinking of our nation's energy systems and processes. Despite significant advances in battery technology for electrification, much of our economy, especially the segments that are difficult to electrify, will continue to rely on liquid fuels and products. The role of biomass feedstocks as a source material for low-carbon liquid fuels and other products remains critical.

One question to be addressed is how much feedstock for new bioenergy uses could be sustainably available within the United States, and what would be required to bring that biomass to market. As with the preceding three iterations of this series, the 2005 Billion-Ton Study, the 2011 *U.S. Billion-Ton Update*, and the *2016 Billion-Ton Report*, this report seeks to address the fundamental question of biomass availability, with geospatial resolution and the economic accessibility of multiple feedstocks in various regions of the country. Similar to previous iterations, we conclude that the United States has the potential to sustainably produce more than a billion tons of biomass feedstock given adequate market conditions. The actual quantities produced will depend on market demand, technical advances, and local conditions. BT23 considers near-term feedstocks available from the waste, forestry, and agriculture sectors, as well as emerging resources such as energy crops, microalgae, macroalgae, and CO_2. The long-term sustainability of these feedstocks is addressed, along with good management practices for growing these feedstocks.

This report is the collective effort of numerous scientists from our national laboratories, multiple government agencies—notably the U.S. Department of Energy and U.S. Department of Agriculture—various universities, and industrial stakeholders. BT23 is based on the most credible scientific information from this wide array of stakeholders and contributors, developed as a guide to help address the decarbonization challenges that lie before us. I would like to express my appreciation to Mark Elless, technology manager, and Nichole Fitzgerald, program manager for Renewable Carbon Resources, as well as the various authors, especially the lead author, Matthew Langholtz of Oak Ridge National Laboratory.

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List of Acronyms

4FRI	Four Forests Restoration Initiative
AEO	Annual Energy Outlook
AFDW	ash-free dry weight
ARPA-E	Advanced Research Projects Agency–Energy
BAT	Biomass Assessment Tool
BAU	business as usual
BCF	billion cubic feet
BECCS	bioenergy with carbon capture and storage
BETO	Bioenergy Technologies Office
Bioenergy KDF	Bioenergy Knowledge Discovery Framework
BioSum	Bioregional Inventory Originated Simulation Under Management
BMP	best management practice
BT16	*2016 Billion-Ton Report*
BT2	2011 *U.S. Billion-Ton Update*
BT23	*2023 Billion-Ton Report*
BTS	2005 Billion-Ton Study
Btu	British thermal unit
C&D	construction and demolition
CNG	compressed natural gas
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
CONUS	conterminous United States
CRP	Conservation Reserve Program
CWI	Central Washington Initiative
DBH	diameter at breast height
DOE	U.S. Department of Energy
EEZ	exclusive economic zone
EIA	U.S. Energy Information Administration

EPA	U.S. Environmental Protection Agency
FIA	Forest Inventory and Analysis
FOG	fats, oils, and grease
ForSEAM	Forest Sustainable and Economic Analysis Model
GHG	greenhouse gas
GHGRP	Greenhouse Gas Reporting Program
G-MACMODS	Global MacroAlgae Cultivation MODeling System
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies
HHV	higher heating value
LFG	landfill gas
LNG	liquefied natural gas
LPG	liquefied petroleum gas
LUC	land use change
MARINER	Macroalgae Research Inspiring Novel Energy Resources
MBSP	minimum biomass selling price
MMBtu	million Btu
MSW	municipal solid waste
N_2O	nitrous oxide
NCCOS	National Centers for Coastal Ocean Science
NETL	National Energy Technology Laboratory
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
PIL	priority investment landscape
POLYSYS	Policy Analysis System Model
quad	quadrillion (10^{15}) Btu
RFS	Renewable Fuel Standard
RIN	renewable identification number
RNG	renewable natural gas
RPA	Resources Planning Act
SAF	sustainable aviation fuel

SOC	soil organic carbon
SRTS	SubRegional Timber Supply
TBtu	trillion British thermal units
TEA	techno-economic analysis
TPO	Timber Products Output
USDA	U.S. Department of Agriculture
USFS	U.S. Forest Service
WCS	Wildfire Crisis Strategy

Executive Summary

The following online companion materials are available:

- Report landing page: https://www.energy.gov/eere/bioenergy/2023-billion-ton-report-assessment-us-renewable-carbon-resources
- Data portal: https://bioenergykdf.ornl.gov/bt23-data-portal

Bioenergy provided the largest single source of renewable energy in the United States in 2022, comprising approximately 5% of U.S. energy produced (EIA 2023) (Figure ES-1). The mission of the U.S. Department of Energy (DOE) Bioenergy Technologies Office (BETO) is to develop and demonstrate technologies to accelerate net greenhouse gas emissions reductions through the cost-effective, sustainable use of biomass and waste feedstocks across the U.S. economy. This report assesses the potential for renewable biomass resources to support DOE goals by displacing fossil resources such as petroleum with renewable biogenic carbon resources that, when managed efficiently, have a lower climate impact than petroleum sources of carbon. Demand for renewable fuels is growing, especially for the aviation, marine, and rail sectors. For example, the Biden administration's Sustainable Aviation Fuel (SAF) Grand Challenge targets the production of 35 billion gallons per year of SAF by 2050, and the Clean Fuels & Products Shot™, whose target of developing cost-competitive carbon-based products at 85% less greenhouse gas emissions by 2035, can support delivery of approximately 440 million tons per year of low-carbon fuels and chemicals by 2050. Such targets raise the question: Does the United States have sufficient biomass supplies, within a practical range of environmental, economic, and resource constraints, to fill these needs? The answer is yes, provided adequate markets can be established, and that environmental safeguards are established to ensure sustainable outcomes. This report aims to inform stakeholders of the types and quantities of biomass resources that could potentially be available in the future and under what conditions. The report provides a detailed assessment of current and potential biomass production capacity in the United States at defined price points and under conditions that protect food production and environmental integrity.

This report is the latest in a series of national biomass resource assessments supported by BETO (Perlack et al. 2005; DOE 2011, 2016, 2017). Each report represents an advancement in the understanding of biomass resources in terms of production capacity, spatial distribution, and economic accessibility. While the reports have consistently found that the United States could sustainably produce about 1 billion tons of biomass per year under some scenarios, that was not a goal or target; it was merely one outcome of analyses based on available data. Goals of this report are to update the latest available input data (e.g., costs, yields, economic conditions) and improve accessibility of the latest biomass resource data and results. New resources in this report include:

- Intermediate (i.e., off-season) oilseeds

- Western forest fuels (as case studies, not included in national totals)
- Macroalgae and point-source waste carbon dioxide (CO_2).

Market pull is needed to realize the production of biomass resources reported here. In this report, we emphasize this precondition by presenting resource potential in terms of market demand scenarios. The market scenarios used in this report are characterized in Table ES-1 and detailed in Chapter 1. Another key factor in biomass resource availability is the price offered for biomass. Reference prices[1] are used to summarize supply potential, as shown in Figure ES-1, but readers are encouraged to explore the range of potential resource availabilities under different price assumptions at https://bioenergykdf.ornl.gov/bt23-data-portal.

[1] Prices here (and unless otherwise specified) are as raw biomass on a dry-weight, with-ash basis, in 2022 dollars, at the farm gate for agricultural land resources; chipped into a van roadside for timberland resources; collected and sorted for waste resources; after harvest, dewatering, and seasonal storage for microalgae resources; and after harvest and transportation to the nearest port for macroalgae resources. For comparison, the reference price of the previous report (DOE 2016) was $60 per dry ton in 2014 dollars—i.e., approximately $74 per dry ton in 2022 dollars. Biomass resources currently used for energy have varying market prices and are not reported here.

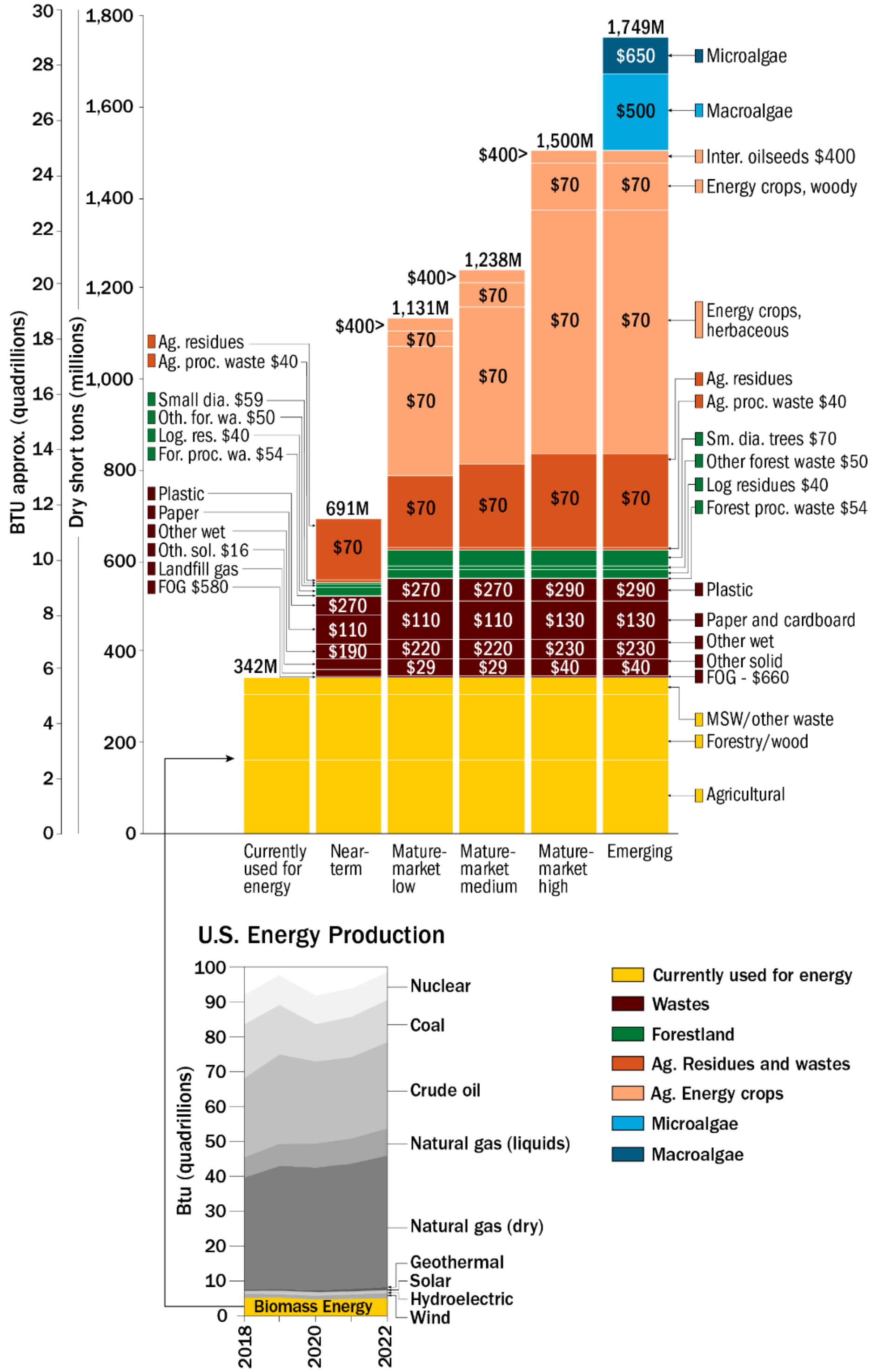

Figure ES-1. Currently used and potential future biomass resources under near-term, mature-market, and emerging scenarios. Reference prices are in dollars per dry ton, without transportation costs. Prices are reported as rounded weighted averages for wastes and marginal prices for all other resources. Market prices of currently used resources are not reported here. The energy equivalent does not account for conversion process efficiency. Values for 2018–2022 production are from the U.S. Energy Information Agency (2023). Select values are provided in Table ES-2. Underlying data for this figure and a version using alternate units can be found at https://bioenergykdf.ornl.gov/bt23-data-portal.

Table ES-1. Characterization of Market Scenarios Used in This Report (Attributes Detailed in Chapter 1 Table 1.2)

Market Scenario	Characterization
Current	Current uses of biomass for energy (i.e., power and fuels) and coproducts.
Near-term	Resources that are completely unused currently and can be used in the next 5–10 years, in addition to current uses.
Mature-market low	Low market pull, low supply push: business-as-usual (BAU) projections for the agriculture, forestry, and waste sectors, and no purpose-grown energy crop yield improvements, in addition to current uses.
Mature-market medium	Moderate market pull, moderate supply push: BAU projections and moderate (1%) purpose-grown energy crop yield improvements, in addition to current uses.
Mature-market high	High market pull and high supply push: 3% improvements of purpose-grown energy crops; conventional crop yields improve 1.5 times the USDA trend; BAU waste projections with higher waste demand increase waste prices, in addition to current uses.
Evolving and emerging resources	Potential future production of microalgae, macroalgae, and capture of point-source waste CO_2. These resources are considered as prospectively available, contingent upon future innovations, in addition to the mature-market high scenario.

Biomass resource availability is dependent in large part upon markets, and the timing and pace of market development is not known. Thus, this report provides estimates of biomass resource potential in response to market demand scenarios, rather than year-specific projections of biomass availability. Results here aim to indicate national biomass resource potential as estimated under the specific conditions and assumptions constructed in the analyses for each market scenario. Thus, resources reported here are less than the total raw biophysical potential for biomass production, but reflect the proportion thereof that complies with specified economic and environmental constraints (e.g., restricted land use change), and allow for satisfaction of conventional product demands, as illustrated in Figure ES-6. Results are based on national modeling simulations and are not intended to be predictive or precise, particularly for the county-level data provided in the data portal (https://bioenergykdf.ornl.gov/bt23-data-portal). The results are meant to provide general insights about the potential magnitude of biomass resource availability per specific conditions, which can be useful for resource allocation planning and future policy development. Local stakeholder innovation is expected to uncover synergistic practices that can increase both biomass potential and ecosystem services, which is not captured in this national analysis. Thus, this national assessment is approximate and probably conservative. The importance of market pull and the use of these data for decarbonization studies are explored further in Chapter 8. Key results of this national assessment follow.

Future production capacity of more than 1 billion tons per year of biomass is identified, which could approximately triple the current U.S. bioenergy economy. More than 1 billion tons of biomass production capacity is identified nationally, while meeting projected demands for food, feed, fiber, and exports. As provided in the data portal, this supply increases at higher prices or with the inclusion of microalgae, macroalgae, or CO_2, which could be accessible if technological innovations are realized in the future. In the mature-market low scenario, approximately 1 billion tons of total biomass is identified, including current uses, whereas in the mature-market high scenario, approximately 1 billion tons of new biomass production is identified, above current uses (Figure ES-1). One billion tons per year of biomass is roughly enough biomass to produce approximately 60 billion gallons of fuel, or 1.7 times the quantity needed to achieve the SAF Grand Challenge. In the mature-market medium scenario, 1.5 billion tons of biomass per year is more than enough to meet the goals of the SAF Grand Challenge and the Clean Fuels & Products Shot™: Alternative Sources for Carbon-based Products. However, this analysis is agnostic with regard to end use.

Near-term resources can provide approximately 350 million tons per year of biomass above current uses, which would roughly double the current U.S. bioenergy economy (Figure ES-1 and Table ES-2). This “low-hanging fruit” of the biomass portfolio includes biomass resources that exist today, even in the absence of additional market pull for biomass, but are currently unused. Some of these resources, such as wastes, are already collected but then landfilled. Others, such as agricultural residues and timberland resources, exist in fields and forests but must be collected for use.

Table ES-2. Current and Potential Future Biomass Resources under Near-Term and Mature-Market Scenarios (million dry short tons per year). Market Scenario Assumptions Are Specified in Chapter 1.[a]

		Scenario			
Analysis Class [b]	Analysis Subclass [b]	Near-Term	Mature-Market Low	Mature-Market Medium	Mature-Market High
Currently Used for Energy and Coproducts	Agricultural	162	162	162	162
	Forestry/wood	144	144	144	144
	Municipal solid waste (MSW)/other wastes	37	37	37	37
Potential Waste and Byproducts [c]	Fats, oils, and grease (FOG)	3	4	4	4
	Gaseous resources	15			
	Other solid waste	24	38	38	38
	Other wet waste	32	43	43	43
	Paper	64	84	84	84
	Plastic	41	49	49	49
Potential Forestland Resources	Forest processing waste	1	1	1	1
	Logging residues	19	19	19	19
	Other forest waste	8	8	8	8
	Small-diameter trees	3	35	35	35
Potential Agricultural Land Resources	Agricultural processing waste	6	6	6	6
	Agricultural residues	134	158	183	205
	Energy crops, herbaceous		284	345	535
	Energy crops, woody		34	53	103
	Intermediate oilseeds		28	28	28
	Total [d]	691	1,131	1,238	1,500

[a] Currently used resources have a range of current prices not reported here. Waste quantities are reported at all modeled prices. Agricultural and forestry resource quantities are provided at up to $70 per dry ton. Prices in this table are reported as farm gate (i.e., at roadside), which includes costs of production and harvest but excludes transportation costs. Prices in this report are provided in 2022 dollars unless otherwise specified.
[b] Classes, subclasses, and resource are provided in the glossary.
[c] Waste totals do not match the sum of county-level data due to differences in the spatial resolution of data, as described in Chapter 3.
[d] Totals may not sum due to rounding.

Mature-market resources can provide approximately 800–1,200 million tons per year of biomass above current uses (Figure ES-1). The largest growth in the mature-market scenarios is due to the adoption of purpose-grown energy crops. Because future energy crop production can have interactions with conventional crop markets on agricultural lands, energy crop potential was assessed with an economic model as described in Chapter 5. Modeled scenarios of energy crop production require fulfilment of future demands for food, feed, fiber, and exports from the 2023 U.S. Department of Agriculture (USDA) baseline projection, which includes increased demand for conventional crops relative to previous projections. In response, the modeled potential of purpose-grown energy crops is down 3% (in the mature-market medium scenario) from the *2016 Billion-Ton Report* reference scenario (DOE 2016), but still shows potential of approximately 300–600 million tons across the three mature-market scenarios (Table ES-2). Modeling results for energy crops shown in Figure ES-1 and Table ES-2 are produced on 8%–11% of agricultural land while still meeting projected demands for conventional crops and leaving 8% of cropland unused. Results show purpose-grown energy crops having comparative economic advantage over other cropland use options primarily in the southern Plains, but not in highly productive agricultural regions where higher-value conventional crops dominate (Figure ES-4). Modeled increases on U.S. finished food prices associated with the energy crop production shown in Figure ES-1 are less than 1%; modeled increases in total farm net revenues range from 26% to 31% (Table ES-3). Changes in energy crop production would result in approximately proportional changes in these modeled effects.

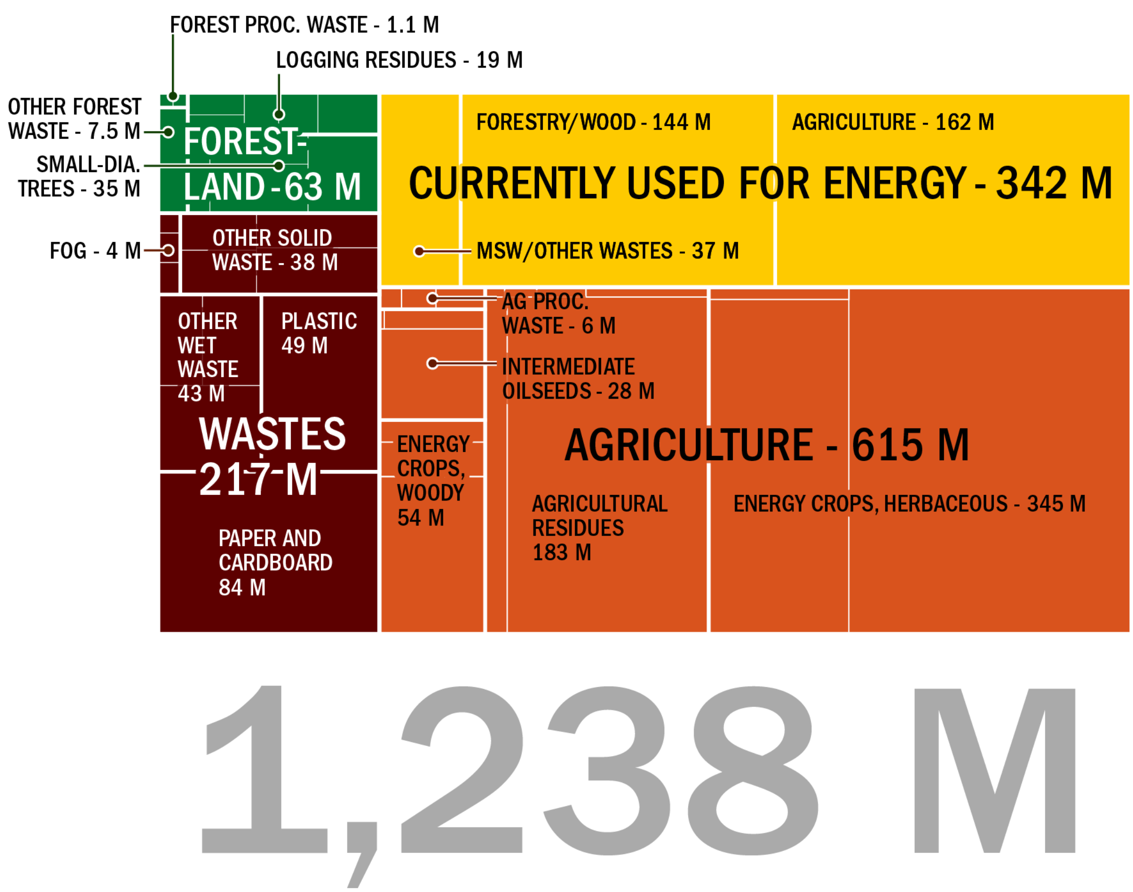

Figure ES-2. Biomass resources in the mature-market medium scenario, totaling 1.2 billion dry short tons per year (under reference prices shown in Figure ES-1). This figure for other scenarios and units is available at https://bioenergykdf.ornl.gov/bt23-data-portal.

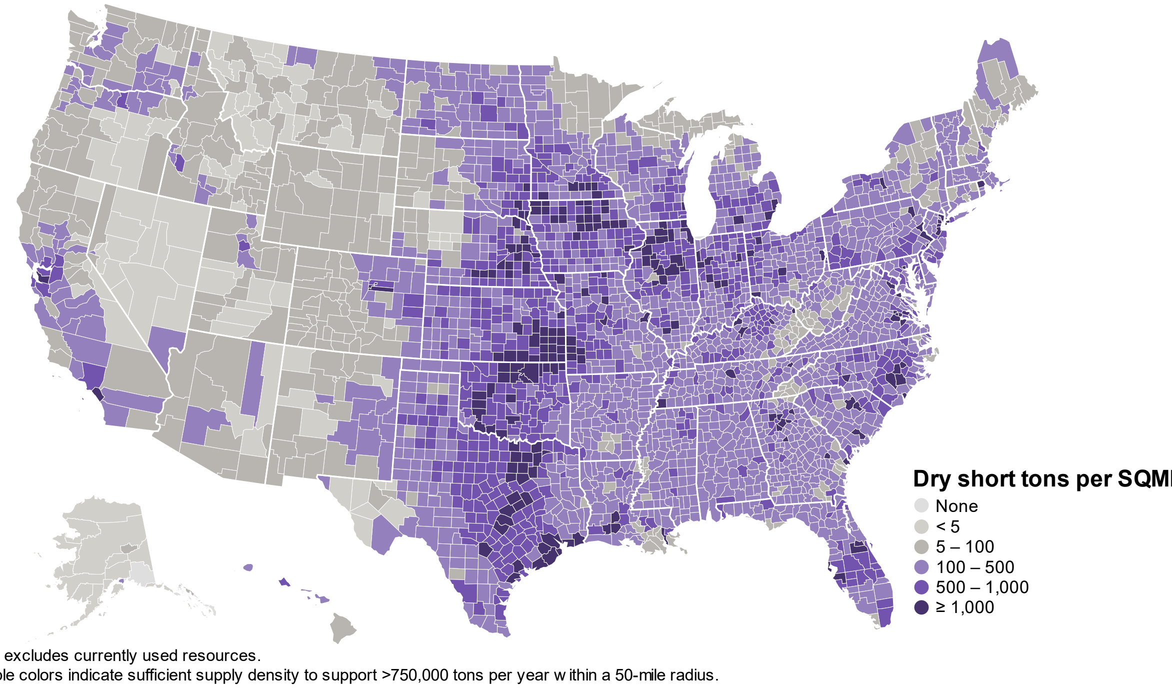

Figure ES-3. Spatial distribution of biomass resources from all sources shown in the mature-market medium scenario as specified in Figure ES-1, Figure ES-2, and Table ES-2, excluding currently used resources. Purple shades indicate adequate spatial density to support a facility of at least 725,000 dry tons per year within a 50-mile radius (i.e., at least 100 dry tons per square mile). Scenario- and class-specific versions of this figure are available at https://bioenergykdf.ornl.gov/bt23-data-portal.

The mature-market scenarios also carry forward resources from the near-term scenario with the following modifications:

- Waste quantities increase slightly, associated with projected increases in population over 20 years. Waste resources include urban wastes (e.g., MSW, FOG) and agricultural and forestry processing wastes (e.g., mill wastes).
- Demand for biomass from timberlands (i.e., logging residues and trees less than 11 inches in diameter at breast height) is increased to a sustained yield of 54 million tons per year, with market prices of up to $70 per dry ton.
- Agricultural residues increase to about 175 million tons per year in the mature-market medium scenario, up from about 130 million tons per year in the near-term scenario.

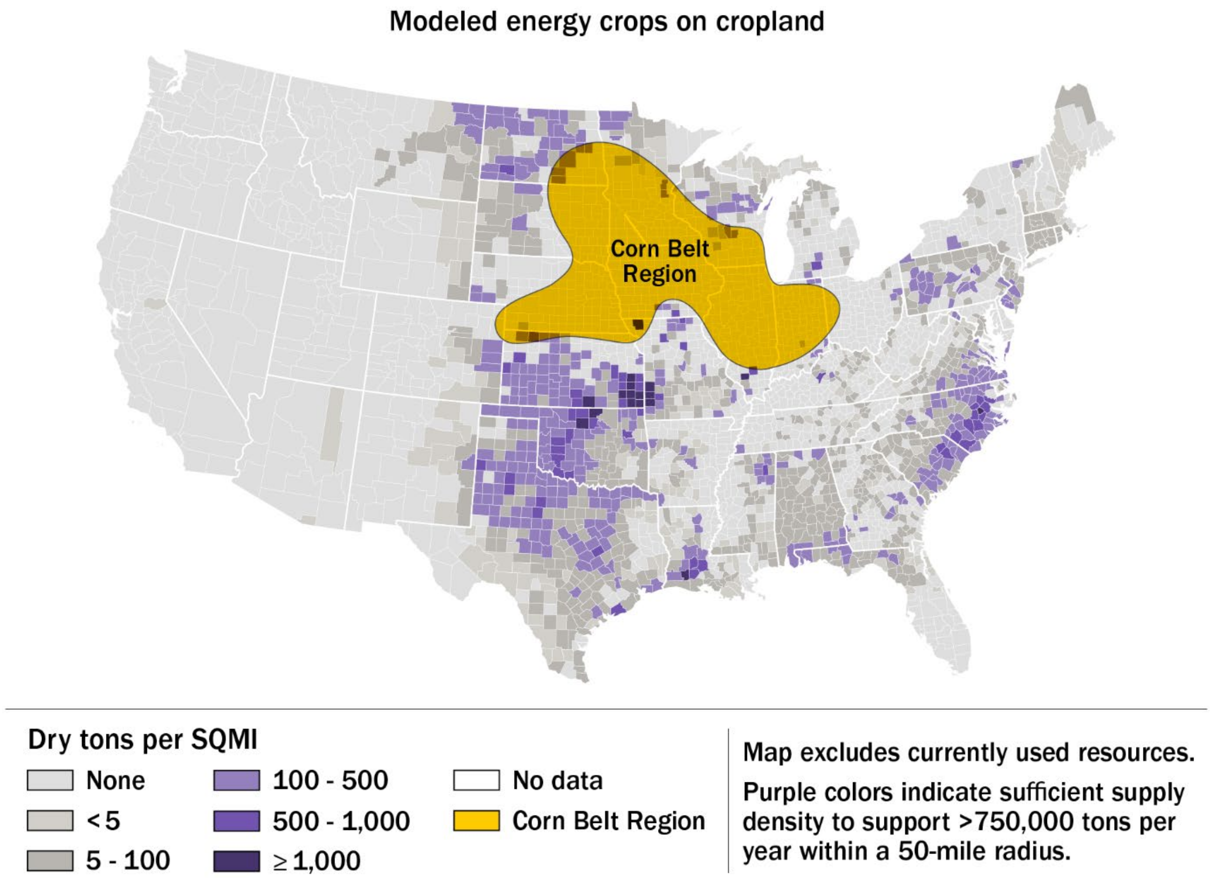

Figure ES-4. Spatial distribution of purpose-grown energy crops under the mature-market medium reference scenario on cropland, illustrating the comparative economic advantage of commodity crops in the corn belt. The orange region indicates a corn/soy production region as shown by the USDA National Agricultural Statistics Service (2023), where energy crops are largely excluded from cropland.

Table ES-3. Modeled Impacts of Energy Crop Scenarios on U.S. Commodity Crop Production, Commodity Crop Prices, Food Prices, and Farm Revenues. Future Yield Improvements Simulated in the Mature-Market High Scenario Mitigate Impacts on Conventional Production and Increase Biomass Production. Details Are Provided in Chapter 5.3.

Scenario [a]	Energy Crops Produced (million dry tons) [a,b]	Agricultural Residues Harvested (million dry tons) [c]	Production of Corn, Soy, and Wheat	Change in Finished Food Price	Total Farm Market Net Revenues
			Percent Change from Baseline, Mature Market		
Mature-market low	318	152	−3%	+0.6%	+26%
Mature-market medium	398	177	−3%	+0.7%	+31%
Mature-market high	638	200	−1%	+0.1%	+31%

[a] Mature-market scenarios are described in Chapter 5 and summarized in Table ES-1.
[b] Sum of modeled cellulosic terrestrial (i.e., excluding intermediate oilseeds and algae) purpose-grown energy crops within modeling constraints as summarized in Figure ES-1.
[c] Corn stover and wheat straw.

Resource quantities vary by price. The summaries above provide an illustration of potential biomass resources under specified market prices. However, different types and quantities of biomass resources are expected to be available at different prices. Biomass resource availability as a function of offered price for the mature-market medium scenario is illustrated in Figure ES-5. Users are encouraged to explore scenario-, price-, and resource-specific spatially explicit resource availability in the data portal.

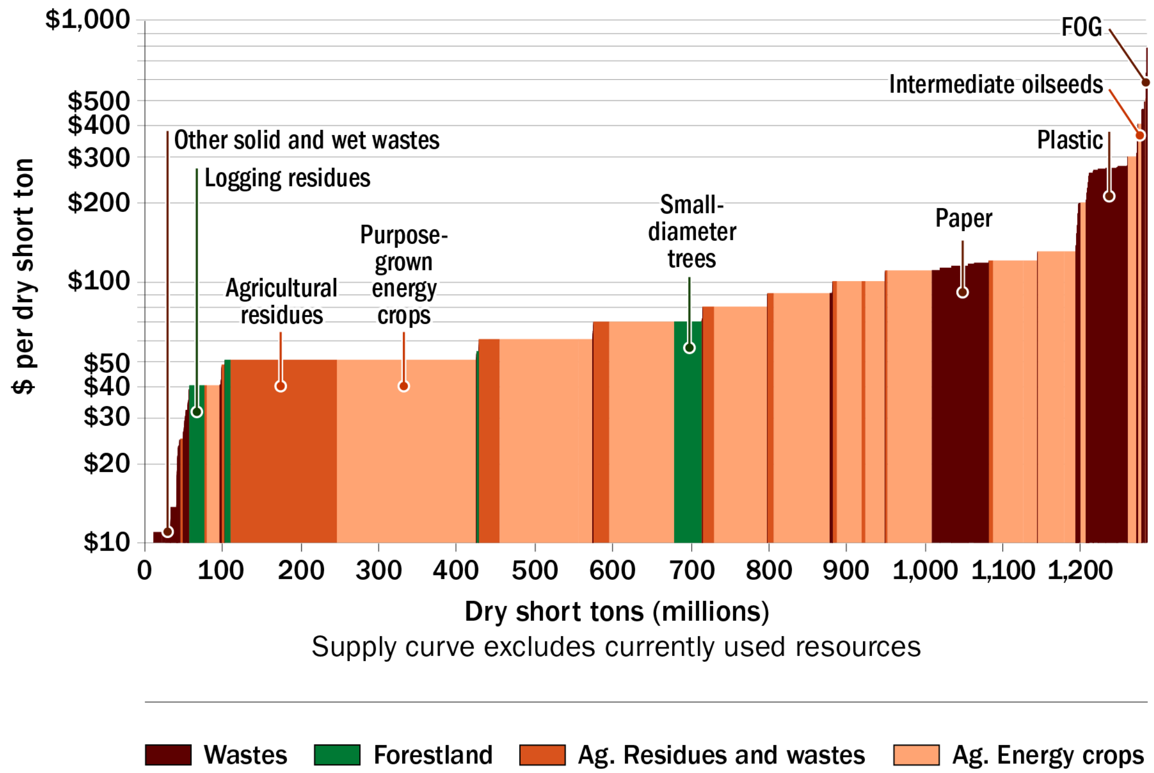

Figure ES-5. Supply curve of the mature-market medium scenario, excluding currently used resources and including agricultural resources above the $70 per dry ton price shown in Figure ES-1. Prices are reported as farm gate (i.e., after harvest and before transportation) in 2022 inflation-adjusted dollars. Interactive versions of this figure for other scenarios and units are available at https://bioenergykdf.ornl.gov/bt23-data-portal. Note that the y-axis is logarithmic.

Resource potentials reported here are not total national supplies "in field," but rather the economically accessible fraction within specified sustainability constraints (Figure ES-6). The economic and environmental constraints implemented in this report mean results are not maximum potential resource availability, but rather a fraction of resources that meet select sustainability constraints within specified prices. The results are representative of what is deemed accessible in potential futures if market demand is realized and other policy goals or conditions are met (such as food security or environmental integrity). For example, to meet modeled soil conservation constraints, about one-third of total national "in-field" agricultural residues are reported as available in the mature-market scenarios. Available waste resources represent about half of total national supplies after accounting for recycling and current uses.

Total timberland resource harvests, including for conventional wood products, are about one-third less than annual net forest growth, and less than 1% of total forest volumes. Purpose-grown biomass crops are not targeted to maximum production potential, but rather simulated to occupy 7% of cropland and 9% of agricultural lands in the mature-market medium scenario, where results indicate they have comparative economic advantage, within a mosaic of conventional agricultural uses. Changes in future costs, yields, or other factors (including policies and environmental and social conditions) would cause deviations from the estimated results in this report. Further, resources evaluated here are not exhaustive of all potential resources, which may include other sources of biomass from natural or anthropogenic activities such as winter herbaceous crops (Malone et al. 2023), storm debris, removals of beetle kill conifers or invasive exotics, realization of U.S. Forest Service forest fuel reduction goals, or purpose-grown energy crops produced on reclaimed mined lands or other underproductive lands (Field et al. 2023). The diversity of potential resources suggests that overestimation of some resource types is likely to be mitigated to some degree by underestimation of others. Ultimately, the market scenarios are provided to inform a range of future potential accessibility of national biomass resources. This analysis is not a prediction of what will be used, but rather an assessment of the possible economic accessibility of a portfolio of resources within specified constraints and modeled conditions, and with steady market development providing a demand "pull."

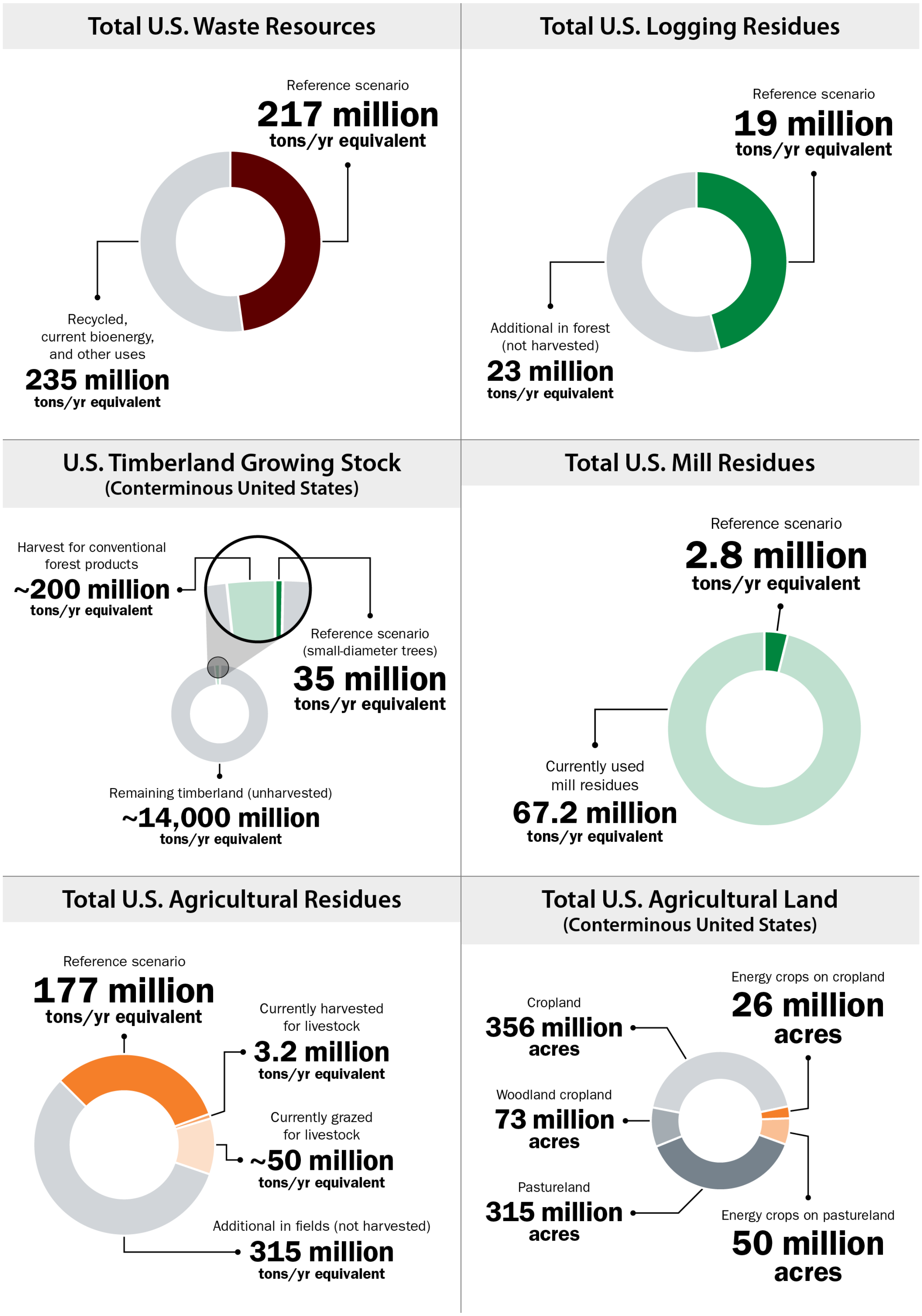

Figure ES-6. Available resources in the mature-market medium reference scenario in proportion to in-field supplies and competing uses.

Deviation from the sustainability constraints considered in this analysis could result in overharvesting and negative environmental effects. New in this report is an assessment of estimated risk of deviating from sustainability constraints used here. For example, relaxing agricultural residue retention constraints causes modeled residue harvest to nearly double, risking soil erosion or loss of soil carbon. Also, increasing biomass prices above $70 per ton at roadside, though currently cost prohibitive from a biofuels perspective, could incentivize harvest of some sawlog-class trees to be economically viable for bioenergy. Modeled prices higher than $70 per ton incentivize more production of purpose-grown energy crops and increase the market effects summarized in Table ES-3. Monitoring and evaluation are recommended to ensure that conservation practices are maintained, and consideration should be given to demand levels that might drive prices higher than evaluated here. Good practices that safeguard sustainability need to be appropriate for local conditions; consider practical, place-based opportunities and constraints; and be developed with stakeholders who are informed by reliable monitoring and evaluation data to support continual improvement. Biomass markets that provide performance-based incentives can support safeguards by promoting investment in technologies for more sustainable practices that reduce supply chain emissions and other detrimental effects. A discussion of the risk of deviating from modeling constraints is provided in Chapter 6.

Evolving and emerging resources represent additional potential. Chapter 7 in this report explores other resources that could be available at scale if technological innovations are realized. Microalgae (i.e., pond-grown algae) resources can be produced on underutilized lands using waste CO_2 streams and saline groundwater. Macroalgae (i.e., ocean-grown seaweed) can be cultivated in ocean farms with vast growth potential. CO_2 point-source waste streams can be targeted for decarbonization strategies. Combined, these resources could double or triple the billion-ton biomass resource potential reported here, but supplies vary greatly with price. An example of potential supplies at select prices is provided in Table ES-4. Perfect comparisons among resources are not possible with the data from this report alone. For example, economic results from the microalgae analysis include a 10% internal rate of return, whereas the macroalgae analysis is at breakeven cost. Microalgae is conversion-ready following harvest, dewatering, and seasonal storage (included in the economic results contributing on the order of about $100/ton to the presented microalgae biomass costs), whereas other resources still require transportation and preprocessing costs before conversion (not included in the economic results for those resources). Downstream factors of logistics and feedstock quality attributes, essential for comparing biomass resource options, are not included in this report.

Table ES-4. Emerging Resources at Reference Prices

Resource Category	Modeled Potential Supply at Specified Prices (million tons per year)
Microalgae (≤$650 per dry ton, with ash)	170
Macroalgae (≤$500 per ton, with ash)	80
CO_2 (high-purity)	47.2

Report organization. Chapter 1 provides background on the intent of this report and methods used in relation to previous billion-ton reports, including detailed descriptions of the market scenarios and sustainability constraints modeled. Chapter 2 details current uses of biomass for energy and coproducts. Chapters 3, 4, and 5 provide updated descriptions of the waste, forest, and agricultural biomass resource assessments, respectively. Chapter 6 explores sustainability issues in biomass resource production, including new quantitative analyses on food security impacts and the effects of relaxing sustainability constraints. Chapter 7 provides assessments of evolving and emerging feedstocks from microalgae, macroalgae, and CO_2 waste streams. Chapter 8 provides additional context on how this assessment can be used in decarbonization studies and priorities for future work, including modeling of energy crop production on marginal land and under future climate change.

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U.S. DEPARTMENT OF ENERGY
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Chapter 01 | Background and Introduction

Table of Contents

1 Background and Introduction

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This report and supporting documentation, data, and analysis tools are available online:

- Report landing page: https://www.energy.gov/eere/bioenergy/2023-billion-ton-report-assessment-us-renewable-carbon-resources
- Data portal: https://bioenergykdf.ornl.gov/bt23-data-portal

Summary

- In support of national decarbonization goals, the mission of the U.S. Department of Energy (DOE) Bioenergy Technologies Office (BETO) is to develop and demonstrate technologies to accelerate net greenhouse gas (GHG) emissions reductions through the cost-effective, sustainable use of biomass and waste feedstocks across the U.S. economy. This includes a focus on reducing net emissions of aviation and other sectors with low-net-emissions renewable carbon sources (Figure 1.1) (DOE 2023; DOE et al. 2023). Understanding the quantity, cost, and spatial distribution of renewable biomass resources is foundational to goals of decarbonizing key sectors of the economy.
- This is an updated assessment of biomass resources that could be available nationally, within specified economic and environmental constraints, if demand for biomass resources is actualized. This assessment includes more than 40 biomass resources, including wastes, agricultural resources, forestland resources, algae, and others.
- Policies are expected to change over time, which can influence market pull and, in turn, resource availability. Thus, this report is policy agnostic and end-use agnostic, but also intended to be supportive of current and future DOE objectives and to contribute to the body of knowledge of the bioenergy stakeholder community.
- This report does not quantify all resources “in the field,” but rather the potential availability of resources within specified environmental and economic constraints. For example, in the mature-market medium reference scenario, this report captures about one-third of agricultural residues, less than 1% of timberland growing stock, and less than half of wastes resources.

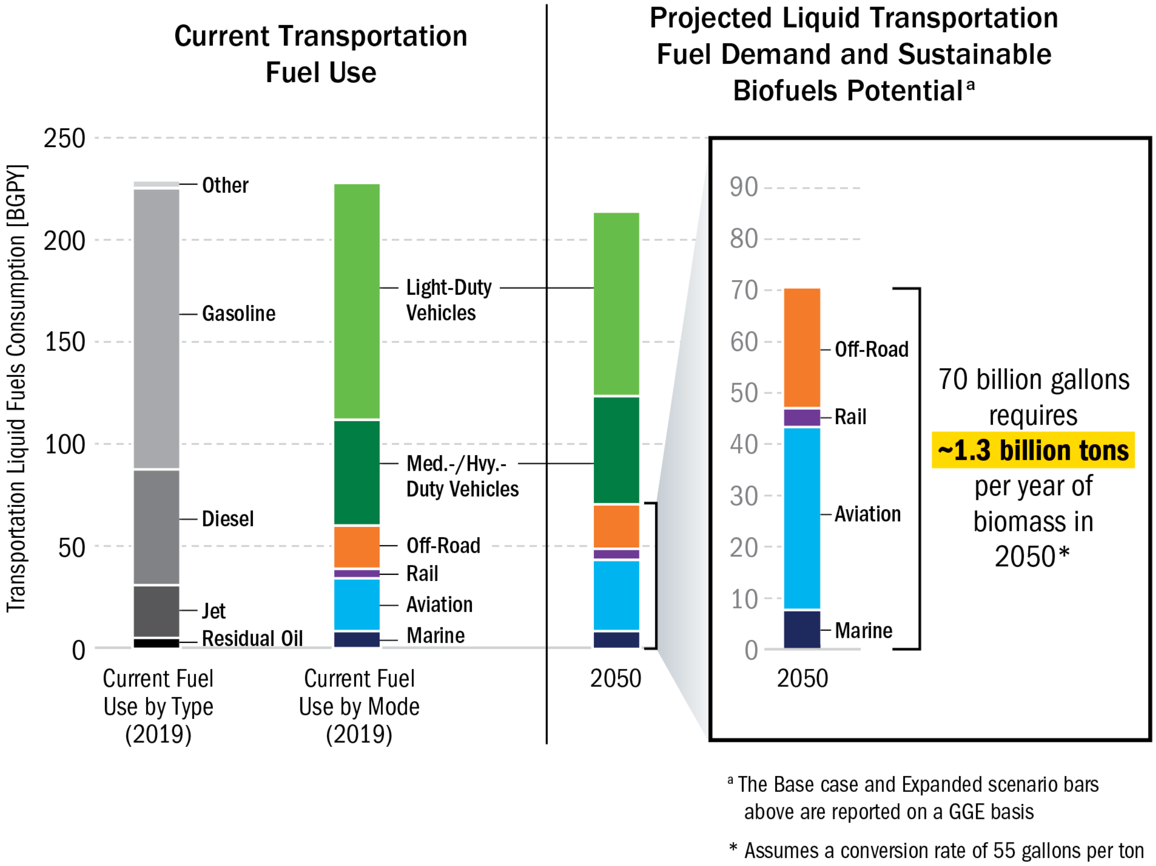

Figure 1.1. Current and projected liquid transportation fuel demand and sustainable biofuel supply.

Source: DOE et al. (2023)

- Consistent with previous billion-ton reports, this analysis identifies about 1 billion tons of biomass resources available annually in the United States, including 0.6–0.9 billion tons per year above current uses, within specified economic and environmental sustainability constraints. This number could increase with the addition of micro- and macroalgae and carbon dioxide (CO_2) resources (Chapter 7), which could be more accessible with future innovations. These results are not intended to be predictive of future biomass production, but rather to provide an estimate of future industry potential. Supplies vary by market scenario and generally increase with offered price, as described in this report.
- Consistent with previous billion-ton reports, about 400 million tons per year, or about half of the national biomass resource potential, can come from energy crops. This energy crop production potential is evaluated within agriculture land and economic constraints, generally identifying how farmers in a free market could reasonably intensify agricultural production in response to markets for biomass while meeting projected demands for food, feed, fiber, and exports. Modeling results of the mature-market medium reference scenario show production of nearly 400 million tons per year of cellulosic purpose-grown energy crops on about 7% of cropland and 9% of agricultural lands overall. This

additional production is modeled to increase retail food prices by up to 0.7%. However, this production could also increase agricultural net returns by up to 31% and contribute to the economic and environmental sustainability of agriculture and food security, domestically and internationally. Impacts on production and prices are reported in Chapter 5.

- Adjustments for changes since the last report (e.g., inflation, demand projections from the U.S. Department of Agriculture [USDA], updated cost assumptions) had minimal impacts for most biomass resources in terms of cost in real terms, but costs are adjusted to 2022 dollar values.
- As with previous reports, biomass resources quantified in this assessment are constrained by environmental sustainability criteria. This report includes an assessment of the risk of deviating from these constraints in future forestry and agricultural practices. Results suggest that regulation may be needed to ensure adherence to certain practices to ensure environmental sustainability.
- New in this report are several near-term (oilseed cover crops and wildfire reduction thinnings) and forward-looking (macroalgae and waste CO_2) biomass resources. Algae and CO_2 resources are excluded from biomass supplies at a reference price of $70/dry ton but are considered as potential resources that could become economically accessible with future innovations. Also new are data and visualizations available to make the report more accessible and useable for researchers and the informed public.

1.1 Background of the Billion-Ton Report Series

1.1.1 Progression of the Billion-Ton Report Series

The *2023 Billion-Ton Report* (BT23) is the latest in a series of billion-ton reports produced by DOE: the 2005 Billion-Ton Study (BTS) (Perlack et al. 2005), the 2011 *U.S. Billion-Ton Update* (BT2) (DOE 2011), and Volumes 1 and 2 of the *2016 Billion-Ton Report* (BT16) (DOE 2016, 2017). These reports, spanning nearly two decades, have progressed from estimating national quantities to economic and environmental modeling at county-level resolution. BT23 aims to account for changes in economic conditions since the last analysis, incorporate new biomass resources, and improve accessibility of inputs, modeling, assumptions, results, and key conclusions to a broader stakeholder community. Report attributes are summarized in Table 1.1.

Table 1.1. Attributes of Billion-Ton Reports to Date

	BTS (2005)	BT2 (2011)	BT16 (2016, 2017)	BT23 (Current)
Resources	Resources from forestry, agriculture, and wastes	Same as BTS, plus economically modeled herbaceous and woody energy crops	Same as BT2, with environmental economic modeling of seven energy crops and microalgae	Same as BT16, plus three oilseed crops, macroalgae, and select CO_2 point sources
Cost Analysis and Dollar Year Reporting	No cost analyses—just quantities	Supply curves by feedstock by county, costing at the farm gate/forest landing. Reported in nominal dollars.	Costing both at the farm gate/forest landing and at the biorefinery delivery point. Reported in 2014 dollars unless otherwise specified.	Same as BT16. Reported in 2022 dollars unless otherwise specified
Spatial Resolution	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	Same as BT16
Time Horizon	Long-term, inexact time horizon (2005, ~2025, and 2040–2050)	2012–2030 timeline (annual time step)	2016–2040 timeline (annual time step)	Reported under near-term and mature-market scenarios (annual available separately)
USDA Projections	2005 USDA agricultural projections; 2000 forestry Resources Planning Act (RPA)/Timber Products Output (TPO)	2009 USDA agricultural projections; 2007 USDA Census; 2010 Forest Inventory and Analysis (FIA); 2007 forestry RPA/TPO	2015 USDA agricultural projections; 2012 USDA Census; 2015 FIA inventory; projected forest products demands from U.S. Forest Products Module/Global Forest Products Model	2023 USDA baseline projections; projected forest product demands from 2023 Forest Resource Outlook Model
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)	Same at BT2, plus operational constraints as specified to simulate advancement of variable-rate harvesting	Same as BT16
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 features evaluation of key environmental sustainability indicators of select biomass production scenarios from Volume 1.	Same as BT16
Data Reporting Format	No external data	County-level data as a function of farm gate price and scenario	County-level data, plus online companion data available for interactive visualization linked to select figures and tables	Same as BT16

1.1.2 Role of This Report

This report aims to inform stakeholders of what biomass resources are available today and what can be available in the future. Paramount to interpreting biomass resource potential is an awareness of the conditions needed for this resource availability to be realized. Thus, we also emphasize the economic conditions (i.e., the market scenarios presented below) required for some resources to be available. As with the three previous billion-ton reports, this report is policy agnostic, end-use agnostic, not prescriptive, and not predictive. However, the report is also intended to provide BETO with national and regional biomass resource information needed to meet BETO goals.

1.2 New in This Report

1.2.1 Market Scenarios

Market maturity plays a key role in the availability of biomass resources. In particular, market pull is needed to realize availability of purpose-grown energy crops. Market demand is simulated in agriculture and forest sector economic models as described in this report. Stakeholder feedback suggested that reporting in terms of specific future years implied prediction as to when biomass would be available. To avoid implied precision regarding the temporal development of market demand and associated biomass resource availability, this report quantifies biomass resources in terms of market conditions—i.e., near-term and low, medium, and high mature-market conditions—and not by specific years (though the year-explicit results are available upon request). The four market scenario characterizations and example attributes are shown in Table 1.1. Additional context around the recent history of U.S. cellulosic bioenergy policy and markets is provided in Chapter 8.

Table 1.2. Characterization of Market Scenarios

Market Scenario	Scenario Characterization	Scenario Attributes		
		Wastes	Agricultural Lands	Timberlands
Current	Current (2022) uses of biomass for energy (i.e., power and fuels) and coproducts.	Observed in 2022	Observed in 2022	Observed in 2022
Near-term	Resources that are currently unused and are currently (e.g., 2023 and beyond) available if collected or harvested.	Represents 2023 supplies and market conditions.	Residues assume modeling year 2030 within county-level soil conservation constraints; purpose-grown energy crops not available; conventional crops assume USDA baseline projection.	Modeling year 2030 under demand trajectory modeled in Chapter 4.
Mature-market low	Low market pull, low supply push: business-as-usual (BAU) projections and no purpose-grown energy crop yield improvements.	BAU scenario adjusted to 2050 population estimates.	Residues assume modeling year 2041; residue harvest technology improves from 50% to 90% potential but within county-level soil conservation constraints; purpose-grown energy crops have no future yield improvements; conventional crops assume BAU USDA baseline projection. Intermediate oilseeds are included.	Modeling year 2050 under demand trajectory modeled in Chapter 4.
Mature-market medium	Moderate market pull, moderate supply push: BAU projections and moderate purpose-grown energy crop yield improvements.	Same as wastes in mature-market low.	Residues assume modeling year 2041; residue harvest technology improves from 50% to 90% potential but within county-level soil conservation constraints; purpose-grown energy crops have 1% per year future yield improvements; conventional crops assume BAU USDA baseline projection. Intermediate oilseeds are included.	Same as timberlands in mature-market low scenario.
Mature-market high	High market pull and high supply push: high yield improvements of purpose-grown energy crops and conventional crops; BAU waste projections with higher waste demand increase waste prices.	Supplies same as waste supplies in mature-market low scenario but with higher waste prices associated with increased resource demand.	Residues assume modeling year 2041; residue harvest technology improves from 50% to 90% potential but within county-level soil conservation constraints; purpose-grown energy crops have 3% per year future yield improvements; conventional crop yields improve 1.5 times the USDA baseline trend rate of yield improvement. Intermediate oilseeds are included.	Same as timberlands in mature-market low scenario.
Evolving resources	In addition to the mature-market high scenario, includes novel resources that could decrease in cost with future innovations.	Includes mature-market high resources and: • Microalgae from open pond cultivation • Macroalgae in ocean cultivation • CO_2 from point-source waste emissions.		

1.2.2 New Resources

This report includes four new resource categories:

1. **Oilseed cover crops:** Pennycress, carinata, and camelina are included as oilseed cover crops that can be cultivated within existing rotations while reducing soil erosion and maintaining soil organic carbon.
2. **Forest fuel reduction:** In collaboration with the U.S. Forest Service (USFS), a case study (Byproducts of Fire-Focused Management) is included to introduce potential biomass availability from forest fuel reduction to contribute to the USFS Wildfire Crisis Strategy (WCS), but not assessed in national totals.
3. **Algal biomass:** Macroalgae (seaweed) and microalgae (pond algae) are included in this report.
4. **Point-source waste CO_2:** Though not biomass, CO_2 is included in this report as a potential component of carbon resource management.

1.2.3 Enhanced Data Portal and Report Landing Page

In previous versions of these reports, county-level data for all scenarios and all years were made available to end users at https://bioenergykdf.ornl.gov. An enhanced data portal for this report is available at https://bioenergykdf.ornl.gov/bt23-data-portal providing data selection, visualization, and access. The data portal is designed as online companion material complementary to this report. Full datasets (i.e., intervening years) are available upon request. A guided report orientation is available at www.energy.gov/eere/2023-billion-ton-report.html.

1.2.4 Renewable Fuel Standard Qualification of Resources

Because this report is policy agnostic and end-use agnostic, resources evaluated in this report are not constrained to those included in the Renewable Fuel Standard (RFS) of the Energy Independence and Security Act. However, stakeholder feedback indicated interest in understanding which resources may qualify for the RFS. Types and quantities of biomass resources included in this report that qualify for the RFS as of 2023 are shown in Table 1.3. For qualification status, readers are referred to Table 1 to § 80.1426—Applicable D Codes for Each Fuel Pathway for Use in Generating RINs.[1]

[1] Available at https://www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-80/subpart-M/section-80.1426.

Table 1.3. RFS Qualification Status of Biomass Resources in the Mature-Market Medium Scenario, Excluding Currently Used Resources; Algae Resources Are Included from the Emerging Scenario.

For qualification status, readers are referred to Table 1 to § 80.1426—Applicable D Codes for Each Fuel Pathway for Use in Generating RINs at www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-80/subpart-M/section-80.1426.

Qualified	BT23 Feedstock	RFS Feedstock	Approved Pathway (2023)	Annual Tons (Millions)
Yes	Switchgrass	Switchgrass	K, L, N	230
Yes	Corn stover	Crop residue	E, K, L, M	159
Yes	Miscanthus	Miscanthus	K, L, N	110
Yes	Microalgae	Algae	F, H	170
Yes	Macroalgae	Algae	F, H	80
Yes	Pennycress	Pennycress, non-cellulosic components of annual cover crops	F, H, K, L, M, P	23
Yes	Animal manure	Biogas from agricultural digesters	Q, T	21
Yes	Wheat straw	Crop residue	E, K, L, M	18
Yes	Hardwood, upland small-diameter trees	Pre-commercial thinnings	K, L, M	13
Yes	Food waste	Biogas from separated municipal solid waste (MSW) digesters, cellulosic portions of separated food waste, non-cellulosic portions of separated food waste	P, Q, T	12
Yes	Hardwood, lowland small-diameter trees	Pre-commercial thinnings	K, L, M	11
Yes	Wastewater sludge	Biogas from municipal wastewater treatment facility digesters	Q, T	9.5
Yes	Clean urban wood	Biogas from separated MSW digesters, separated yard waste	K, L, M, Q, T	9.4
Yes	Yard trimmings	Separated yard waste	K, L, M	8.0
Yes	Forest waste, human generated	Slash	K, L, M	7.5
Yes	Softwood, planted small-diameter trees	Pre-commercial thinnings	K, L, M	6.8
Yes	Softwood, natural logging residues	Slash	K, L, M	6.1

Qualified	BT23 Feedstock	RFS Feedstock	Approved Pathway (2023)	Annual Tons (Millions)
Yes	Cotton field residues	Crop residue	E, K, L, M	4.8
Yes	Pruning residues, non-citrus	Tree residue, crop residue	E, K, L, M	4.2
Yes	Carinata	Carinata, non-cellulosic components of annual cover crops	F, G, H, I, P	4.2
Yes	Hardwood, lowland logging residues	Slash	K, L, M	4.0
Yes	Softwood, natural small-diameter trees	Pre-commercial thinnings	K, L, M	3.7
Yes	Hardwood, upland logging residues	Slash	K, L, M	3.6
Yes	Biomass sorghum	Crop residue	E, K, L, M	3.5
Yes	Rice straw	Crop residue	E, K, L, M	3.3
Yes	Pruning residues, tree nuts	Tree residue, crop residue	E, K, L, M	2.3
Yes	Softwood, planted logging residues	Slash	K, L, M	2.8
Yes	Mixedwood logging residues	Slash	K, L, M	2.8
Yes	Cotton gin trash	Crop residue	E, K, L, M	2.1
Yes	Pruning residues, citrus	Tree residue, crop residue	E, K, L, M	2.0
Yes	Fats, oils, and grease (FOG), animal fats	FOG	F, H	1.7
Yes	FOG, brown grease	FOG	F, H	1.4
Yes	Sorghum stubble	Crop residue	E, K, L, M	1.4
Yes	Rice hulls	Crop residue	E, K, L, M	1.3
Yes	FOG, yellow grease	FOG	F, H	1.0
Yes	Energy cane	Energy cane	K, L, N	0.6
Yes	Barley straw	Crop residue	E, K, L, M	0.5
Yes	Camelina	Camelina sativa oil	F, H, I	0.3
Yes	Mixedwood small-diameter trees	Pre-commercial thinnings	K, L, M	0.2
Yes	Oats straw	Crop residue	E, K, L, M	0.01

Qualified	BT23 Feedstock	RFS Feedstock	Approved Pathway (2023)	Annual Tons (Millions)
No	Paper and paperboard			84
No	Plastics			49
No	Willow			40
No	Textiles			14
No	Eucalyptus			8.6
No	Rubber and leather			6.6
No	Poplar			5.4
No	Softwood, processing residues	Pre-commercial thinnings and tree residue		2.2
No	Hardwood, processing residues	Pre-commercial thinnings and tree residue		0.6
No	Pine			0.01

1.3 Sustainability Constraints

As with previous versions of this report, supplies reported here are not total resources "in the field," but rather a subset of resources that could be available within specified economic and environmental sustainability constrains. These environmental constraints are applied to agricultural and timberland resources. The constraints are intended to indicate potential resource availability with limited risk of unintended environmental impacts (e.g., soil erosion, overharvesting). Deviation from these sustainability constraints in the future could lead to adverse environmental consequents, such as overharvesting leading to soil erosion. An analysis of the biomass supply impacts of relaxing these constraints and associated risks is provided in Chapter 6. This subsection provides an overview of modeling constraints used in this report and risks of deviating from these constraints in future practices.

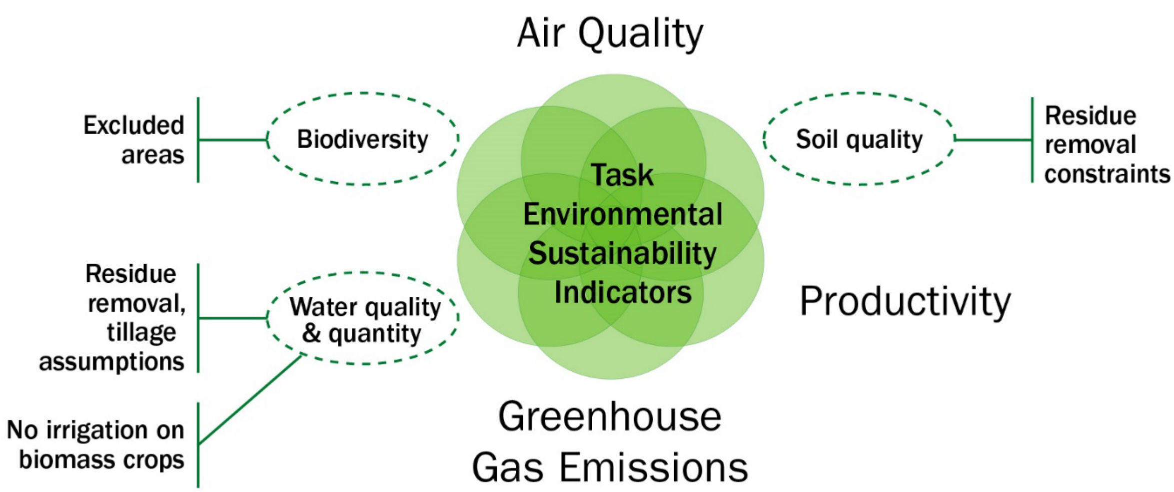

Figure 1.2. Sustainability constraints and sustainability indicator categories (green dashed circles) implemented in this report

1.3.1 Example Sustainability Constraints and Assumptions in the Agricultural Model

Sustainability constraints are employed in the Policy Analysis System Model (POLYSYS), which simulates the U.S. agriculture sector (as illustrated in Chapter 5, Figure 5.5). Only current agricultural land area—including land cover categories of permanent pasture, cropland pasture, and cropland, as classified in the 2022 USDA cropland data layer—can be used for energy crops (Table 1.4). A major assumption is that nonagricultural areas such as forestlands are not allowed to transition to agriculture; the agricultural land base is constant.

POLYSYS simulations used for this report fulfill projected primary demands for conventional crops (e.g., corn, soy, cotton, wheat, rice). These conditions are intended to address "food vs. fuel" concerns by estimating the amount of additional biomass that can be supplied for bioenergy or bioproducts beyond what is required to meet future demands for food, feed, fiber, and exports. Many global biomass resource assessments exclude agricultural lands from production for food security reasons (WBGU 2009; van Vuuren, van Vliet, and Stehfest 2009; Beringer, Lucht, and

Schaphoff 2011), but this report seeks to quantify the inevitable economic interactions among competing crop alternatives.

Most sustainability assumptions and constraints in POLYSYS relate to tillage, residue removal, and irrigation (Table 1.4). Good management practices related to tillage and residue removal maintain or promote soil quality and water quality, and they relate to the long-term productive capacity of soils (Li et al. 2019). Irrigation constraints protect water availability for other uses.

Table 1.4. Sustainability Assumptions and Constraints for Agricultural Resources. Most Have Been Included in POLYSYS Assumptions for the Last 15 Years.

Sustainability Assumption or Constraint	Sustainability Category	Implementation
1. Crop residue removal based on wind and water erosion estimates and soil carbon loss	Soil quality, water quality	Residue removal tool used to estimate retention coefficients
2. No residue removal for soy	Soil quality, water quality	Management assumption
3. Acceptable residue removal different for reduced and no till	Soil quality, water quality	Residue removal tool to estimate retention coefficients
4. Multi-county Natural Resources Conservation Service crop management zones (e.g., tillage assumptions)	Soil quality, water quality	Spatially explicit rotation and management assumptions
5. Irrigated cropland or pasture excluded	Water quantity	Excluded land area
6. No supplemental irrigation of energy crops	Water quantity	Management assumptions
7. No transition of nonagricultural lands, including forest and native grassland, to energy crops, cropland, or grazing	GHG emissions, biodiversity	Excluded land area
8. Energy crops on all pastureland assume management-intensive grazing costs	Food	Economic model
9. Fulfillment of projected needs for food, feed, forage, and fiber	Food	Economic model meets projected conventional demands from extended 2023 USDA Baseline Projection

1.3.2 Example Sustainability Constraints and Assumptions in the Forestry Model

Sustainability constraints for forest residue removal focus on the objectives of maintaining site productivity, maintaining habitat, controlling erosion, maintaining nutrients, and mitigating nutrient deficiencies (Table 1.5). To reduce concerns about potential deforestation, harvesting intensity was limited. In this report, the forestry model was not limited to Class 2 tree stands (i.e., less than 11-inch diameter at breast height [DBH]); however, at a reference biomass price of $70 per dry ton, no trees greater than Class 1 are included in modeled solutions for biomass. The minimum residue retention is 30% for clearcut lands, with no minimum for thinned forest. All stands are assumed to replant or regenerate in the same stand type (e.g., natural hardwoods regenerate back to natural hardwood forests). Additional biomass from forest fuel treatments is available but not modeled in ForSEAM (see Byproducts of Fire-Focused Management case study in chapter 4).

Table 1.5. Sustainability Assumptions and Constraints for Timberland Resources Included in Forest Sustainable and Economic Analysis Model (ForSEAM) Runs

Sustainability Assumption or Constraint	Sustainability Category	Implementation
Growth exceeds harvests of conventional and biomass harvests (state level) (removal less than 2014 base year harvest plus annual growth that occurs on remaining stands in each state)	Growth and yield	Management assumptions
Harvest costs assume best management practices	Growth and yield	Management assumptions
Leave at least 30% of logging residues in clearcut stands	Soil quality	Excluded land area
No logging residues removed on slopes >40%, except where cable systems are in use (Northwest United States)	Soil quality	Excluded land area
No biomass removal in wet areas to avoid soil compaction	Soil quality	Excluded land area
Annual harvesting intensity for whole trees limited to 5% of timberland area in ForSEAM region	Biodiversity	Management assumption
No production in administratively reserved forestlands, such as wilderness areas and national parks	Biodiversity	Excluded land area
No production on lands that are more than 0.5 miles from existing road systems	Biodiversity	Excluded land area
Fragile, reserved, protected, and environmentally sensitive forestland excluded	Biodiversity	Excluded land area

1.3.3 Risk of Deviation from Sustainability Constraints and Binding Analyses

Analyses in this report include economic and environmental sustainability constraints. The economic constraints can be considered self-administering because they include costs incurred by the biomass producer in the near term. However, there may be market conditions where producers have an economic incentive to deviate from environmental constraints included in this report. To assess risk of future practices deviating from key environmental sustainability constraints, we relaxed these constraints to determine where economic factors could drive production beyond what is deemed environmentally sustainable. Results of this analysis, as well as a summary of typical carbon intensity values, are provided in Chapter 6.

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U.S. DEPARTMENT OF ENERGY
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Chapter 02 Biomass Currently Used for Energy and Coproducts

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2 Biomass Currently Used for Energy and Coproducts

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This report and supporting documentation, data, and analysis tools are available online:

Report landing page: https://www.energy.gov/eere/bioenergy/2023-billion-ton-report-assessment-us-renewable-carbon-resources

Data portal: https://bioenergykdf.ornl.gov/bt23-data-portal

Summary

- 342 million tons of biomass were used for energy and bio-based chemicals in 2022. Corn grain for biofuels and forestry/wood and wood waste for heat and power remain top bioenergy sources. Biomass consumption highlights in 2022:[1]
  - 162 million dry tons of agricultural biomass.
  - 144 million dry tons of forest and woody biomass.
  - 37 million dry tons of biomass from waste resources.
- Trends in biomass energy production and consumption since BT16 Volume 1:[2]
  - Total biomass energy production in all 50 U.S. states decreased by approximately 0.5%. Total biomass energy consumption decreased by approximately 5.5% from the 365 million dry tons of total biomass consumption in BT16 Volume 1 but has been trending upward since 2020.
  - Biofuels increased biomass consumption by approximately 14% (from 127 to 146 million dry tons of feedstock).
  - Woody biomass energy consumption fell 25% (from 171 to 144 million dry tons of feedstock), and waste energy consumption fell 10% (from 41 to 37 million dry tons of feedstock).

[1] See Table 2.6 for more comprehensive biomass consumption data.
[2] Comparing biomass energy usage in 2014 (BT16 Volume 1 reporting year) to 2022 (BT23 reporting year).

2.1 Introduction

This chapter reviews primary domestic energy production and consumption; quantifies biomass as a feedstock for energy uses in all 50 U.S. states; provides details on biomass currently used to produce biomass-based transportation fuels, fuels for heat and power generation, and bio-based coproducts; and discusses emerging sources of bioenergy. It compares current consumption to the historical rates included in BTS, BT2, and BT16 Volume 1 (DOE 2005, 2011, 2016). The following chapters in this report discuss primary uses of biomass for sectors other than power production, heat generation, and transportation and offer estimates of the future potential of these uses.

2.2 Primary Energy Consumption

Primary energy consumption across all sectors is from the 2023 U.S. Energy Information Administration (EIA) Annual Energy Outlook (AEO) (EIA 2023a). All energy consumption comparisons in this chapter compare 2022 to the 2014 values that were reported in the 2016 Billion-Ton Report, based on the 2015 Annual Energy Outlooks, unless explicitly stated otherwise. Primary energy consumption is presented in units of quadrillion (10^{15}) British thermal units (Btu), or quads. Million Btu are expressed as MMBtu, and trillion Btu are expressed as TBtu. For perspective, 1 barrel (42 gallons) of crude oil produced in the United States contains about 5,691,000 Btu (5.69×10^6 Btu), and 1 quad equals about 176 million barrels of oil.

Primary energy consumption in the United States has decreased by 0.5% (from 95.3 quads to 94.8 quads) since 2014. At the time of publication of BT16 Volume 1, the total energy consumption was reported at 98.3 quads, but the EIA has since revised energy consumption estimates to match international formats more closely and update reporting methodology for current conditions (EIA 2023e, Appendix E). Consumption peaked at 97.4 quads in 2018, followed by a decline in total primary energy consumption in 2020 and 2021, primarily driven by reductions in fossil fuel use during the COVID-19 pandemic (Figure 2.1). From 2014 to 2022, coal consumption decreased approximately 45% (from 18.0 quads to 9.8 quads), and natural gas consumption grew about 21.9% (from 27.4 quads to 33.4 quads) as coal-fired power generation was phased out and replaced with renewables and natural gas.

Since 2014, total renewable energy consumption has risen by 19% (from 6.8 quads to 8.1 quads) (Figure 2.2), while fossil energy consumption decreased by about 2% (from 80.0 quads to 78.5 quads). In 2022, biofuels were the largest single category of renewable energy with 30% of total renewable energy consumption (2.4 quads), followed by wood energy at 24.5% (2.0 quads), wind at 18.3% (1.5 quads), hydropower at 11.1% (0.9 quads), solar at 9.4% (0.8 quads), waste at 5.1% (0.4 quads), and geothermal power at 1.5% (0.1 quads). Growth in renewable energy consumption was driven by increases in the consumption of wind (140%, 0.9 quads) and solar energy (373%, 0.6 quads). Biomass-based renewable energy constituted 60% (4.8 quads) of the total renewable energy consumption in 2022.

The following sections explain current bioenergy consumption, broken into biofuels and heat and power. Additional discussion of waste resource consumption is described in more detail in Chapter 3: Waste Resources and Byproducts.

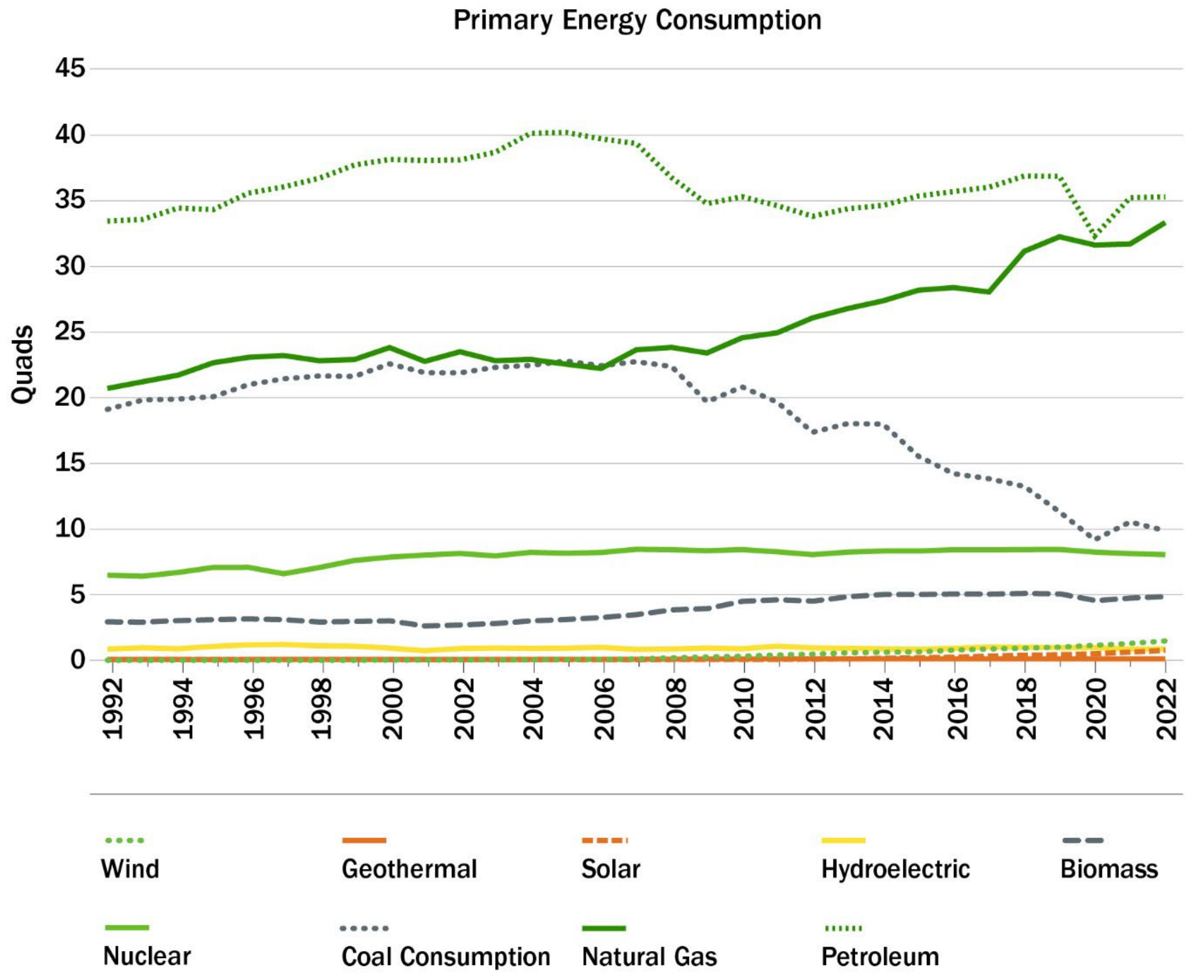


Figure 2.1. Primary energy consumption by source (1992–2022).

Source: (EIA 2023e, Table 1.3)

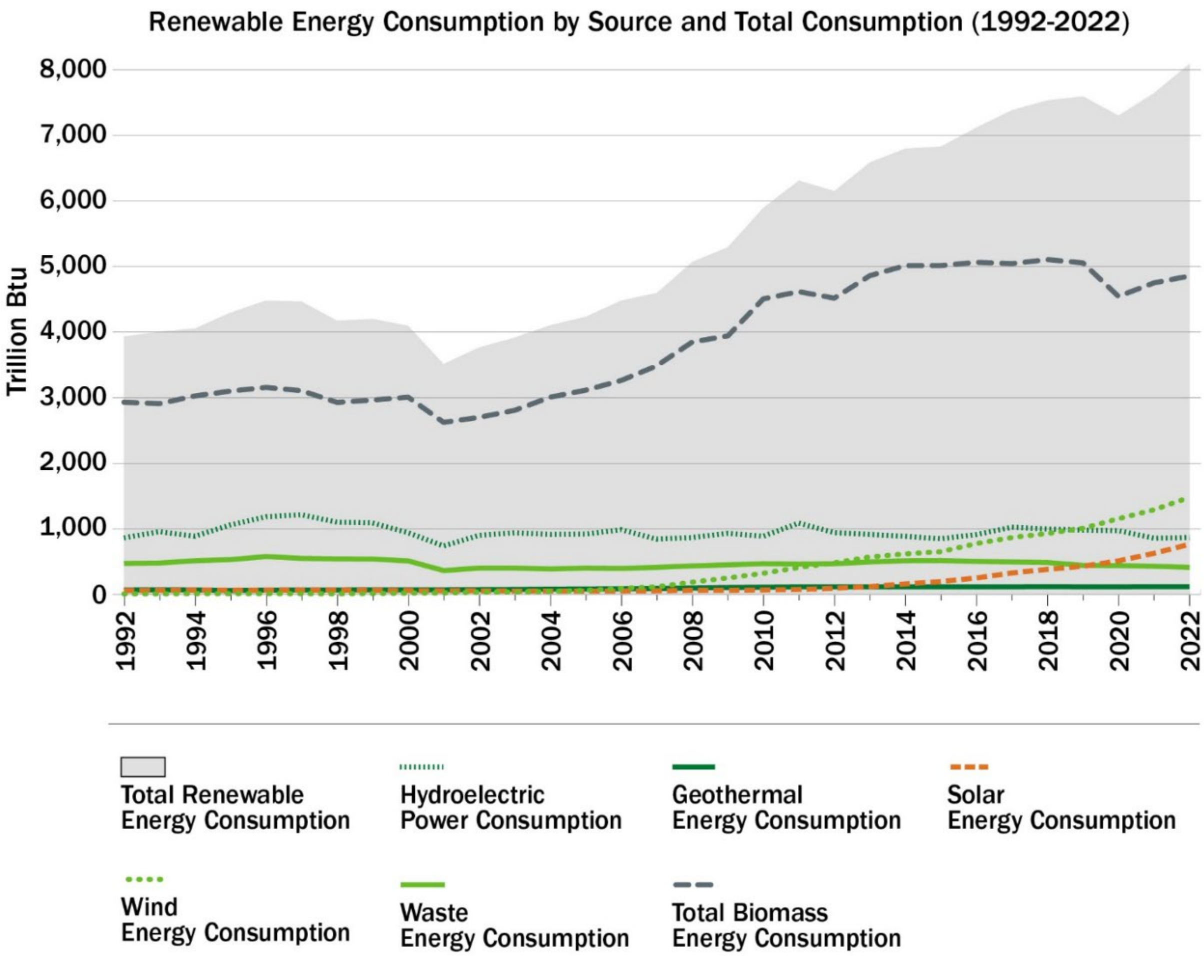


Figure 2.2. Primary renewable energy consumption by source and total consumption (1992–2022).

Source: *(EIA 2023e, Table 10.1)*

2.3 Transportation Fuels

The following sections discuss current biofuel production, describe the references and assumptions used to estimate the amount of biomass resources consumed in converting feedstocks to biofuels, and discuss trends in usage. The data on biofuel production for this report come from three sources: EIA (EIA 2023a), U.S. Environmental Protection Agency (EPA) renewable identification numbers (RINs) (EPA 2023c, 2024c), and the U.S. Department of Agriculture (USDA) (USDA 2023b).

EIA's reporting on biofuels includes fuel ethanol, biodiesel, renewable diesel, renewable heating oil, renewable jet fuel, renewable naphtha, renewable gasoline, biobutanol, and "other" biofuels and biointermediates. In 2022, the EIA reported that 18.7 billion gallons of biofuels were produced in the United States, and about 17.6 billion gallons were consumed (EIA 2022). In the same year, the EIA also reported that renewables accounted for 5.7% of the U.S. transportation sector's energy consumption (EIA 2023e, Table 2.5).

Corn Ethanol

Technological advancements have revolutionized the agricultural landscape, enabling farmers to reduce resource usage and costs and promote environmental stewardship. One such advancement is the significant reduction in fertilizer use, a crucial step toward cost efficiency, carbon reduction, and responsible ecological practices. Minimizing fertilizer application reduces costs and lessens the carbon intensity of crops. Innovative technologies enable precise and efficient fertilizer application, matching the exact needs of crops.

Ethanol production has played a pivotal role in enhancing the social and economic sustainability of rural communities. The establishment of ethanol biorefineries has created a steady and dependable market for grain. This has brought a new generation to farming and rejuvenated communities. Jobs and prospects offered by ethanol facilities strengthen agricultural economies, providing many positive influences on rural life.

Crops serve as a carbon sink, capturing CO_2 from the atmosphere. During CO_2 fermentation, some of this recycled CO_2 can be harnessed for various applications, such as carbon capture and storage, where it can be compressed or stored underground. The convergence of lower input costs, improvement of ethanol production, and CO_2 management showcases a sector poised to contribute to a sustainable and prosperous future.

Photo by Jan tenBensel, Nebraska Ethanol Board

The EPA reports public data for RINs generated as part of the RFS program for aggregated data on biofuel production and the feedstocks used for RIN generation (EPA 2023c). RINs (an energy-equivalent unit containing 77,000 Btu) are reported in terms of domestic or foreign/import production, and therefore may not match the EIA consumption numbers (Table 2.1). Some changes in the RIN reporting from 2014 used in BT16 Volume 1 include category name changes from biogas, compressed natural gas (CNG), and liquefied natural gas (LNG) to add the word "renewable" to the category: renewable CNG, renewable LNG, and renewable liquefied petroleum gas (LPG). This reporting converts RINs into RIN-gallons or gallons (the actual volume of biofuel). The total RIN-reported fuel volume domestically produced in 2022 was 18.2 billion gallons. The USDA also has primary data on many feedstocks used for biofuel production. For the EPA RINs and EIA data, domestic biofuel production in the United States grew 16.9%–18.5% from the 2014 reporting values, with significant increases in renewable diesel, renewable jet fuel/sustainable aviation fuel (SAF), and biogas.

Table 2.1 compares the 2014 and 2022 EIA and EPA RIN biofuel production volumes. Table 2.2 calculates the tons of feedstocks consumed during biofuel production for the RIN reporting year, following a similar methodology to that in Section 2.3 of BT16 Volume 1 (DOE 2016).

Table 2.1. Comparison of EPA RINs and EIA Bio-Based Fuel Production in 2014 and 2022 in the Current Bioeconomy (Million Gallons)

	Ethanol (Including Cellulosic)	Gasoline Blendstock/ Naphtha	Biodiesel	Renew. Diesel	Renew. Jet (SAF)	Biogas, Renew. Natural Gas (RNG)/Renew. LNG, Renew. LPG	Other	Total
2014 EIA totals	14,313	-	1,279	159	-	-	12	15,763
2022 EIA totals	15,361	-	1,622	1,499	-	-	203	18,685
% change EIA	7.4	0.0	26.8	833	0.0	0.0	1,591	18.5
2014 EPA totals	14,047	12.1	1,307	159	0.78	53	-	15,578
2022 EPA totals	14,433	63.4	1,620	1,452	7.9	636	-	18,211
% change EPA	2.7	424	23.9	813	912	1,100	0.0	16.9

Table 2.2. Bio-Based Fuel Production in the Current Bioeconomy (Million Gallons) for 2022 EPA RINs Data on Biofuels Produced Domestically

	Conv. Ethanol	Cellulosic Ethanol	Biodiesel	Renew. Diesel	Renew. Jet	Biogas, Renew. CNG, Renew. LNG, Renew. LPG	Naphtha, Gasoline Feedstock	Total
Cellulosic biomass – agricultural residues	-	1.40	-	-	-	-	-	1.4
Starch – corn	14,201	-	-	-	-	-	-	14,201
Sorghum – grain	76.7	-	-	-	-	-	-	76.7
Soybean oil	-	-	980	250	-	-	-	1,230
Canola oil	-	-	258	-	-	-	-	258
Biogenic waste fats, oils, and greases (FOG)	-	-	293	645	-	-	-	938
All other feedstock biodiesel/renewable diesel [a]	-	-	-	557	-	-	-	557
All other feedstock renewable jet	-	-	89.3	-	7.89	-	-	97.2
Non-cellulosic portions of separated food wastes	-	-	-	-	-	-	46.6	46.6
All other feedstocks naphtha	-	-	-	-	-	-	16.7	16.7
All other ethanol	152	-	-	-	-	-	-	152
Biogas from landfill [b]	-	-	-	-	-	481 [c]	-	481
Biogas from anaerobic digestion [b]	-	-	-	-	-	131	-	131
Biogas from municipal wastewater digesters [b]	-	-	-	-	-	19.4	-	19.4
Other for LPG [b]	-	-	-	-	-	4.4		4.4
Total	14,430	1.4	1,620	1,452	7.9	636	63.2	18,210

[a] Includes mixed feedstocks.
[b] Gases are reported in RIN-gallons (77,000 Btu/RIN-gallon).
[c] Estimated from total domestic RINs.

Table 2.3. Biomass Consumed for Fuel Production in the Current Bioeconomy (Million Bioenergy-Equivalent Dry Tons) Using a Combination of EPA and USDA Feedstock Data

Biomass Resource Category	Ethanol (Including Cellulosic)	Gasoline Blendstock/ Naphtha	Jet/ Aviation Fuels	Biodiesel/ Renew. Diesel	Biogas, Renew. CNG, Renew. LNG, Renew. LPG	Total
Agricultural residue	0.013	-	-	-	-	0.01
Corn grain	123.4	-	-	-	-	123.4
Vegetable oils	-	-	-	7.3	-	7.3
Other FOG	-	-	-	3.8	-	3.8
Feed for gasoline blendstock/naphtha	-	0.3	-	-	-	0.3
Feedstocks for renewable jet	-	-	0.01	-	-	0.01
Biogas from anaerobic digestion	-	-	-	-	0.8	0.8
Landfill gas	-	-	-	-	6.7 [a]	6.7
Algae	-	-	-	-	-	-
Total	123.4	0.3	0.01	11.1	7.5 [b]	142.3

[a] Estimated from total domestic RINs.
[b] Also includes biogas from municipal wastewater treatment facility digesters and others for LPG.

The following sections discuss the individual fuel pathways and feedstocks.

2.3.1 Fuel Ethanol

The EIA reported 15.4 billion gallons of fuel ethanol production (15.1 billion gallons when excluding denaturant) and 14.0 billion gallons of fuel ethanol consumption in the transportation sector, where most fuel ethanol is blended into finished motor gasoline (EIA 2023e, Table 10.3; USDA 2023b). The EPA generated RINs for 14.4 billion RIN-gallons of conventional ethanol and 1.5 billion RIN-gallons of cellulosic ethanol (EPA 2023c), and records show 1.3 billion gallons of ethanol were exported in 2022 (Renewable Fuels Association 2023). BT16 Volume 1 estimated that 14.1 billion gallons of ethanol were produced in 2014.

Feedstock for ethanol production is primarily corn grain (98% feedstock tonnage), with contributions from sorghum, soybean oil, and unlisted sources. Using the methodology described in multiple sources (Irwin 2023; Jayasinghe and Miller 2017), an average yield of 2.9 gallons of ethanol per bushel of corn was calculated from the ethanol production information provided by the EIA and bushels of corn provided for fuel ethanol production from the National Agricultural Statistics Service reports on corn grain and coproducts milling (EIA 2023f; National Agricultural Statistics Service 2023). Ethanol production consumed an estimated 123 million dry tons of corn grain, assuming 56 lbs. per bushel and 15.5% moisture content (EIA 2023d, Table 2a; USDA 2023a). BT16 Volume 1 estimated that corn grain was 100% of ethanol feedstock, and 119.6

million dry tons were consumed in 2014 (DOE 2016). Corn grain losses in the supply chain for biofuel production are estimated to total 14.5 million dry tons.

The EIA estimates that 1.7 million tons of sorghum grain were consumed for ethanol production in 2022 (EIA 2023d, Table 2a). Using the generated RIN-gallon estimates and a yield of 80 gallons per dry ton (Amosson et al. 2011), 0.96 million tons of sorghum were consumed for ethanol production.

Cellulosic ethanol grew from 0.0007 billion gallons in 2014 to 0.0014 billion gallons in 2022, per the EPA's RINs reporting (EPA 2024b). The 2022 RINs feedstock report indicates that this production used "Cellulosic Biomass – Agricultural Residues." The cellulosic ethanol volume is estimated to be derived from 0.013 million tons of agricultural residue using the 2022 EPA RINs feedstock volume data and an assumed yield of 109.2 gallons per dry ton (Wang et al. 2012).

2.3.2 Biodiesel and Renewable Diesel

Bioderived diesel fuels include biodiesel and renewable diesel. ASTM International standard D6751 defines biodiesel as a fatty acid methyl ester (ASTM International 2023). Renewable diesel is processed to be chemically equivalent to petroleum-derived diesel fuels and meets ASTM D975 specifications for petroleum in the United States (ASTM International 2022). Biodiesel is the second-largest type of biofuel behind fuel ethanol, and renewable diesel is a close third.

In 2022, the EIA reported that 1.62 billion gallons of biodiesel were domestically produced and 1.66 billion gallons of biodiesel consumed, which makes up 8.2% of biofuel consumption (EIA 2023e, Tables 10.4a and 10.2c). For the 2022 RINs reporting year, 1.62 billion gallons of biodiesel were produced (EPA 2023c). Biodiesel production consumed 3.6 million tons of soybean oil (EIA 2023d, Table 2c). Soybean oil generated more than 50% of all biodiesel RIN credits, followed by biogenic waste FOG at 16% and canola oil at 14%.[3]

The EIA reported that renewable diesel increased to represent 7.8% of biofuel consumption in 2022 (EIA 2023e, Tables 10.4b and 10.2c). In 2022, the EIA reported 1.5 billion gallons of renewable diesel were produced domestically, and 1.7 billion gallons were consumed (EIA 2023e, Table 10.4b). The EPA generated RINs for 1.5 billion RIN-gallons in the same year (EPA 2023c). In 2022, consumption outpaced production by about 0.02 billion gallons per month (14%) (EIA 2023e, Table 10.4b). The EIA reports 1.7 million tons of soybean oil was consumed in renewable diesel plants, accounting for 32% of the total soybean oil used for biodiesel and renewable diesel production combined (EIA 2023d, Table 2c). BT16 Volume 1 estimated that 0.16 billion gallons of renewable diesel were produced in 2014 (DOE 2016).

Bio-based heating oil also receives RIN credits but is reported as heat and power generation in this report—a change from BT16 Volume 1, which included this volume in transportation fuels.

[3] This includes imported feedstocks from the feedstock summary generation report.

2.3.3 Renewable Jet Fuel

In 2022, there were 15.8 million gallons of renewable jet fuel produced (7.89 million gallons of renewable jet fuel was reported for EPA RINs domestic production and 7.93 million gallons as foreign) (EPA 2023c), which is nearly 10 times more than the total production of about 0.8 million gallons in 2014 (Alternative Fuels Data Center 2023; U.S. Government Accountability Office 2023). While this volume is still moderately low compared to biodiesel and renewable diesel, it represents a sharp increase in production in a relatively short time frame. At the time of this report, there was only one North American producer of commercial renewable jet fuel, with a facility in California based on the HEFA (hydrotreated esters and fatty acids) process using agricultural fats and waste oils (Alternative Fuels Data Center 2023). Using the same waste oil yield as renewable diesel at 267 gallons per ton, an estimated 0.03 million tons of feedstock created the domestic supply of renewable jet fuel that accrued these RIN credits under the category "all other feedstocks."

In 2022, DOE, the U.S. Department of Transportation, and the USDA launched a memorandum of understanding and road map to set goals for SAF production at 3 billion gallons annually by 2030 and 35 billion gallons annually by 2050 (Bioenergy Technologies Office 2023).

2.3.4 Renewable Gasoline Blendstocks and Naphthas

In 2022, the EPA reported that 63.2 million RIN-gallons of bioderived naphtha were produced, an increase from the 2014 EPA-reported volumes of 29,000 RIN-gallons of cellulosic renewable gasoline blendstock and 12 million gallons of naphtha (EPA 2023c). Most reported feedstock was listed as "Non-Cellulosic Portions of Separated Food Wastes," which comprised 74% of the RINs generated, with the remainder listed as "other."

2.3.5 Biogas

Renewable biogas includes renewable CNG (primarily methane), renewable LNG (methane), and renewable LPG. The AgSTAR database provides information on anaerobic digesters on livestock farms across the United States (EPA 2023a). The database indicated 93 dairy farms had digesters providing biogas for end use as CNG in early 2023, with additional operations producing pipeline gas. In 2022, the EPA reported the equivalent of 546 million RINs-equivalent gallons of RNG, about 74% of that derived from landfills and 23% from biogas from waste digesters. In addition, 84.1 million gallons of renewable LNG were produced, almost all of which were generated from landfills (EPA 2023c). About 4.4 million RINs-equivalent gallons of LPG were produced (EPA 2023c). Using a conversion of 1.036 MMBtu per thousand cubic feet, this would mean 71.5 billion cubic feet (BCF) of biogas from landfills, 19.5 BCF from anaerobic digesters, and 2.89 BCF from municipal wastewater treatment facilities was consumed (EPA 2023c). An additional 0.13 BCF of renewable LPG was consumed (EPA 2023c). AgSTAR reports 0.76 million tons of manure consumed for biofuel production through biogas pathways. This was not a reported resource in BT16 Volume 1 to account for an increase.

The bioenergy resources used to produce RNG and LNG for transportation from landfills are estimated using the same approach as in BT16 Volume 1: landfill gas is represented as tons of biomass by applying a conversion factor of about 0.267 lbs. per cubic foot (DOE 2016). This report converts all biogas generated to tons of biomass using the same conversion factor as landfill gas. A discussion of landfill gas for heat and power generation follows in Section 2.4.3.

2.4 Heat and Power Generation

Biomass is the United States's primary renewable source for heat and power generation, with industrial uses dominating the consumption of heat and power from biomass. Biomass contributes a small amount of overall renewable generation sources when compared to wind and solar, however its production of heat as a co-product allows for industrial uses that are distinct from other, non-combustible renewable sources. MSW, landfill gas, and woody biomass contribute to the electricity sector, and woody biomass contributes to residential and small-scale community heat and power operations. Animal manure can be collected and used as fuel in anaerobic digesters and heat to produce biogas, which can be collected and consumed for power and heat generation or flared off to remove the impact of methane from animal waste on the environment. In this chapter, we only consider facilities with operational anaerobic digesters.

EIA's *Electric Power Annual 2022* (EIA 2023b, Tables 5.5, 5.6, 5.7, and 5.8) record 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 the 2023 AEO (EIA 2023a, Table 17). The AgSTAR database provides information on anaerobic digesters on livestock farms across the United States. It reports that an additional 114 anaerobic digester operations have begun construction or entered operation since the reporting in BT16 Volume 1 (EPA 2023a).

Table 2.4 shows the inherent energy of biomass consumed for heat and power generation in the United States for 2022 across the electricity generation, industrial, commercial, and residential sectors. Table 2.5 calculates the tons of feedstocks consumed for heat and power generation across the sectors, following a similar methodology to that in Section 2.4 of BT16 Volume 1.

Heat and power generation saw a 19% net decrease in energy generated from biomass from BT16 Volume 1 (from 2,311 TBtu to 1,893 TBtu), driven by decreases in biomass resources used for both industrial and residential sectors. The industrial decrease was primarily driven by the closure of pulp and paper mills, reducing the biomass energy use in the industrial sector. Wood use in residential homes as the primary or secondary heating source also decreased.

Table 2.4. Inherent Energy of Biomass Resources Consumed for Heat and Power in 2022 (TBtu)

Biomass Category	Electricity		Industrial		Commercial		Residential		Farm Use	Total		
	E	T	E	T	E	T	E	T	Total	E	T	Total
Wood/wood waste	172	26.2	151	790	1.1	3.2	-	423	-	324	1,242	1,567
Animal manure	-	-	-	-	-	-	-	-	35.1	-	-	35.1
Biogenic MSW	56.5	3.0	0.0	0.0	52.0	9.3	-	-	-	109	12.2	121
Other waste biomass	10.4	9.1	4.9	33.4	4.5	2.6	-	-	-	19.9	45.2	65.1
Landfill gas	96.4	1.1	1.2	0.7	6.0	0.5	-	-	-	104	2.4	106
Total	335	39.4	157	824	63.7	15.6	0.0	423	35.1	556	1,302	1,893
% change from BT16	−24%	25%	−29%	−14%	74%	31%	0%	−27%	0%	−20%	−18%	−19%

Note: E = biomass consumed for electricity generation and T = biomass consumed for thermal energy output.

Table 2.5. Biomass Resources Consumed for Heat and Power in 2022 (Million Dry Tons)

Biomass Category	Electricity	Industrial	Commercial Residential	Farm Use	Total
Wood/wood waste	15.2	72.4	32.8	-	120
Animal manure	-	-	-	2.7	2.7
Biogenic MSW	6.6	-	6.8	-	13.4
Other waste biomass	2.4	4.8	0.9	-	8.1
Landfill gas	7.9	0.2	0.5	-	8.6
Total	32.1	77.3	41.1	2.7	153
% change from BT16	−5%	−17%	−17%	−74%	−18%

The following sections provide additional information on each feedstock type, noting when a conversion or efficiency factor is required to reach a resulting biomass tonnage.

2.4.1 Woody Biomass and Wood Waste

Using the EIA's *Electric Power Annual 2022*, it was reported that approximately 1.2% of U.S. annual energy consumption was from wood and wood waste (bark, sawdust, wood chips, wood scrap, and paper mill residues) (EIA 2023b, Tables 5.6d and 5.6e). The EIA's reporting estimates the tonnage and TBtu values of the incoming feedstock for heat and power generation, which was used to generate the values in this report section. When comparing the latest data, wood/wood waste electricity generation decreased from 0.4 quads in 2014 to 0.3 quads in 2022, and wood/wood waste thermal energy generation decreased from 1.5 quads in 2014 to 1.2 quads in 2022. Based on the midpoint in the range of energy contents included in EIA form EIA-923 detailing power plant fuel allowed energy ranges, an average energy content of 13 MMBtu per dry ton is assumed (EIA 2007), which results in an estimated 120.4 million dry tons of wood being consumed in 2022. Losses in the supply chain for wood/wood waste bioenergy are estimated to total 13.2 million dry tons using the same methodology as in Section 2.4.1 of BT16 Volume 1.

In BT16 Volume 1, wood pellets were reported separately, as most wood pellets were noted to be primarily for export. The latest data from the U.S. International Trade Commission noted that 9.9 million tons were exported (5%–10% moisture) (Pellet Fuels Institute 2017; Atasoy, Zhang, and Prestemon 2023), resulting in a total production of 11.6 million tons. This requires 10.5 million dry tons of timber and wood waste as feedstock for production, an increase of 38% from BT16 Volume 1. In this report, wood pellets are already included in the EIA generation report data for wood and wood waste and are not reported separately in this section. Losses in the supply chain for wood pellet energy are estimated to total 1.2 million dry tons using the same methodology as in Section 2.4.1 of BT16 Volume 1.

The decline in heat and power production from wood/wood waste energy is driven by the closure of pulp and paper mills, COVID-19 extended mill shutdowns, and extended maintenance cycles to buoy decreasing commodity prices (EIA 2023c). Table 2.4 details the breakdown of wood/wood waste by sector and energy type for heat and power.

2.4.2 Biogenic MSW

The biogenic portion of MSW not landfilled includes sludge waste, agricultural crop byproducts, and other biomass solids and liquids that can be separated and combusted for electricity and thermal energy generation. It excludes wood and wood-derived products (including black liquor) and biofuel feedstocks. The EIA estimated that 13.4 million dry tons of biogenic MSW were consumed to generate 108.5 TBtu of electricity and 12.2 TBtu of thermal energy in 2022 (EIA 2023b, Tables 5.7d and 5.7e). This is a reduction from the BT16 Volume 1 reporting of 135.8 TBtu of produced electricity and 15.2 TBtu of thermal energy. EIA's *Electric Power Annual 2022* assumes the estimates are in dry tons; using the methodology established in Section 2.4.2 of BT16 Volume 1 to estimate dry tons based on energy consumption yields a variance of less 0.1% from the reported tonnage estimates (EIA 2023b, Table 5.7c). Tables 2.4 and 2.5 summarize the biogenic MSW usage breakdown by sector and energy type for heat and power.

2.4.3 Landfill Gas

EIA's *Electric Power Annual 2022* reports the volume of landfill gas used as heat and power in the United States and reports the values in billion Btu and million cubic feet. EIA reported 216 BCF of landfill gas was consumed to produce 103.6 TBtu of electrical power and 2.4 TBtu of thermal energy in 2022 (EIA 2023b, Tables 5.6d and 5.6e). Consumption declined from the estimated 272 BCF of landfill gas used in the BT16 Volume 1 reporting, which generated 132.8 TBtu of electricity and 0.4 TBtu of thermal energy (DOE 2016). There has been a shift to producing transportation fuels from landfill gas, contributing to the decline in heat and power generation from this source (Mintz and Vos 2022). Table 2.4 details the breakdown of the usage of landfill gas for heat and power purposes by sector and energy type.

There are differences in the totals reported by the EIA and EPA for landfill gas usage, with EIA reporting that 216 BCF were consumed for heat and power, while EPA data report 334 BCF (EIA 2023b, Tables 5.6d and 5.6e; EPA 2023b). For consistency within the chapter, EIA estimates are included in this section; however, further details on the estimates from both sources are included in the appendix.[4]

In the United States, landfill gas is collected for both heat and power and used as biogas as a renewable transportation fuel, and those data are reported via RIN credits (EPA 2023c). Section 2.3.5 discusses anaerobic digester gas used for transportation fuels in the United States.

2.4.4 Anaerobic Digestion

EIA's *Electric Power Annual 2022* includes digester slurries and biogases as part of "other waste biomass" but does not segregate between the included materials, and therefore could contain overlap with this feedstock category. Approximately 55% of manure produced and collected in the United States is used for agricultural fertilizer, with an additional 4.6% going to anaerobic digestion (Milbrandt et al. 2018). The animal waste consumed in anaerobic digestion produces 40%–50% waste CO_2 and 50%–60% methane gas that can be burned to produce heat and power (EPA 2024a). Anaerobic digesters were estimated to use 1.9 million dry tons of manure in 2015 and had 264 active projects (Milbrandt et al. 2018; EPA 2023a). The 2023 reported data from the AgSTAR database show 250 active anaerobic digester projects in the United States producing heat and power energy by consuming 2.7 million dry tons of manure, an increase of 42% from BT16 Volume 1 (EPA 2023a, 2023c). Total anaerobic digester energy production (biofuel and heat and power production) increased 230% (from 1.9 to 3.5 million dry tons).

Anaerobic digestion biogas is also used to produce transportation fuels, as reported in Section 2.3.5, which is reported via calculations based on RIN credits and are not double counted here. Tables 2.4 and 2.5 summarize the breakdown of the usage of anaerobic digester gas for heat and power by sector and energy type.

2.4.5 Other Waste Biomass

In EIA's E*lectric Power Annual 2022*, "other waste biomass" for power and heat generation includes sludge waste, agricultural byproducts, other biomass solids, other biomass liquids, and other biomass gases (including digester gases, methane, and other biomass gases) (EIA 2023b, Tables 5.8d and 5.8e). It also reports the aggregate "other waste biomass" utilized for net generation in the electric utilities, independent power producers, commercial sector, and industrial sector, as was reported for landfill gas and MSW. Both the dry tons of biomass and TBtu values are estimated.

[4] Access BT23 appendices at www.energy.gov/eere/2023-billion-ton-report.html.

EIA reports a total of 8.1 million dry tons of "other waste biomass" were consumed to produce a total of 19.9 TBtu of electrical power and 45.2 TBtu of thermal energy in 2022 (EIA 2023b, Tables 5.8d and 5.8e). This is a reduction from the estimated 11.5 million dry tons consumed in the BT16 Volume 1 reporting that generated 29.4 TBtu of electricity and 62.5 TBtu of thermal energy.

Tables 2.4 and 2.5 summarize the breakdown of other waste biomass usage by sector and energy type for heat and power purposes. Chapter 3: Waste Resources and Byproducts reports several other waste resources for other uses (e.g., recycling, animal feed) that are not reported in this chapter.

2.5 Bio-Based Chemicals

The bio-based chemicals included in this section are generated as byproducts of bioenergy operations or directly compete for biomass resources with bioenergy operations. The most recent BioPreferred report (2021) reviewed the volume of biomass consumed in the bioproducts industry and estimated the same ratio between corn, soybean, and other oilseed crop processing for bioproducts as was reported in BT16 Volume 1 (Daystar et al. 2021). In 2021, 7.1 million dry tons of corn and 0.73 million dry tons of soybeans and other oilseed crops were consumed to generate starches and other bioproducts. This represents an increase from the BT16 Volume 1 reported numbers of 5.6 million dry tons for corn and 0.32 million dry tons for soybeans (Daystar et al. 2021).

2.6 Algae

Other emerging biomass-to-energy sources are noted in Chapter 7: Emerging Resources. At the time of this report in 2023, algae is not a measured energy source of significance in the U.S. bioeconomy.

2.7 Summary

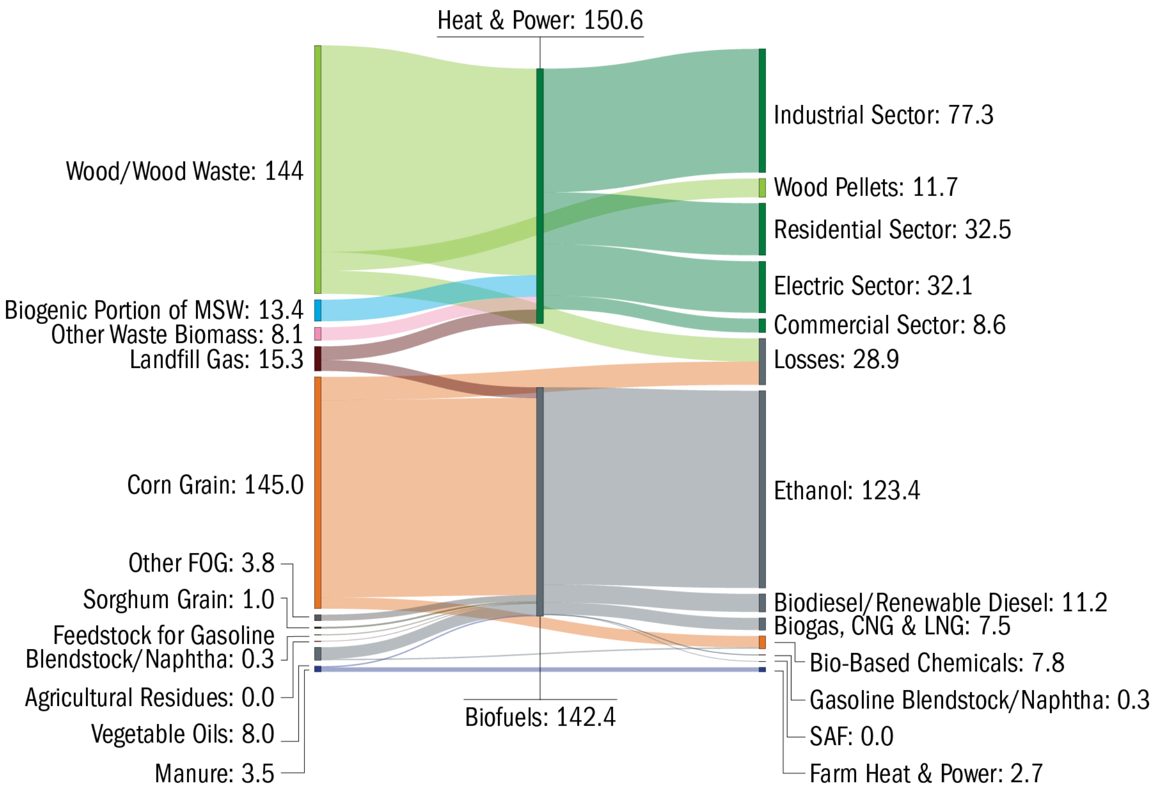
The total consumption of biomass resources for energy, including transportation, power, and heat, is reported in Table 2.6. Overall, the total biomass resources currently consumed to produce biomass-based transportation fuels and fuels for heat and power generation decreased from BT16 Volume 1 by about 18 million tons annually (6%). Biofuel production increased 19%, consuming about an additional 16 million tons of feedstock annually (11%), while the biomass used for heat and power generation fell 35 million tons per year (19%) and landfill gas usage increased 36% from BT16 Volume 1.

The flow of these resources from feedstock to end product is shown in the Sankey diagram in Figure 2.3. The primary biomass sources in the current bioeconomy remain corn grain for transportation fuel and forestry/wood and wood waste for heat and power.

Table 2.6. Total Current Consumption of Biomass for Energy Production and Bio-Based Chemicals, Including Losses (Million Bioenergy Dry Tons per Year)

Biomass Resource Category	Transportation Fuel	Heat and Power	Bio-Based Chemicals	Wood Pellets	Total Utilized Biomass
Agricultural	150	2.7	8.6	-	162
Corn grain	137	-	7.9	-	145
Sorghum grain	1.0	-	-	-	1.0
Vegetable oils	7.3	-	0.7	-	8.0
Other FOG	3.8	-	-	-	3.8
Feed for gasoline blendstock/naphtha	0.3	-	-	-	0.3
Agricultural residues	0.01	-	-	-	0.01
Manure	0.8	2.7	-	-	3.5
Forestry/wood	-	134	-	9.9 [a]	144
Wood/wood waste	-	132	-	-	132
Wood pellets	-	1.7	-	9.9 [a]	11.6
Energy crops	-	-	-	-	-
Herbaceous energy crops	-	-	-	-	-
Woody energy crops	-	-	-	-	-
MSW/other wastes	-	21.5	-	-	21.5
Biogenic portion of MSW	-	13.4	-	-	13.4
Other waste biomass	-	8.1	-	-	8.1
Landfill gas	6.7	8.6	-	-	15.2
Algae	-	-	-	-	-
Total biomass	157	167	8.6	8.9	342
% change from BT16	11%	−19%	31%	17%	−6%

[a] Wood pellets here are the exported-only mass.



NOTE: Units in million dry tons per year equivalent

Figure 2.3. Sankey diagram of feedstock, sector consumption, and final product distribution (million dry tons per year)

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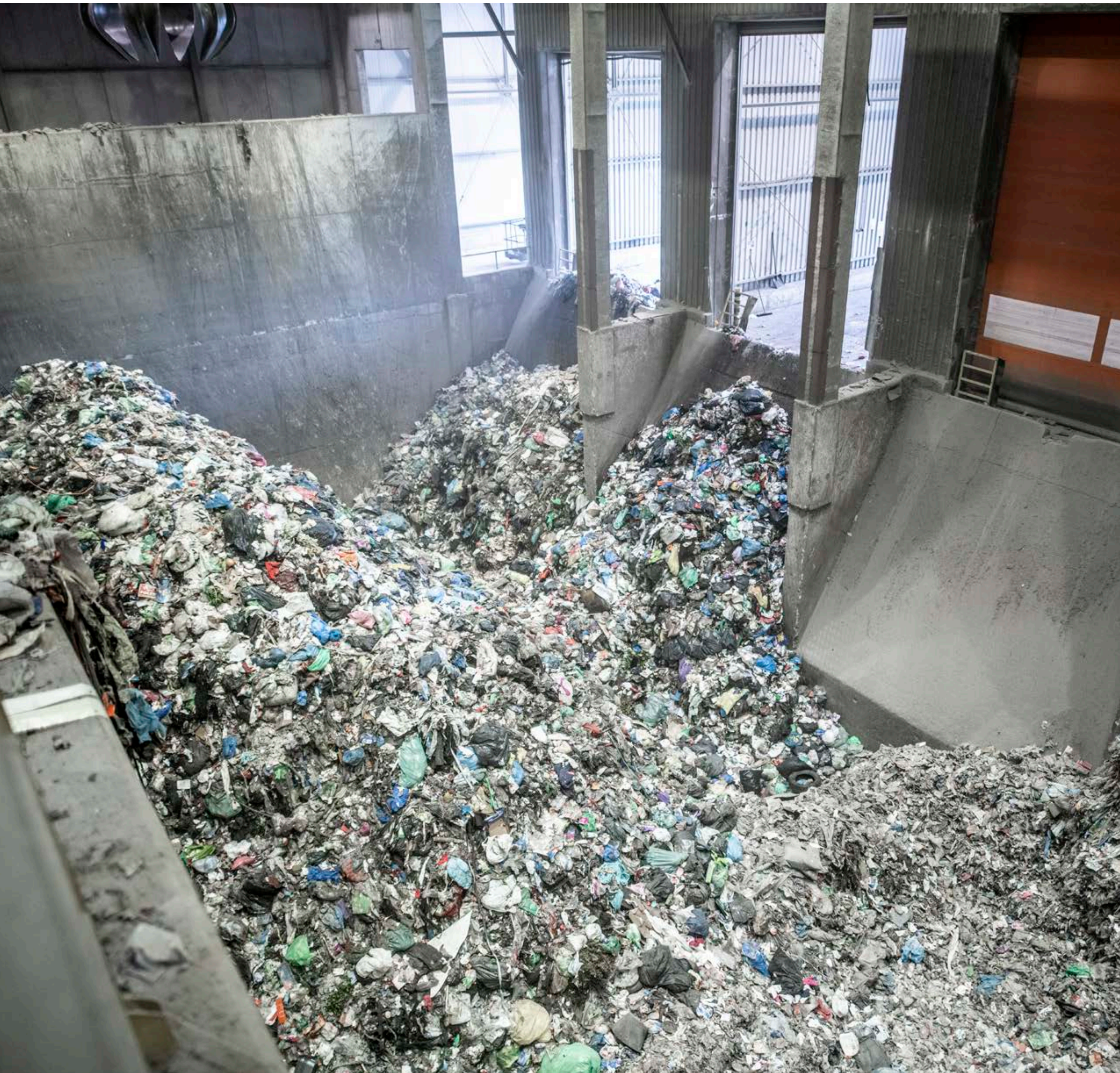
Chapter 03 | Waste Resources and Byproducts



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Summary

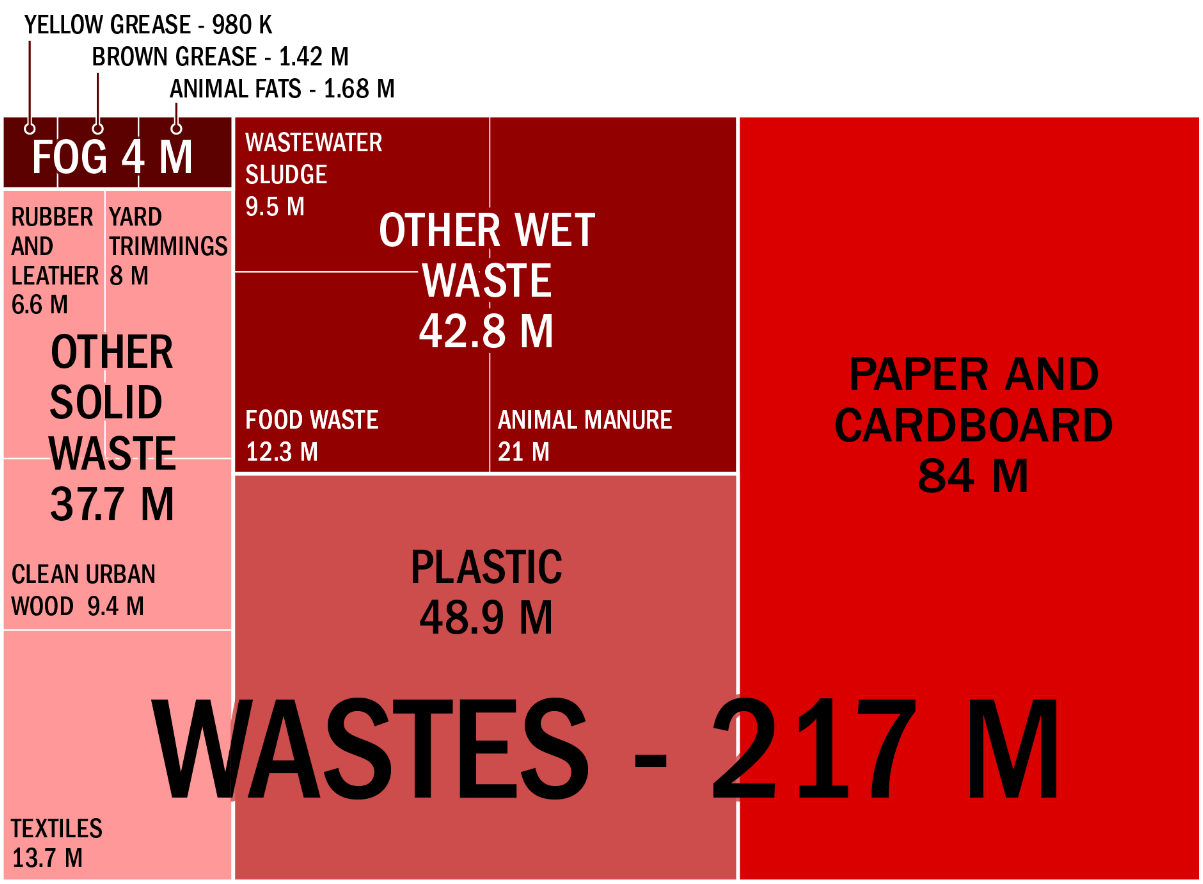


Figure 3.1. National waste resources, mature-market medium scenario, all prices

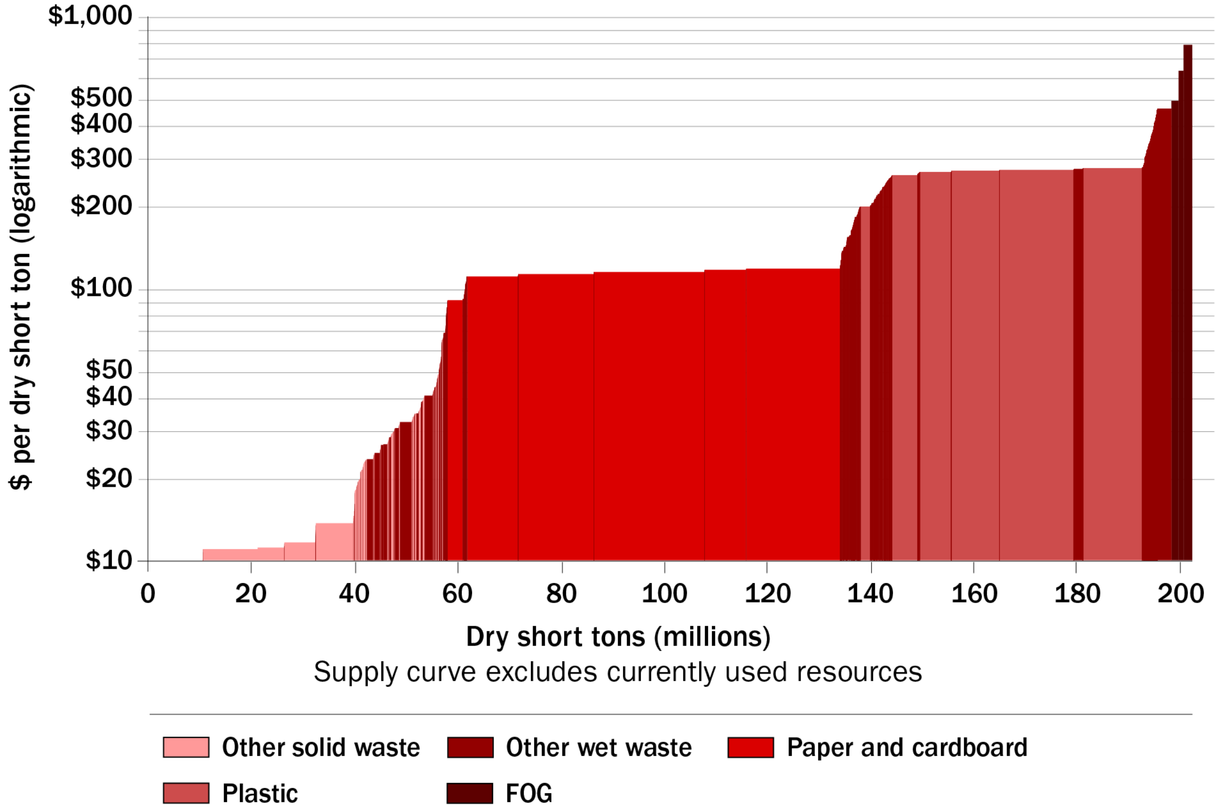


Figure 3.2. Stepwise supply curve of waste resources, mature-market medium scenario

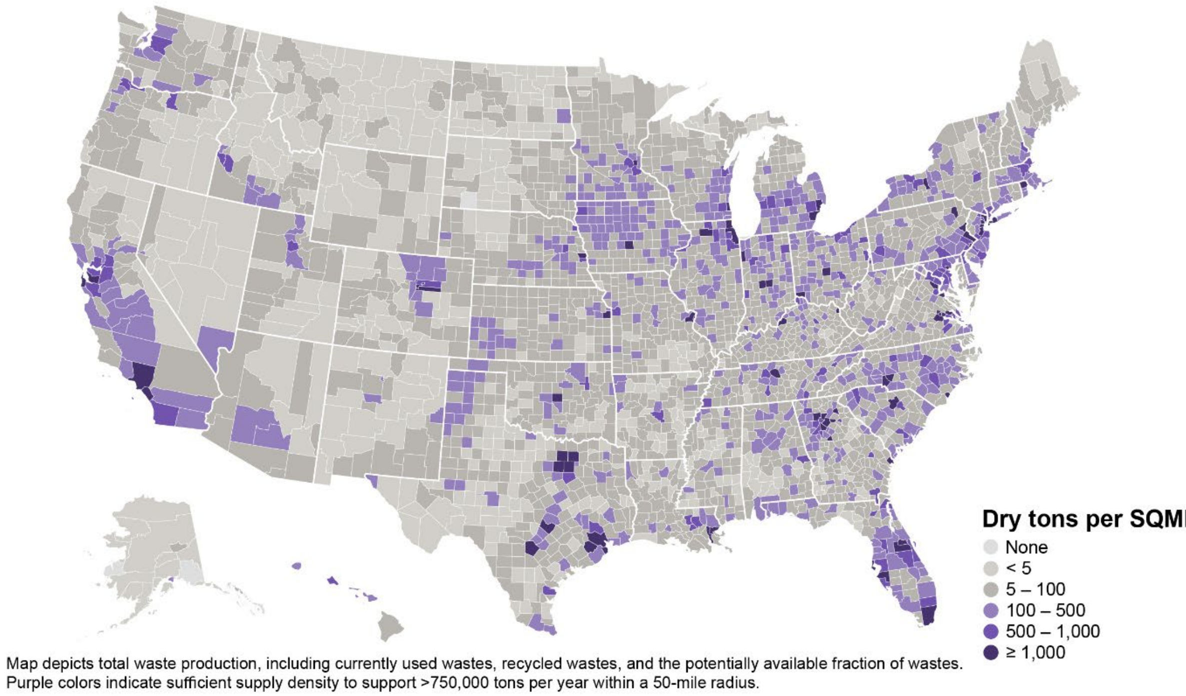


Figure 3.3. Spatial distribution of waste resources, mature-market medium scenario, all prices

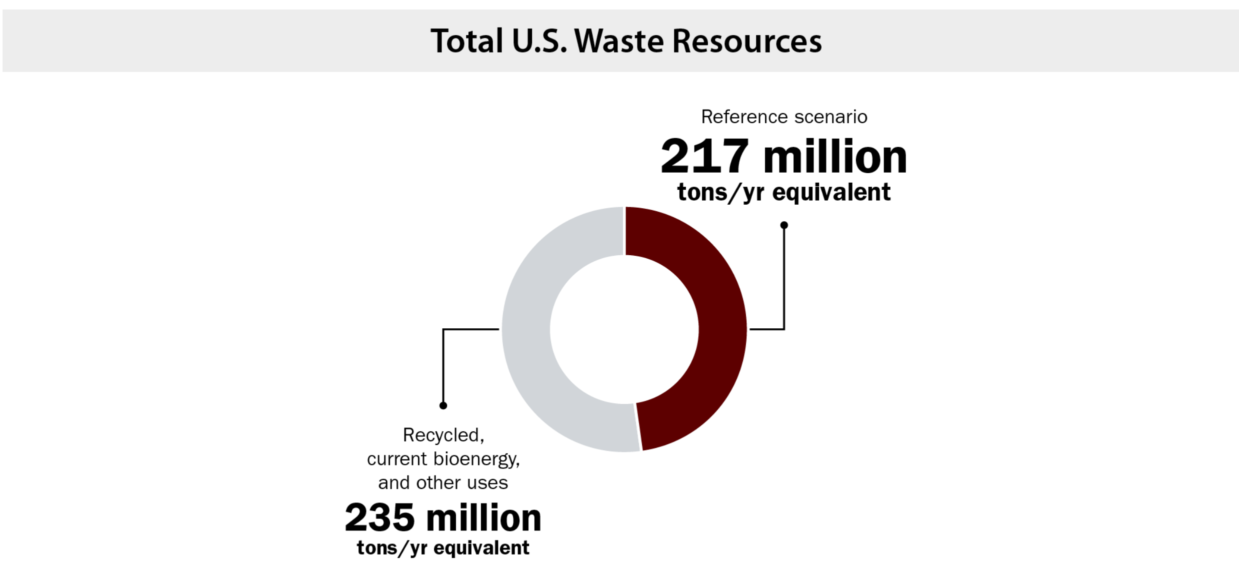


Figure 3.4. Waste resources reported as available in mature-market medium scenario in proportion to total production

- On average, about 161 million dry tons (415 million wet tons) per year of wet and solid waste resources are available above current uses in the near term. 217 million dry tons per year are estimated to be available above current uses in mature-market scenarios.

- Wastes are diverse with potentially low prices, but prices vary with feedstock and market conditions.
- Some of these materials may not be economically obtainable due to collection challenges and preprocessing required such as separation, sorting, dewatering, and depackaging.
- Waste supplies are not intrinsically linked to demand and are therefore expected to change little with demand. Thus, a mature-market scenario may result in little change in supply but higher prices compared to a near-term scenario.

3.1 Introduction

The waste resources and byproducts evaluated here can be categorized as follows: (1) wet waste resources such as animal manure, wastewater sludge, food waste, and inedible FOG; (2) solid waste resources entering the MSW stream such as paper/cardboard, plastics, wood, rubber/leather, textiles, and yard trimmings; (3) gaseous resources/intermediates (landfill gas [LFG]); and (4) byproducts, namely glycerol, black liquor, and distillers grains.

There are several factors making these resources different from the resources discussed in other chapters that affect their price and logistics. One is their geographic distribution. Except for animal manure and byproducts, generation of these resources follows population dynamics and is primarily concentrated near urban areas. This results in a close proximity to demand centers and access to labor and energy supply, and minimizes the cost of transporting feedstock to a processing facility. The concentration of these resources in a given area also provides an opportunity for their combined use (blending) in a processing facility and reduced costs through economies of scale for the utilization pathway. Another factor that makes these resources different from conventional biomass resources is that some are already commoditized (e.g., FOG, plastic waste, paper/cardboard waste, glycerin, distillers grains, and to some extent manure and urban wood). In other words, these waste materials have become standardized, marketable products with an economic value. Simultaneously, a large portion of these materials are viewed as waste by the entities generating them. In other words, they are not typically associated with a market value by these entities—but represent a liability, as they require disposal—and in some cases, their management must meet local environmental regulations. Even commoditized resources are sometimes treated as waste and disposed of at landfills, which represents a loss of their technical and market value. Conversely, from a user's perspective, waste resources are viewed as a valuable, underutilized feedstock for energy and resource recovery in the context of a circular economy. The balance between these different views on waste resources affects their economics—low demand and treatment as waste keeps their price low, but a high market demand increases prices.

3.2 Supply and Prices

Table 3.1 summarizes the total and available (subtracting current uses) waste resources and byproducts supply at the national level, their average prices, and inherent energy content under a near-term scenario. Future total supply and prices for wet and solid waste resources under a mature-market scenario are also presented. The estimated total wet and solid waste resources in the near term amount to about 290 million dry tons (876 million wet tons) annually, of which slightly more than half is available for bioenergy and other purposes considering current uses of these materials. While the estimated available supply is likely a reasonable estimate of overall generation, utilization of all these resources may not be economical due to preprocessing costs associated with activities such as separation, sorting, purification, dewatering, depackaging, and shredding. Competing demands for these resources (e.g., land application, composting, fertilizer, recycling, animal feed, pharmaceuticals, cosmetics, lubricants, export) also limit their availability for bioenergy purposes.

Table 3.1. Annual Waste Resources in Near-Term and Mature-Market Scenarios [a]

Waste Resources and Byproducts	Near-Term Total Annual Average Resources		Near-Term Available Annual Average Resources		Mature-Market Low/Medium/High Total Annual Average Resources		2022 Average Price in $/Wet Ton			2022 Average Price in $/MMBtu		
	Million Wet Tons/yr (Million Dry Tons/yr)	Energy Content (TBtu)	Million Wet Tons/yr (Million Dry Tons/yr)	Energy Content (TBtu)	Million Wet Tons/yr (Million Dry Tons/yr)	Energy Content (TBtu)	Near Term	Mature-Market Low/Medium	Mature-Market High	Near Term	Mature-Market Low/Medium	Mature-Market High
Wet Waste	622 (71)	1,027	273 (32)	450	668 (81)	1,166						
Animal manure [b]	417 (41.5)	540	167 (16.5)	215	422 (46)	598	$2.5	$2.5	$4.5	$1.8	$1.8	$3
Wastewater sludge	137 (13.7)	178	68.5 (6.9)	89	163 (16.3)	212	$21	$21	$23	$16	$16	$18
Food waste	61 (15.3)	77	35 (8.8)	44	75 (18.8)	94	$76	$76	$81	$61	$61	$65
FOG [c]	6.8	232	3	102	7.8	262	$554	$554	$568	$16	$16	$17
Animal fats	3.2	109	0.9	31	3.2	109	$686	$686	$706	$20	$20	$21
Used cooking oil/yellow grease	1.4	48	0.2	7	1.8	61	$550	$550	$571	$16	$16	$17
Trap/brown grease	2.2	75	2	68	2.7	92	$426	$426	$447	$13	$13	$13
Solid Waste	254 (219)	3,725	142 (129)	2,387	303 (261)	4,260						
Paper and cardboard [c,d]	121 (114)	1,624	68 (64)	910	142 (134)	1,903	$93	$93	$110	$7	$7	$8
Plastics [c,d]	48.6 (47.6)	1,334	41.6 (40.8)	1,142	56.8 (55.7)	1,560	$230	$230	$248	$8	$8.4	$9
Clean urban wood (MSW and construction and demolition [C&D]) [d]	22.6 (19.2)	307	5.6 (4.8)	76	28 (23.8)	381	$11	$21	$31	$0.8	$1.5	$2.3
Rubber and leather [d]	9.2 (8.7)	151	5 (4.7)	82	11.3 (10.6)	186	$11	$20	$29	$0.7	$1.2	$1.8
Textiles [d]	17 (15.3)	230	11.3 (10)	153	21 (19)	285	$11	$19	$28	$0.8	$1.4	$2
Yard trimmings [d]	35.4 (14.2)	79	10.5 (4.2)	24	43.9 (18)	101	$11	$14	$18	$5	$6.3	$8
Gaseous Resources/Intermediates												
LFG [e]	33 (836 BCF)	423	15 (383 BCF)	194	–	–	–	–	–	–	–	–

Waste Resources and Byproducts	Near-Term Total Annual Average Resources		Near-Term Available Annual Average Resources		Mature-Market Low/Medium/High Total Annual Average Resources		2022 Average Price in $/Wet Ton			2022 Average Price in $/MMBtu		
	Million Wet Tons/yr (Million Dry Tons/yr)	Energy Content (TBtu)	Million Wet Tons/yr (Million Dry Tons/yr)	Energy Content (TBtu)	Million Wet Tons/yr (Million Dry Tons/yr)	Energy Content (TBtu)	Near Term	Mature-Market Low/Medium	Mature-Market High	Near Term	Mature-Market Low/Medium	Mature-Market High
Byproducts												
Glycerin [c]	0.7	13	Negative	n/a	–	–	$218 (crude), $744 (refined)	–	–	$12 (crude), $41 (refined)	–	–
Black liquor	65	129	Negligible	n/a	–	–	$150–$350	–	–	$76–$177	–	–
Distillers grains [c]	36	564	0	n/a	–	–	$197	–	–	$12.6	–	–
Total Wet and Solid Waste Resources	876 (290)	4,752	415 (161)	2,837	971 (342)	5,426						

[a] Data sources and analysis methodology are presented in Section 3.3. In summary, wet waste resource quantity is adopted from Milbrandt et al. (2018), and wet waste resource prices are adopted from Badgett, Newes, and Milbrandt (2019). Paper and cardboard waste quantity and prices are summarized from Milbrandt et al. (2024), and plastic waste quantity and prices are summarized from Milbrandt et al. (2022). These data sources provide detailed resource breakdowns and further information. The data sources and methodology for estimating the quantity and prices for the remaining waste resources and byproducts are presented in Section 3.3.

[b] Total and available manure values are presented for 50 U.S. states and include dairy, beef, and swine manure. The downloadable spatial data are only available for 23 states, and therefore the data by county totals a lower value (341 million wet tons, or about 35 million dry tons).

[c] Commodities, 3-year (2019–2021) average price as reported, in $2022.

[d] The available amount represents landfilled quantity.

[e] LFG is produced from most resources listed above; thus, its potential should be viewed separately to avoid double counting. Future LFG generation is unknown and will depend on waste diversion rates.

n/a = not applicable; – = data not available.

The future quantity and prices of waste resources and byproducts will likely be influenced by several factors such as population growth, market demand, resource competition between industries, supporting policy (e.g., organic waste ban, zero-waste initiatives), and technology development (e.g., cost-effective sorting). Generation of waste resources is somewhat fixed and does not respond to shifts in market price or demand for the material. For a conventional market commodity, if the market demand increases, supply is likely to increase to meet this increased demand. As waste resources directly correlate with human and animal populations, their supply is linked to their dynamics and does not directly change in response to market drivers such as demand.

While supply dynamics for these resources are complex, changes in the utilization and market for these materials are likely to shift their prices. Previous work has estimated that some of these resources are available at negative prices, a situation where an entity using the waste could receive it for free or be paid to take the material (Badgett, Newes, and Milbrandt 2019). These negative prices are often referred to as "tipping fees" at the point of disposal, but from a waste generator's perspective would also include costs of collection and transport. Here, we do not attempt to forecast the occurrence of negative prices due to the forward-looking nature of the price projections provided in the mature-market scenarios. While negative prices are known to occur today in certain locations, the market, regulatory, and technological factors that could impact them in the future are highly uncertain. For example, the development of an advanced waste conversion pathway could drastically increase demand for waste feedstocks in the local area, shifting prices from negative to positive. Due to the high costs of transporting organic wastes with high moisture content, this new demand might only have a localized impact, and feedstocks generated farther away would not see price shifts. While these considerations are important for securing feedstock supply, they are beyond the scope of this analysis.

3.2.1 Wet Waste Resources

The wet waste resources considered here include animal manure (dairy, beef, and swine), wastewater sludge, food waste, and inedible FOG. The FOG category includes used cooking oil/yellow grease, trap/brown grease, and animal fats such as inedible tallow, choice white grease, and poultry fat, which is edible but widely used in technical applications including biofuels. The current/near-term supply of total wet waste resources amounts to about 622 million tons (71 million dry tons, excluding FOG) annually, of which roughly 45% is available considering current uses of these materials (Table 3.1); Milbrandt et al. (2018) provide more detailed information about this current/near-term supply. Future total supply is estimated at about 668 million tons (81 million dry tons, excluding FOG), and Figure 3.5 illustrates this supply by county. The analysis methodology for estimating future supply is presented in Section 3.3. More than half of this potential is generated by animal manure. As their collective name implies, these resources have high moisture content and thus are suitable for conversion processes able to handle this type of feedstock—such as anaerobic digestion, fermentation, and hydrothermal liquefaction. Despite widespread availability, their distributed nature, collection logistics, and compositional variability, among other nontechnical factors (e.g., lack of strong supporting polices in the past), have limited their utilization to date (DOE 2017). Although many of these resources are concentrated near urban areas (except animal manure), which allows for combined use in processing applications, such blending of resources is limited in existing installations. Future projections for wet waste generation suggest that these resources will continue to be concentrated near urban areas, with generation directly correlating with human population (and animal population for manure). While the U.S. population is projected to increase, certain areas are estimated to experience rapid population growth while others could see decreases in population.

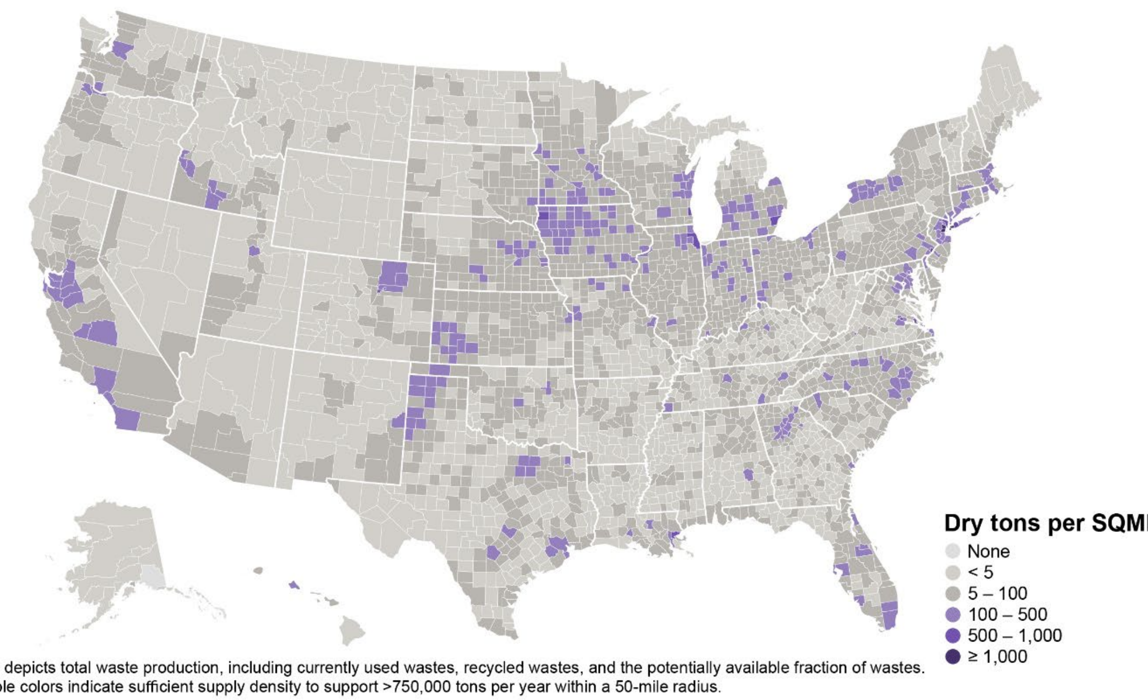


Figure 3.5. Total supply of wet waste resources in the United States under the mature-market scenario.

Note: The map includes animal manure data for 23 states due to lack of geospatial data for the remaining states. However, these 23 states represent the majority of manure production: 94%, 76%, and 93% of confined cattle, dairy, and swine, respectively. For more information, please refer to Milbrandt et al. (2018).

Wet waste resource prices vary by geography and depend on whether a resource is commoditized or treated as waste (Badgett, Newes, and Milbrandt 2019). If a resource has been commoditized (e.g., FOG), its price is determined by market demand. Conversely, if a resource is regarded as waste, its price is driven by the cost of its disposal. In Table 3.1, for current/near-term and future market scenarios, we do not forecast negative prices for wet waste resources. However, we do factor in a price of zero for materials in certain locations where the avoided cost of disposal (i.e., landfill tipping fees) is likely to be high. In reality, some of these resources could be available at negative prices, meaning that a purchaser may receive these materials for free or be paid to accept them in some locations. This situation is highly localized and may not exist in all places with high wet waste generation. Resources with estimated prices of zero are not uniformly distributed and are most likely to occur in areas with organic waste disposal bans, high population densities, and high landfill tipping fees. Most FOG is commoditized, with an existing market as a biofuel feedstock and in other industries, which explains why the prices are higher than the price for other wet waste resources in Table 3.1. FOG prices do not vary greatly geographically; however, they do vary between types of FOG. Waste grease (used cooking oil and trap grease), for example, tends to be cheaper than animal fats (e.g., tallow and poultry fat).

Future wet waste resource prices reflect several key drivers that impact the markets for these materials. Mainly, these drivers include changes in generation of the resource and increasing market demand for the material. Increasing generation of wet wastes in locations with strong population growth can drive down the cost for diverting the material from its standard disposal pathway. Many waste conversion pathways can reduce costs through increasing economies of scale—in other words, the more waste the pathway manages, the lower the cost to manage said waste (Badgett and Milbrandt 2021). Through economies of scale with conversion pathways, increasing access and collection of generated waste can push management costs (and likely prices) lower in certain locations. Additionally, the high moisture content in wet waste resources makes the cost of transporting them high, requiring conversion facilities to be located close to the point of generation/aggregation or that the feedstock is dried to a lower moisture content. Currently operating waste management technologies such as landfills rely on economies of scale to minimize their capital and operational expenses per ton of waste. Diverting resources that are currently allocated to these existing technologies could favor the economics of the conversion pathway, but might also impact the economics of the currently operating waste management technology.

Market forces can also impact wet waste resource prices. While the supply of these resources is fixed to animal and human populations, their prices do respond to changing market forces. One of the most attractive aspects of utilizing waste resources is their potential to be available at low to negative prices. These low prices exist because these resources have not conventionally been utilized in bioenergy pathways and have instead been disposed of in accordance with waste management practices and regulations (Badgett and Milbrandt 2020). As with any material, if demand increases, the price is also likely to increase, suggesting that zero- to negative-price waste resources are not likely to always exist. If utilization of these resources in bioenergy pathways increases, prices are likely to increase in step with increased demand, as shown in the mature-market scenario (Table 3.1).

3.2.2 Solid Waste Resources

The solid waste resources considered here include the following materials entering the MSW stream: paper/cardboard, plastics, clean urban wood, rubber/leather, textiles, and yard trimmings. The current/near-term supply of total solid waste resources amounts to about 254 million tons (219 million dry tons) annually, of which roughly 56% is available considering current uses of these materials (Table 3.1). The available portion of these materials represents their landfilled quantity—in other words, materials sent to landfills that could be used beneficially, including in bioenergy applications. Most of the available quantity (about 85%) comprises paper/cardboard and plastic waste. The estimate for paper/cardboard waste is derived from Milbrandt et al. (2024)

and for plastic waste from Milbrandt et al. (2022). The data sources and methodology for estimating the quantity for the remaining solid waste resources are similar to those used in BT16 and are presented in Section 3.3. Future total supply is estimated at about 303 million tons (261 million dry tons), and Figure 3.6 illustrates this supply by county. The analysis methodology for estimating future supply is presented in Section 3.3.

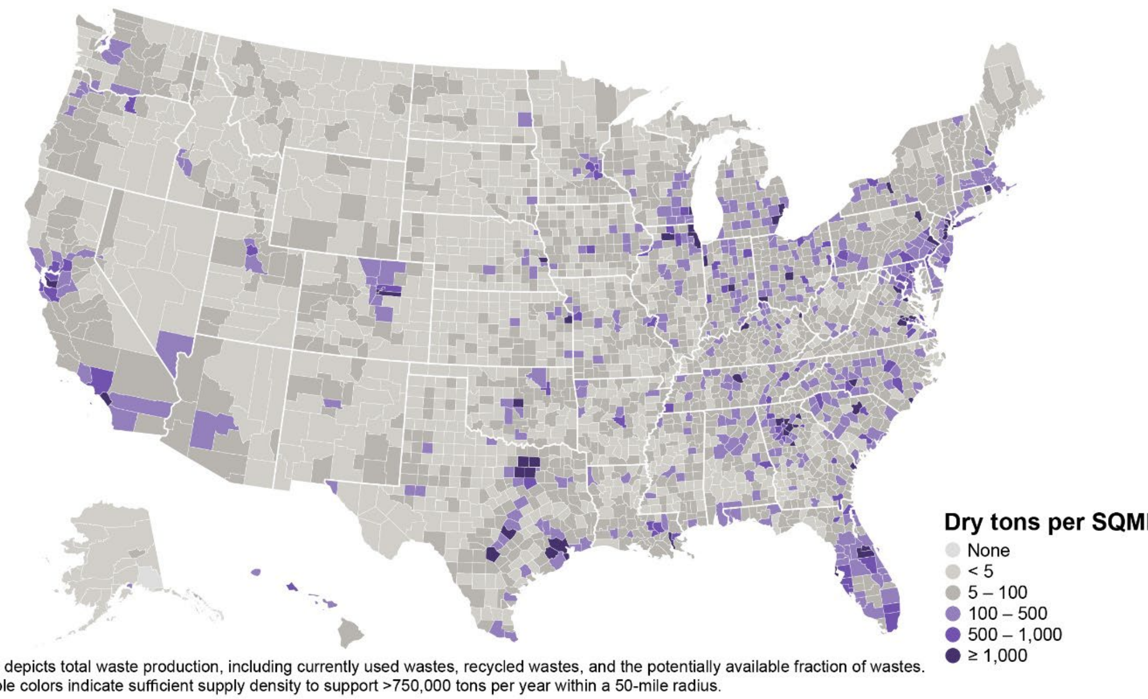


Figure 3.6. Total supply of solid waste resources in the United States under the mature-market scenario.

Note: The map includes available (landfilled) paper/carboard waste and plastic waste, not total, due to lack of geospatial data for total generation potential at the county level.

The solid waste resources considered here are typically constituents of the MSW stream, and therefore their generation, and to a large extent disposal, is associated with populated places. Despite their high energy density (Table 3.1), these resources' collection logistics, separation from mixed waste, and compositional variability, among other nontechnical factors (e.g., lack of supporting polices), have limited their utilization to date. Like wet waste resources, supply of solid waste material is expected to correlate with changes in population from location to location. Areas of the country with rapid population growth are likely to see increased supply of these resources, while areas with population declines are estimated to see decreases in supply.

Prices for these materials vary geographically and, similarly to wet wastes, depend on whether a resource has been commoditized or treated as waste. Prices for commoditized resources are determined by market demand. For resources regarded as waste, their price is driven by the cost of its disposal (local landfill tipping fees) or local market demand. Table 3.1 shows the average price for these materials. Prices for commoditized resources (plastic and paper/cardboard waste) include source separation cost and baling, which is why these prices are higher. For non-commoditized solid waste resources, prices correlate with regional landfill tipping fees and added costs for separating the resource. Locations with higher landfill tipping fees are estimated to have lower waste prices, as the avoided cost of sending these materials to landfills is significant. For example, if a construction company that generates wood waste must pay a landfill tipping fee of $100/ton to dispose of their wood waste, they might be willing to pay anything less than $100/ton to take their wood waste instead. What the bioenergy facility could charge or is willing to pay for its feedstock is dependent on the process economics and is beyond the scope of this resource assessment.

Price drivers for solid waste resources are similar to those discussed for wet wastes. Mainly, the low prices estimated for solid waste resources are likely to respond to increasing demand by increasing beyond the low values estimated here. This effect is captured in the MM scenarios, where prices for non-commoditized solid waste resources increase uniformly with projected increase in demand (Table 3.1) (Langholtz et al. 2022).

3.2.3 Gaseous Resources/Intermediates

LFG, a mixture of roughly 50% methane and 50% CO_2, is produced through decomposition of organic matter in landfills (EPA 2023a). Total LFG potential is estimated at about 33 million tons, or roughly 836 BCF (EPA 2023c). This potential accounts for the current LFG amount available at landfills that is currently or most likely able to support a project. The available LFG potential is estimated at about 15 million tons, or roughly 383 BCF, and represents the "total" value minus the gas flows to all operational, construction, and planned projects (i.e., the "used" LFG mentioned in Chapter 2). More information about the methodology for estimating LFG potential is presented in Section 3.3. It should be noted that the wet and solid waste resources discussed earlier are also disposed of at landfills and contribute to LFG generation. To avoid double counting, the total waste resource potential in Table 3.1 excludes LFG and includes only wet and solid waste resources. In addition, LFG is often considered an intermediate, not quite a resource (that would be the organic material) or a final product (e.g., power, heat, renewable natural gas [RNG]). We include its potential in this report as a reference.

3.2.4 Byproducts

This category includes materials generated as byproducts in various biomass processing applications, namely glycerin, black liquor, and distillers grains. These materials are mostly used locally by various industries, including bioenergy production, and are included here for completeness rather than contributors to the overall biomass resource potential. It is possible that in the future these materials may be utilized more for bioenergy purposes, given technological advances and market demand.

Glycerin, also known as glycerol, is a nontoxic, colorless, and odorless liquid used in a wide variety of applications (e.g., food, pharmaceuticals, cosmetics). Glycerin is a byproduct of soap and biodiesel production, with the latter being most common today (Goyal, Hernandez, and

Cochran 2021). Glycerin is initially produced in a crude form and can be further processed into refined or high-purity glycerin, a high-value product that is free of water and other impurities. Crude glycerin without further processing can be combusted to generate heat and power, gasified with other biomass resources to produce syngas (a mixture of CO and H_2), used in steam reforming for hydrogen production, fermented for alcohols (e.g., ethanol and butanol) and hydrogen, and co-digested with other organic wastes to produce biogas (He 2018). Production is about 700,000 tons annually (Table 3.1) (S&P Global 2021). Available potential is negative due to lower production than consumption and the deficit being supplied by imports.

Black liquor, a byproduct of the pulp- and paper-making process, is currently used to recover and reuse the valuable cooking chemicals and for electricity production on-site to offset energy costs. Therefore, nearly all of the estimated total resource (about 65 million tons annually; EIA 2018) is not available for higher-value bioenergy products such as fuels and chemicals (Table 3.1).

Distillers grains, a byproduct of the corn ethanol industry, are typically used as a protein-rich animal feed (Olson and Capehart 2019). Production was about 36 million tons in 2022 (Table 3.1) (USDA 2022a). For local markets, distillers grains are sold in wet form. For longer distances, distillers grains are dried to about 10% moisture to reduce weight (Olson and Capehart 2019). In addition to domestic use, dried distillers grains are also exported. Distillers grains can be used as fertilizer, for bioplastic production, and as a feedstock for transportation fuels production (Lei et al. 2011; University of Minnesota 2024). However, the probability of these other uses of distillers grains to occur is very low due to high demand of these materials as a livestock feed.

Table 3.2. Comparison with BT16

Resource	Same as BT16	Changes from BT16
Citrus residues		Reclassified to agricultural processing wastes
C&D wood		Updated BT16 method with latest EPA data (2018)
Cotton gin trash		Reclassified to agricultural processing wastes
Cotton residue		Reclassified to agricultural processing wastes
Food waste		Residential food waste included in addition to industrial, institutional, and commercial food waste
Hog manure		Detailed assessment by county
Dairy manure		Detailed assessment by county
Beef manure		Detailed assessment by county
FOG		Detailed assessment by county
MSW wood		Updated BT16 method with latest EPA data (2018)
Non-citrus residues		Reclassified to agricultural processing wastes

Resource	Same as BT16	Changes from BT16
Other forest residue		Reclassified to forest processing wastes
Other forest thinnings		Reclassified to forest processing wastes
Other MSW		Removed; all MSW materials amenable to bioenergy conversion have been included in the waste resources section
Paper and paperboard		Detailed assessment of available (landfilled) resources by county
Plastics		Detailed assessment of available (landfilled) resources by county
Primary mill residue		Reclassified to forest processing wastes
Rice hulls		Reclassified to agricultural processing wastes
Rice straw		Reclassified to agricultural processing wastes
Rubber and leather	Same BT16 method with latest EPA data (2018)	
Secondary mill residue		Reclassified to forest processing wastes
Sugarcane bagasse		Removed, is currently used
Sugarcane trash		Reclassified to agricultural processing wastes
Textiles	Same BT16 method with latest EPA data (2018)	
Tree nut residues		Reclassified to agricultural processing wastes
Yard trimmings	Same BT16 method with latest EPA data (2018)	
Glycerin		New in BT23
Black liquor	Using latest EIA data (2018)	
Distillers grains		New in BT23

3.3 Methods

The following assumptions were used in this analysis:

Moisture Content

- Manure: 87%–91%
- Sludge: 90%
- Food waste: 75%
- Paper/cardboard: 5.5%
- Plastic: 2%
- Wood: 15%

- Rubber and leather: 6% (rubber 2% and leather 10%)
- Textiles: 10%
- Yard trimmings: 60%
- Glycerin: 0.3%
- Black liquor: 85%
- Distillers grains: 10%.

Energy Content (Btu/lb, dry weight)

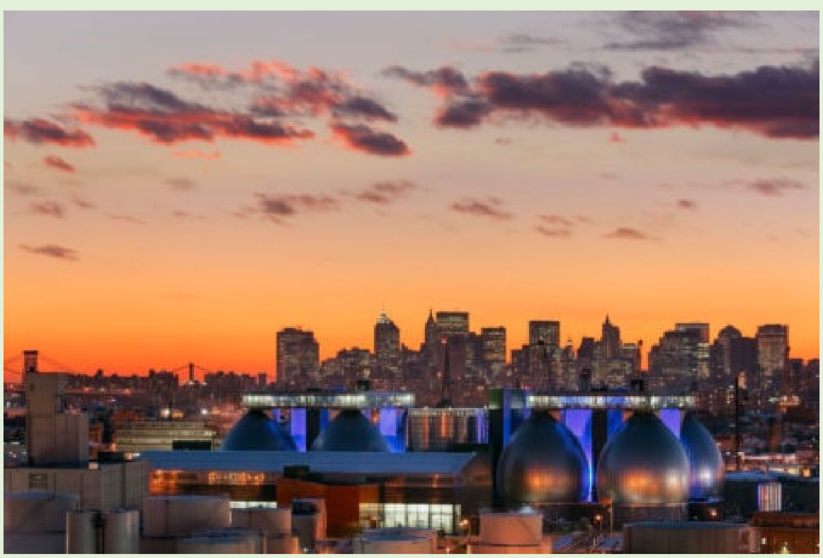
- Manure: 6,500
- Sludge: 6,500
- Food waste: 2,500
- FOG: 17,000
- Paper/cardboard: 7,100
- Plastic: 14,000
- Wood: 8,000
- Rubber and leather: 8,750
- Textiles: 7,500
- Yard trimmings: 2,800
- Glycerin: 9,000
- Black liquor: 6,600
- Distillers grains: 8,703.

Anaerobic Co-Digestion: Combining Various Organic Wastes to Generate Power

Anaerobic digesters process organic waste to reduce volume, the release of the global warming gas methane into the atmosphere and produce energy. Some facilities combine food waste with biowaste at wastewater treatment plants. In 2021, approximately 30 co-digestion facilities were operating in the United States (Dalke et al. 2021). Most of these are wastewater treatment plants that added preprocessing equipment to allow food waste to be added to the biowaste, processed in existing anaerobic digesters with extra capacity for the food waste. In almost all cases at the wastewater treatment plants, the produced biogas is used for combined heat and power generation to heat the digesters and partially power the facility.

One such facility, the Newtown Creek Wastewater Resource Recovery Facility in Brooklyn, New York, began co-digesting collected food waste from the New York City area in 2016. Food scraps from commercial, residential, and institutional sources, including schools and a curbside organics program run by the City of New York Department of Sanitation, provide the waste. Initially, the city collected approximately 30 tons of food waste per day, eventually increasing to more than 200 tons per day before temporarily dropping to 25 tons daily during the COVID-19 pandemic. In 2022, the plant processed about 130 to 140 tons of food waste per day (Karidis 2022). The biogas is used to heat the sites' boilers that provide heat to its buildings. The site, New York City's largest wastewater treatment facility, has partnered with the utility National Grid to clean the biogas to meet quality standards for injection into the natural gas pipeline network.

Other locations in dairy-centric areas such as Wisconsin and the northeast region utilize anaerobic digestion for cow manure combined with food waste. These locations also use the produced biogas for electrical generation or for combined heat and power. Lawnhurst Energy's anaerobic digestion facility in Stanley, New York, combines food waste, yogurt processing waste, and manure from dairy cows to produce combined heat and power. The facility, which began operations in 2014, provides power and heat to the buildings and for dairy processing needs, with excess electrical power being routed to the grid. At full capacity, the facility produces 541 kW of power and a heat output of 1,109 MMBtu per hour (EnviTec Biogas 2022).



Digester "eggs" at Newtown Creek Wastewater Resource Recovery Facility, Brooklyn, New York.
Photo courtesy of Newtown Creek Wastewater Resource Recovery Facility

3.3.1 Wet Waste Generation Estimates

Current/near-term total wet waste resource supply is based on previous work considering modeled and per-capita-derived estimates in 2017, except yellow and brown grease, which were updated to 2019 for this report using county population for that year from the U.S. Census Bureau. The amount of current/near-term available wet waste resources is estimated by subtracting currently used resources outlined in Milbrandt et al. (2018).

Future total supply for sludge, food waste, and FOG is based on generation increase approximated from percent change for population from 2017 to 2050 at the county level (Hauer 2021). Future total supply for animal manure is based on generation increase approximated from percent change for each manure type from 2021 to 2032 (USDA 2022b).

3.3.2 Wet Waste Price Estimates

The methods used to estimate current/near-term and future prices for wet waste resources are based primarily on previous work for wet waste price estimates (Badgett, Newes, and Milbrandt 2019). Cost models from this work were updated to account for inflation in equipment and management costs to 2022 dollars. Current/near-term price estimates use similar methodology to previous price modeling in updated dollar years. Additionally, a price ceiling and price floor are defined, where modeled prices that are lower than the price floor or higher than the price ceiling are assigned prices equal to the respective floor and ceiling values. We assume a price floor of $0.0/wet ton and ceiling of $100/wet ton across all scenarios.

Table 3.3. Methodology for Estimating Wet Waste Resource Prices for Current, BAU, and Mature-Market Scenarios

Scenario Dataset	Dollar Year	Feedstock Generation	Pricing Mechanism
Current/near term	2022 $	Current generation estimates	Supply curve model, updated to 2022 $ basis, price floor and ceiling defined
Mature-market low/medium	2022 $	Current generation updated with population projections	Supply curve model, updated to 2022 $ basis, price floor and ceiling defined, updated waste generation
Mature-market high	2022 $	Current generation updated with population projections	Supply curve model, updated to 2022 $ basis, price floor and ceiling defined, updated waste generation, 100% demand increase at $0.2/dry ton price increase per percent change in demand

These mechanisms are adopted to mitigate the effects of price model behavior in locations with low resource generation. For counties with very low waste generation, the cost to manage the waste ($/wet ton) can be extremely high. The price floor of $0/wet ton reflects uncertainty in the occurrence of negative prices in various locations. While negative prices for wet waste materials are possible and can exist in certain situations, forecasting the occurrence of these opportunities at a national-level analysis is highly uncertain. Detailed location-specific studies to identify these economically favorable situations are needed to confirm viability of negative prices and their elasticity to increased demand for the material.

FOG is priced separately from the other wet waste materials, as the market prices for various FOG subtypes are publicly available. We differentiate FOG prices for used cooking oil/yellow grease and animal fats from *Render* magazine (Johnson Downing 2022). Trap/brown grease prices were collected via survey of relevant collection and processing companies by staff at the National Renewable Energy Laboratory (NREL). These prices are applied to all FOG resources across the United States, as there is little geographic variability. FOG prices for the mature-market high scenario assume a similar 100% demand increase at $0.2/dry ton ($20/wet ton) increase per percent change in demand (Langholtz et al. 2022).

3.3.3 Solid Waste Generation Estimates

Current/near-term total and available supply for plastic waste is based on previous work considering modeled estimates in 2019. Milbrandt et al. (2022) provide more information and breakdown by material type—e.g., polyethylene terephthalate (PET) bottles/containers, high-density polyethylene (HDPE) bottles/containers, film/bags. Current/near-term total and available supply for paper and cardboard waste is based on previous work considering modeled estimates in 2019. Milbrandt et al. (2024) provide more information and breakdown by material type (e.g., cardboard, magazines, compostable paper). Current/near-term total supply for rubber/leather, textile, and yard trimmings is estimated using the same method as in BT16—per-capita generation derived from EPA's nationwide reporting and applied to county population—updated with the latest EPA estimate (2018) and 2018 county population from the U.S. Census Bureau (EPA 2020b). The current/near-term available supply for these materials represents their landfilled quantity; the data are obtained from the EPA and presented at the national level.

Current/near-term total supply for urban wood (MSW and C&D wood) is also estimated using per-capita generation derived from EPA's 2018 nationwide reporting and applied to 2018 county population (EPA 2020a, 2020b). We assume that 50% of MSW wood and one-third of C&D wood is clean (e.g., branches and stumps, clean lumber, most pallets and crates) and thus suitable for bioenergy conversions. Current/near-term available resources are estimated by subtracting the amount of wood that is recycled and combusted, assuming that only clean wood is used in these applications.

Future total supply for all solid waste resources is based on generation increase approximated from percent change for population from 2018/2019 to 2050 at the county level (Hauer 2021).

3.3.4 Solid Waste Price Estimates

Solid waste materials are priced using a separate methodology from wet wastes. If the waste has been commoditized, we report 3-year average (2019–2021) market prices for the material from RecyclingMarkets.net (recyclingmarkets.net/). This approach is applied to plastic and paper/cardboard waste for near-term and mature-market low/medium scenarios.

For the remaining materials where market prices are not readily available, we estimate a possible market price by considering the local landfill tipping fee and added costs for material separation in accordance with methodologies adapted from BT16 (DOE 2016):

$$price = sort\ cost - landfill\ tipping\ fee$$

The $sort\ cost$ can either be $40/wet ton or $60/wet ton, depending on the population in the county. This serves as a proxy for the scale of the separation and packaging equipment, assuming that higher-population counties are likely to leverage greater economies of scale and thus lower costs. Counties with greater than or equal to 250,000 people are assigned a $sort\ cost$ of $40/wet ton, and those with populations below 250,000 people are assigned $60/wet ton. Landfill tipping fees are aggregated at the state level.

As with wet waste materials, locations with estimated negative solid waste prices are set equal to zero. This price floor methodology reflects uncertainties around market development for waste materials discussed earlier.

Table 3.4. Price Estimation Methodology for Solid Waste Materials

Solid Waste	Dollar Year	Pricing Mechanism	Mature-Market Low/Medium Price Adder	Mature-Market High Price Adder
Yard waste	2022 $	Landfill price approximation + price adders for BAU/mature-market scenarios	$4.08/wet ton	$8.08/wet ton
Paper and paperboard	2022 $	Market prices + price adders for BAU/mature-market scenarios	$8.67/wet ton	$17.17/wet ton
Textiles	2022 $	Landfill price approximation + price adders for BAU/mature-market scenarios	$8.67/wet ton	$17.17/wet ton
Rubber and leather	2022 $	Landfill price approximation + price adders for BAU/mature-market scenarios	$9.18/wet ton	$18.18/wet ton
Urban wood	2022 $	Landfill price approximation + price adders for BAU/mature-market scenarios	$10.20/wet ton	$20.02/wet ton
Plastics	2022 $	Market prices + price adders for BAU/mature-market scenarios	$9.18/wet ton	$18.18/wet ton

For the mature-market scenarios, we assume an increase in demand for the solid waste materials that correlates to an increased market price. We assume a 50% increase in demand for the material for the mature-market low/medium scenario and a 100% demand increase for the mature-market high scenario with a $0.2/dry ton increase in price per percent increase in demand across both mature-market low/medium and mature-market high (Langholtz et al. 2022). This price increase is added to initial mature-market low/medium prices to generate price estimates for the mature-market high scenario.

3.3.5 Gaseous Resources/Intermediates

Near-term total and available LFG production data were obtained from the EPA's Landfill Methane Outreach Program as of November 2023 (EPA 2023b). The total estimate considers current LFG amount available (or estimated for those with data gaps) at landfills that are currently or most likely able to support a project. It excludes landfills with only project records of "low potential" or "unknown" and includes landfills with or without a gas collection system. The available estimate considers the "total" value minus "currently used" (gas flows to all operational, construction, and planned projects). The available estimate includes the amount of gas flared at landfills that are only flaring, landfills with only a shutdown project, and landfills with or without a gas collection system. The hierarchy for LFG flow estimates is to use LFG flared, LFG collected, LFG generated, and then estimate from waste in place. For landfills with projects under construction or planned, it is assumed that all the LFG collected will go to the project. For the values in tons, the assumption was made that the LFG is 50% methane and 50% CO_2 for simplicity. In addition to filling some data gaps with estimates, EPA notes that most of the LFG values in their current database are for 2021, as they are still processing 2022 data.

3.3.6 Byproducts Generation and Price Estimates

Data for glycerin production, consumption, and prices were obtained from S&P Global's *Chemical Economics Handbook* published in July 2021 (S&P Global 2021).

Black liquor production data were obtained from EIA's latest Manufacturing Energy Consumption Survey, completed in 2018 (EIA 2018). Data for black liquor prices were obtained through personal communication with David Johnson, a retired NREL scientist with more than 30 years of experience in the field.

Distillers grains production, consumption, and price data were obtained from the USDA Economic Research Service in October 2022 (USDA 2022a).

Table 3.5. Comparison of National- and County-Level Supply Data

Category	Resource	National	County Level
Wet waste	Animal manure	Total, available (50 states)	Total (23 states)
Wet waste	Wastewater sludge	Total, available	Total
Wet waste	Food waste	Total, available	Total
Wet waste	FOG	Total, available	Total
Solid waste	Paper and cardboard	Total, available	Available (landfilled)

Category	Resource	National	County Level
Solid waste	Plastics	Total, available	Available (landfilled)
Solid waste	Clean urban wood (MSW and C&D)	Total, available	Total
Solid waste	Rubber and leather	Total, available	Total
Solid waste	Textiles	Total, available	Total
Solid waste	Yard trimmings	Total, available	Total
Gaseous	LFG candidate projects	Total	Total
Other waste	Glycerin	Total	n/a
Other waste	Black liquor	Total	n/a
Other waste	Distillers grains	Total	n/a

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Chapter 04 | Biomass from the Forested Land Base

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4 Biomass from the Forested Land Base

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This report and supporting documentation, data, and analysis tools are available online:

Report landing page: https://www.energy.gov/eere/bioenergy/2023-billion-ton-report-assessment-us-renewable-carbon-resources

Data portal: https://bioenergykdf.ornl.gov/bt23-data-portal

Summary

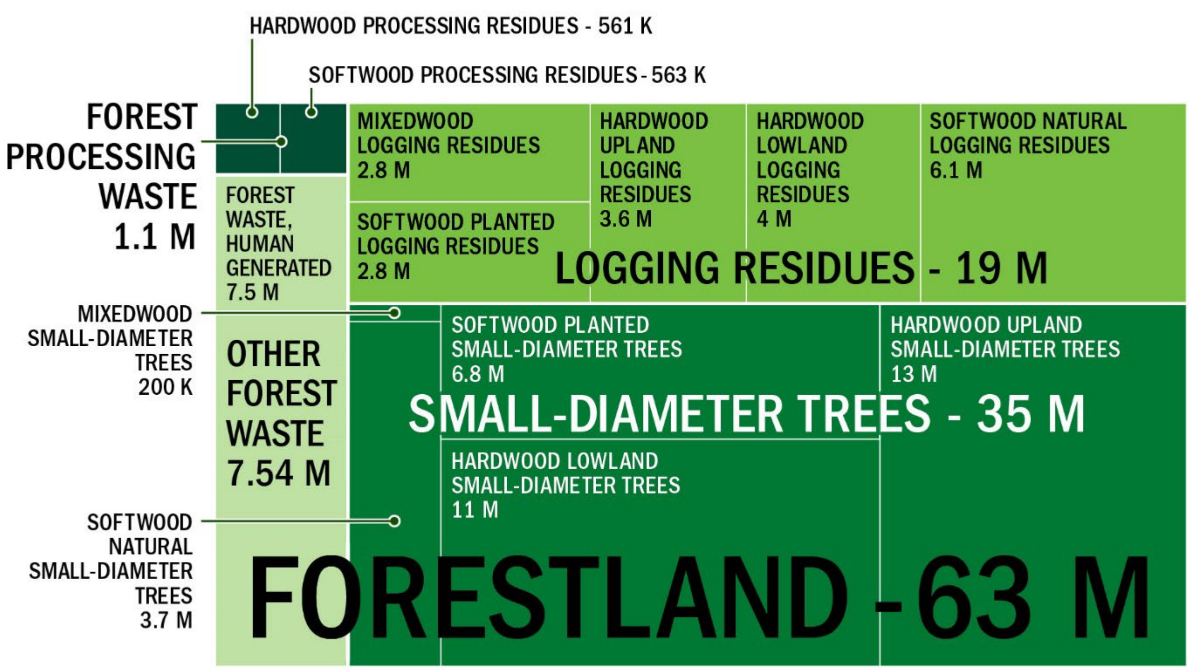

Figure 4.1. National resources from forested lands, mature-market medium scenario at a shadow price of up to $40 per dry ton for logging residues and up to $70.1 per dry ton for small-diameter trees

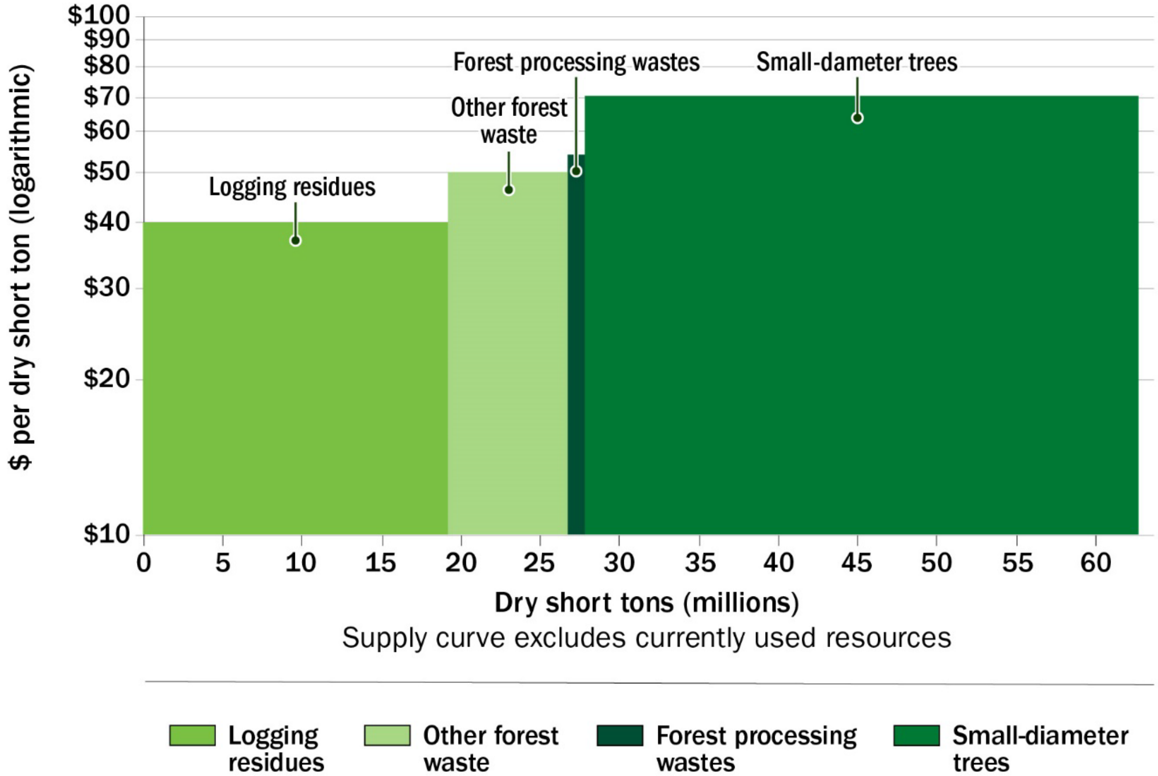

Figure 4.2. Stepwise supply curve of resources from forested lands, mature-market medium scenario

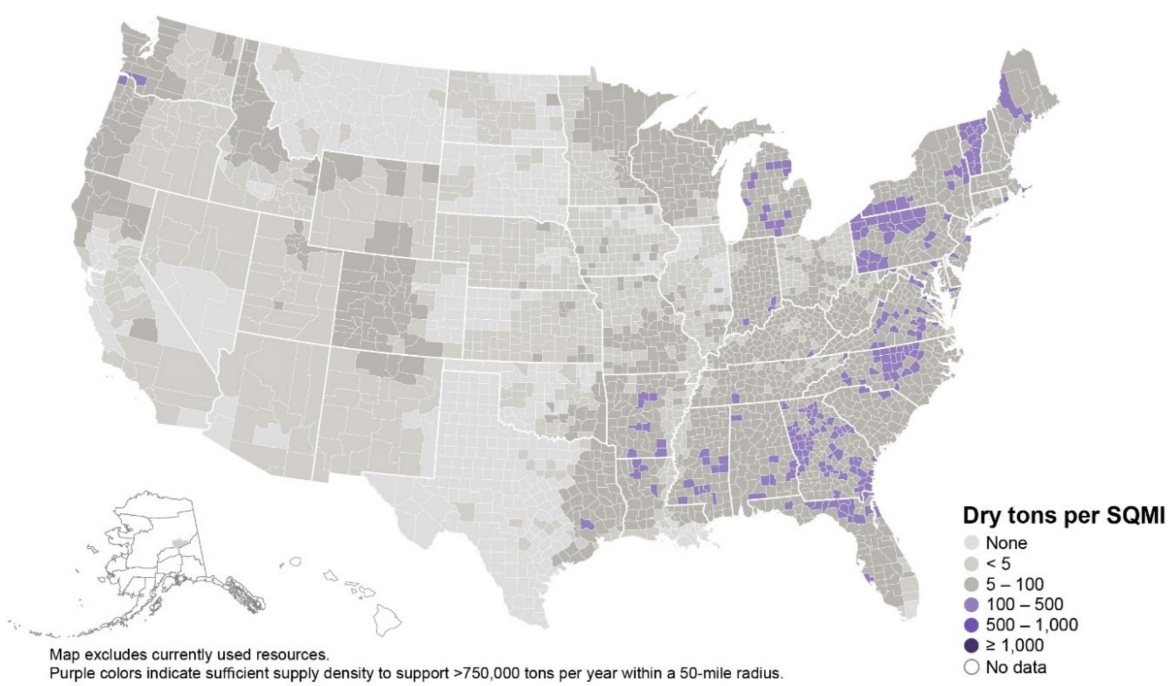

Figure 4.3. Spatial distribution of resources from the forested land base, mature-market medium scenario

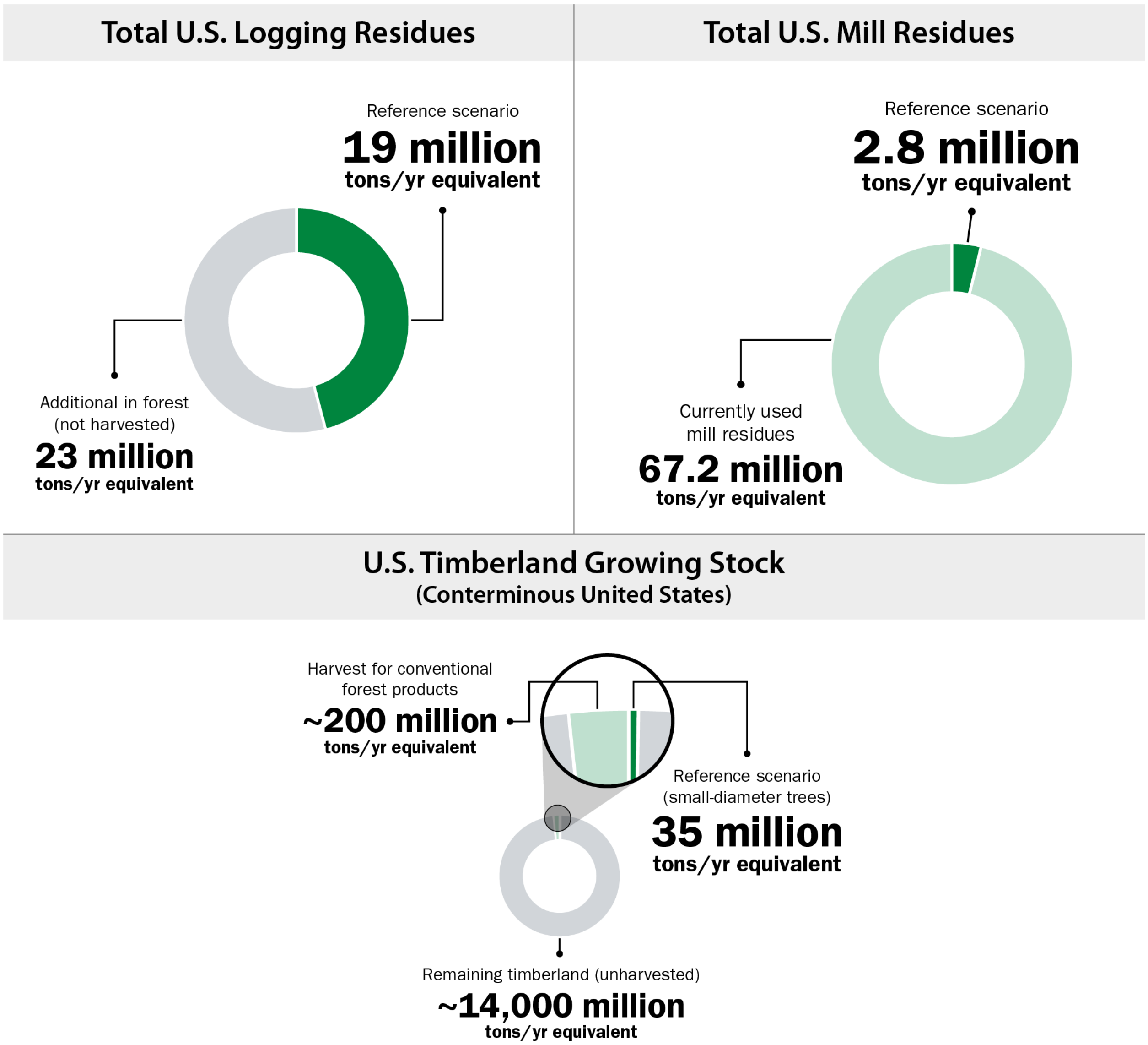

Figure 4.4. Logging residues reported as available in mature-market medium scenario at up to $40 per dry ton in proportion to total residues in forest, not harvested; small-diameter trees and conventional forest products harvest annually in proportion to timberland left unharvested annually; and forest mill residues unused per year in proportion to currently used mill residues

- **Updates to approach:** Consistent with BT16, this section reports biomass availability in the conterminous United States (CONUS) from ForSEAM (arec.tennessee.edu/research/beag/analysis-models/; https://github.com/EERE-Biomass/ForSEAM/) (University of Tennessee 2023), and provides a market analysis for the U.S. South from the SubRegional Timber Supply (SRTS) assessment (github.com/NCState-SOFAC/SubRegionalTimberSupply) (North Carolina State University 2023) to illustrate regional variation. New to this report and to further inform regional variation, we use the Bioregional Inventory Originated Simulation Under Management (BioSum) model (biosum.info/) (USFS 2023b) in collaboration with the USDA-FS to estimate biomass availability from thinning and fuel reduction treatments, aimed at making lands more resilient to wildfire. Federal lands are again included in these forest resource analyses, and biomass from the forested land base includes (1) wood wastes in forests, at mills, and from land conversion; (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 and are included in this section.

- **Sustainability considerations:** The CONUS analysis applies a constraint on land managers that requires planting or regeneration of more trees than are harvested each year, resulting in net regeneration of the forested stands. Other sustainability constraints are summarized in Chapter 1, and the risk of deviating from these constraints is discussed in Chapter 6. There may be additional biomass resources obtainable from treatment of hazardous fuels outside the priority investment landscapes analyzed with BioSum, or if annual treatment area is elevated above current forecasts. Though, this biomass may be left unharvested or be consumed via prescribed fire or wildfire unless its value to society as a recovered resource is recognized more fully. See discussion section 4.6 for more details.
- **Economic availability (assumed roadside or "stumpage" prices):** Results of this analysis suggest a near-term biomass potential of 30.3 million dry tons, with 3.1 million dry tons per year from small-diameter trees and 18.5 million dry tons per year from logging residues, while the remaining biomass is assumed to be available from forest processing waste at mills, as well as other forest waste potentially available from forestland conversion. In this near-term scenario, defined as within the next 10 years or by 2030, shadow prices for logging residues are calculated at up to $40[1] per dry ton, with small-diameter trees calculated at up to $58.5 per dry ton. Further, this analysis showed mature-market biomass availability, defined as after 10 years and before 2050, of 62.7 million dry tons per year, with 34.9 million dry tons from small-diameter trees and 19.2 million dry tons from logging residues. These modeled potential supplies are 18.8 million tons less than BT16 CONUS modeled potential of 81.5 million dry tons per year (see BT16 Table 3.7: baseline, 2040 at $60 per dry ton), because the small-diameter trees have been reported at price (i.e., with profit) rather than at cost. Logging residue shadow prices were again calculated at up to $40 per dry ton, and small-diameter tree shadow prices increased to $70 (Table 4.1). The analysis of timberlands in the Southeast highlighted announced expansions of lumber capacity that will raise the demand for pine sawtimber and generate more byproducts from lumber production than we have observed historically, potentially increasing national results discussed above.

[1] An assumed $40 per dry ton will vary by region and market.

- The textbox "Byproducts of Fire-Focused Management" reports estimates of potential biomass delivery for two of the priority investment landscapes (PILs) targeted for enhancing fire resistance under the Wildfire Crisis Strategy (WCS). Within the approximately 5 million forested acres in these landscapes, about 700,000 could be treated with mechanical thinning to increase fire resistance, annually delivering up to 0.4 million dry tons of harvested woody biomass residue during the initial 20 years of treatments at a delivered price of $70 per dry ton. Estimating the biomass yield from the other 45 million acres to be addressed under the WCS requires engagement with those landscapes and inventory-based analysis that is just now beginning with the support of the Bipartisan Infrastructure Law. While the area targeted for treatment may grow as the WCS evolves, current treatment targets include large areas of forest for which plans call for proactive burning that generates no usable residues. Where forests to be treated contain considerable timber volume in large, merchantable-sized trees, those are infrequently targeted for removal; rather, biomass will be sourced primarily from sub-merchantable-sized trees with low volume and from non-merchantable parts of trees that are primarily of medium and sometimes larger size, moving those stands closer toward desired conditions as defined by the applicable management plan.

Table 4.1. Biomass Production Potential by Resource Type Totals 30.3 Million Dry Tons per Year Available in a Near-Term Scenario and 62.7 Million Dry Tons Available in a Mature-Market Scenario. A Shadow Price of up to $40 per Dry Ton for Logging Residues across Both Scenarios Is Assumed, and up to $58.5 and $70.1 per Dry Ton for Small-Diameter Trees Is Assumed for the Near-Term and Mature-Market Scenarios, Respectively.

Material	Near Term (Million Dry Tons/Year)	Mature Market (Million Dry Tons/Year)
Forest processing waste	1.1	1.1
Logging residues	18.5	19.2
Other forest waste	7.5	7.5
Small-diameter trees	3.1	34.9
Grand total	30.3	62.7

4.1 Background

Roughly 70% of land in the United States has some tree canopy cover, according to the USDA-FS Forest Atlas (USFS 2022c). This analysis includes biomass potential from timberland in the CONUS from the 823 million acres of forest and woodland area (USFS 2023f). The forest products industry generates $300 billion annually in products from this timberland base, contributing 4% of U.S. gross domestic product and making this industry a top employer in 45 U.S. states (USFS 2023c). This report addresses biomass potential on a subset of forest and woodland area. The CONUS analysis includes resources from the 495 million acres of timberland, a special designation of land use type defined by the USFS and the associated forest products industry. This analysis builds on Chapter 3 of BT16 (DOE 2016), accessible through the interactive chapter visualizations (https://bioenergykdf.ornl.gov/bt23-data-portal/), and includes an analysis of additional forestland under special consideration for biomass removal in response to recent wildfires. About an additional 15% of the acres included in the WCS case studies included biomass potential on non-timberland forestland.

4.2 Scope

Similar to BT16, this section models potential biomass resources from timberlands. These resources include woody biomass from forest management, conservation and restoration, and salvage activities. Logging residues and small-diameter roundwood are again included in this section. New in this report are additional potential biomass resources that may be available through the WCS (USFS 2023a). This 10-year strategy identifies areas with a high risk of catastrophic wildfires to develop strategies to effectively reduce those risks through mechanical forest treatment (often removing whole trees and residues), prescribed fire, and other locally utilized management strategies. The WCS initially targeted almost 50 million acres of land nationwide for treatment in PILs. Primarily in the drought-stricken West, these areas include almost 16 million acres of forestland and wildland. Subsequently, the USFS has identified 11 additional PILs for the future focus of this federal investment (USFS 2023a).

4.3 Definitions

Timberlands are defined by the USFS as forestlands capable of producing more than 20 cubic feet of solid merchantable wood per acre per year and are not in reserved status.

Forest woody biomass is a renewable raw material used to produce various resources, including energy (e.g., heat, steam, electricity, transportation fuel), with additional potential to produce value-added products. For this section, forest biomass includes woody biomass from processing mills; wood cut and removed during silvicultural treatments such as thinnings, fuel reduction, and regeneration cuts; and dedicated plantations explicitly grown for biomass on timberland. Non-working forests (e.g., parks) are not sources of biomass in this analysis.

Waste biomass resulting from human activity (e.g., commercial real estate development) that converts land from forestland to non-forestland can also generate biomass and is considered as a potential biomass waste resource utilizing observed land conversion data.

Timber classifications are available from the USFS and various other sources (Stokes et al. 1989). In this analysis and in BT16, tree diameters are classed as average stand diameter: Class 1 has a DBH >11 inches, Class 2 has a DBH of 5–11 inches, and Class 3 has a DBH <5 inches. Below are a few additional key terms:

1. Sawtimber includes trees of a larger size (e.g., Class 1) and higher quality from commercial species, with at least one 12-foot saw log or two noncontiguous saw logs, each at least 8 feet long.
2. Pulpwood includes trees that are harvested specifically for pulp production (e.g., for paper), which allows the use of smaller and younger trees compared to sawtimber.

3 Fuelwood is harvested for energy production for industrial or domestic applications and is often sourced from small-diameter roundwood, branches, or residues and from wood of any size sourced from lower-value or lower-quality species.

4 Chip-n-saw class trees are similar to fuelwood trees, but these trees are converted into two products by one machine: the outside of the log is chipped, and the rest is sawn into smaller cuts of lumber (e.g., two-by-fours). Chip-n-saw trees are the smallest or lowest-quality conifer sawtimber trees. Logs harvested as chip-n-saw must produce lumber or timbers, but a significant proportion of the volume is chipped for pulp production.

Small-diameter tree biomass includes roundwood of various diameter classes, with small-diameter trees (C2 and above) trees contributing all biomass reported within this analysis. This is primarily generated through thinning (a common silvicultural management technique), which reduces competition between trees and promotes more carbon accumulation on the aggregate. This can be chipped or transported as roundwood and utilized for energy.

Stumpage prices represent the value at time of sale 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 (i.e., price for the right to harvest). For additional details on delivered forestland biomass, please see the analysis in Chapter 6 of BT16. Shadow prices represent the cost of biomass as a breakeven price for the last ton harvested.

4.4 Constraints

4.4.1 Other Woody Resources Available from the Agricultural Land Base

Although agricultural land can also be utilized to produce woody biomass, this section does not address resources such as hedgerows and short-rotation woody crops (i.e., fast-growing trees) on agricultural lands. New to this analysis, all woody resources are cataloged in the Bioenergy Knowledge Discovery Framework (KDF) (https://bioenergykdf.ornl.gov), allowing for combinations of woody resources from agricultural or forest land bases. Additional filters are enabled within this dataset to allow sorting by other attributes such as owner (e.g., null or unknown, public, or private).

4.4.2 Embedded Assumptions and Limitations

To limit the complexity of this analysis, we have embedded assumptions as described in the appendices.[2] Analyses consistent with BT16 have minimal descriptions of methodology and assumptions. For example, please see Section 3.4 of BT16 for a description of ForSEAM and its outputs. The analyses that are new to this report have short descriptions of methodology and outside sources available for further investigation. We acknowledge that factors like region-specific merchandizing specifications and product downgrading due to defects are not captured in our analyses.

[2] Access BT23 appendices at www.energy.gov/eere/2023-billion-ton-report.html.

4.5 Methods Overview

Quantifying biomass resources from forestlands must account for the many factors affecting its quantification: sustainability constraints, forest growth rates, operational costs, and competing demands for conventional forest products. The approaches to assessing forest woody biomass are described below, quantified with three forest economic models that each bring a valuable approach to this analysis. As with BT16, national estimated potential derived from ForSEAM addresses market dynamics in the conterminous United States (CONUS) and relies on the USFS national-level market projections. This approach adds value for a CONUS assessment, while leaving a need for specific market or local condition analyses. This report therefore includes two case studies. A market-driven analysis is provided using the SRTS inventory and harvest model for the South. New to this report is modeling of potential supplies made available from the WCS in the West. To account for these landscape-level dynamics influencing potential WCS biomass supplies, we leveraged the established USFS modeling approach to woody biomass estimation, BioSum. The BioSum and SRTS case studies provide additional context to the CONUS analysis. The accompanying visualizations provide comparisons between ForSEAM-modeled potential for these regions and the case studies. Additionally, this report draws on USFS data for currently available biomass from USDA-FS timber products output (TPO) analyses, as well as land removed from USDA-FS forest inventory and analysis (FIA) assessments because of human-induced land conversion (e.g., to development). Through this multi-analysis approach, we provide a comprehensive assessment of potential biomass resources available in the United States.

Wood Provides Fuel for Power

Source: Paul Pikna and Betsy Lesnikoski, Burlington Electric Department

A power plant in Vermont is an example of bioenergy in action, where the electric utility, Burlington Energy, has teamed up with the logging industry to use woods residue for fuel. Its 50-MW wood-fired McNeil Generating Station has been using wood residue to generate energy continuously for 40 years, providing electricity to more than 21,000 customers in Burlington—the most populous Vermont city with about 45,000 people—and surrounding communities.

In 2022, McNeil Station, the largest energy producer in Vermont, used a little more than 350,000 green tons of biomass fuel to generate about 230,000 TMWh of electricity. The vast majority of this fuel—88%—was from residues such as treetops and limbs, or damaged or diseased trees, with most of the remainder being made up of sawmill residuals and waste wood.

The wood plant uses high pressure and high temperatures, up to 1,500 psi and 950°F, to burn the wood chips and heat the water to create superheated steam that feeds a turbine and condenser. That converts the steam to electricity that can be made available on the grid. The utility and its partners prioritize sustainable biomass production and promote natural regeneration and accelerated growth of residual stems.

According to the 2023 final report on McNeil Station's forestry and carbon emissions and sequestration (Innovative Natural Resource Solutions 2023), using biomass at McNeil Station replaces natural gas power generating at alternative electricity generation facilities, preventing more than 80,000 tons per year of CO2 emissions from release. Additionally, utilizing biomass for energy supports a declining logging industry in this region due to sawmill closures and staffing shortages.

Photo from Adam Rabin, Burlington Electric Department

4.5.1 National Timberland Resources Modeled with ForSEAM

Consistent with BT16, logging residues and small-diameter (<11-inch-DBH) roundwood[3] from timberlands in the CONUS are quantified with ForSEAM. ForSEAM is a linear program that solves for the quantity of woody biomass available in a county, given the county's timber stand age class distribution, growth and yield, stumpage prices, and harvest costs. Extensive documentation on the ForSEAM approach is not repeated in this section, and we recommend consulting BT16 for further information (DOE 2016).

4.5.1.1 Methods: ForSEAM

CONUS forest biomass potential is estimated based on national wood demand using ForSEAM. The model first solves for conventional timber demands (i.e., sawtimber, pulpwood, and fuelwood) before estimating available logging residues as a function of conventional timber production. Subsequently, the model solves for price impacts and regional availability of user-specified outyear biomass production targets.

The price at which the demand levels will be met is represented by a shadow price, which is a calculated current price without a cost of delivery of the biomass (i.e., stumpage). The use of a shadow price in this section represents an estimate of future market price of woody biomass and does not consider potential scale-up of operations, which could result in decreased operational prices. For this analysis, ForSEAM was solved iteratively to determine the highest biomass production potential up to a shadow price of $70 per dry ton. This price is consistent with the reference price assumed for biomass crops. Exceeding this price has the potential to harvest Class 1 trees for biomass (Class 1 trees are typically used for sawtimber). The resulting demand trajectory is shown in Figure 4.5, with an initial starting quantity demanded of 0 dry tons annually in Year 1 of the simulation and increasing to 60 million dry tons over the simulation period. Risk of exceeding this demand level is discussed in Chapter 6.

4.5.1.2 Key Assumptions of ForSEAM

- Natural pine, planted pine, mixed (hardwood and pine), upland hardwood, and lowland hardwood are tree types used within ForSEAM and are an aggregation of individual species from the FIA dataset (USFS 2016). Although specific species are not reported out in the model, input species are restricted (e.g., exotics are removed). Please see BT16 Table 3.10 for more details and supplementary information on customized datasets used in this analysis stored on the Bioenergy KDF (https://bioenergykdf.ornl.gov).
- A defined data point (distance to road) within the FIA datasets (USFS 2016), rather than a GIS road layer dataset, was used in ForSEAM for road limitation assumptions to a half-mile distance to the road as a sustainability input.
- Harvesting is limited by the assumed annual growth rate (pine plantation growth rate) determined from the FIA dataset (USFS 2016). That is, total removals of forest woody

[3] Includes tops and limbs, and bole.

biomass are constrained to be less than net annual growth defined in the FIA data. Potential risks and consequences of deviating from sustainability assumptions in this CONUS analysis are discussed in Chapter 6, with further clarification on assumed goods management practices that can address potential effects of biomass harvesting, as well as ways to promote forest biodiversity such as excluding habitats of rare and valued species. These habitats of rare and valued species are not common in production timberlands where ForSEAM is applied. Site-specific analyses are required to evaluate potential environmental costs of biomass harvest from forests.

For a complete list of ForSEAM assumptions, please see BT16 (DOE 2016).

4.5.1.3 Key Input Data to ForSEAM

Costs to producers for the right to harvest (i.e., stumpage fees or procurement price) include replanting costs and are consistent with the analysis in BT16, with updates described in the appendix. These prices were generalized for five zones in the CONUS: Northeast, South, North Central, Midwest, and Pacific Northwest. FIA data on yield were extracted from the FIA database in 2016 (USFS 2016) and have again been used in this analysis. The TPO data were also utilized for traditional forest product harvest (quantity by state), and the density of forests in that state (a density ratio) was applied to the state and distributed at the county level.

The USFS's 2020 Resources Planning Act Assessment (USFS 2023d) provided the baseline (i.e., BAU) scenarios to ForSEAM. The 2020 scenarios considered lower and high GHG emissions futures described by the Intergovernmental Panel on Climate Change's Representative Concentration Pathways 4.5 and 8.5, as well as low, moderate, and high U.S. population and income growth futures characterized by Shared Socioeconomic Pathways 1, 2, 3, and 5, also inspired by the Intergovernmental Panel on Climate Change. The combinations of pathways were consolidated into four distinct scenarios. This analysis used a scenario of higher warming and moderate U.S. income and population growth combined with historic housing and bioenergy assumptions. See the appendix for a complete scenario description.

4.5.1.4 ForSEAM Results for Timberlands in the CONUS

Results suggest that up to 54 million tons of forest industry generated biomass[4] can be produced in a mature-market scenario without exceeding a shadow price (roadside) of $70 per ton and with no net change in timberland acres per model constraints. A summary of these results is shown in Table 4.2.. The model assumes that at the state level, growth exceeds harvest levels, ensuring a wide age class distribution across the landscape. Logging residues are simulated to be greatest at the end of the simulation period. Approximately 19 million tons of logging residues are simulated to be available annually at a stumpage price calculated at up to $40 per dry ton, with

[4] Additional CONUS-based resources may be sourced from hazardous fuels and are not included in this analysis. For example, see Byproducts of Fire-Focused Management: A BioSum Analysis of Two PILs for an analysis of WCS hazardous fuels.

the remainder consisting of small-diameter trees at prices ranging from up to $58.5 per dry ton in a near-term scenario to up to $70.1 per dry ton in a mature-market scenario.

Table 4.2. Biomass Production Potential by Resource Type Modeled in ForSEAM Totals 21.7 Million Dry Tons per Year Available in a Near-Term Scenario and 54.1 Million Dry Tons Available in a Mature-Market Scenario. A Shadow Price of up to $40 per Dry Ton for Logging Residues across Both Scenarios Is Assumed, and up to $58.5 and $70.1 per Dry Ton for Small-Diameter Trees Is Assumed for the Near-Term and Mature-Market Scenarios, Respectively. Distribution across Resource Types Favors Softwood Natural Logging Residues in Both Scenarios, and Softwood Natural Small-Diameter Trees in a Near-Term Scenario. In a Mature-Market Scenario, Hardwood Upland Small-Diameter Trees Supply 37% of Modeled Resources.

Row Labels	Near Term	Mature-Market Medium
Logging residues	18.5 million dry tons at up to $40 per dry ton	19.2 million dry tons at up to $40 per dry ton
Hardwood lowland logging residues	19%	21%
Hardwood upland logging residues	17%	19%
Mixedwood logging residues	21%	14%
Softwood natural logging residues	36%	32%
Softwood planted logging residues	8%	14%
Small-diameter trees	3.1 million dry tons at up to $58.5 per dry ton	34.9 million dry tons at up to $70.1 per dry ton
Hardwood lowland small-diameter trees	16%	33%
Hardwood upland small-diameter trees	10%	37%
Mixedwood small-diameter trees	4%	1%
Softwood natural small-diameter trees	57%	10%
Softwood planted small-diameter trees	13%	20%
Total	21.7	54.1

This analysis shows an initial biomass source (near-term scenario) from logging residues from Class 1 to Class 3, resulting from normal production practices of timber harvest. The modeled availability of softwood biomass from planted trees reaches more than 3 million dry tons annually in the initial years of this simulation and then quickly falls back to below 2 million dry tons per year as stands are modeled to be regenerated. Alternatively, softwood trees under natural regeneration (e.g., no assumed yield increase from genetic improvement) are simulated to yield logging residues of more than 6 million dry tons in Year 9 and sustain more than 5 million dry tons through the simulation period (Year 30). Likewise, lowland hardwoods and mixedwoods annually generate more than 3 million dry tons of logging residues from Class 1 to Class 2, with additional biomass from thinnings of Class 3, within the first 10 years of the simulation's start (Year 4 for mixedwood and Year 8 for hardwood lowland) and sustain this level over the simulation period. Upland hardwoods, however, do not produce more than 2 million dry tons per year of biomass from logging residues until the end of the simulation period. These hardwood upland stands instead produce biomass from Class 2 resulting from thinning operations, reaching more than 2 million dry tons of biomass annually by Year 8 and sustaining this level through Year 27 of the simulation period (Figure 4.5). Over a 30-year period, the model simulations show potential removals of 1.1 billion dry tons of biomass from CONUS timberlands within a half-mile from a road.

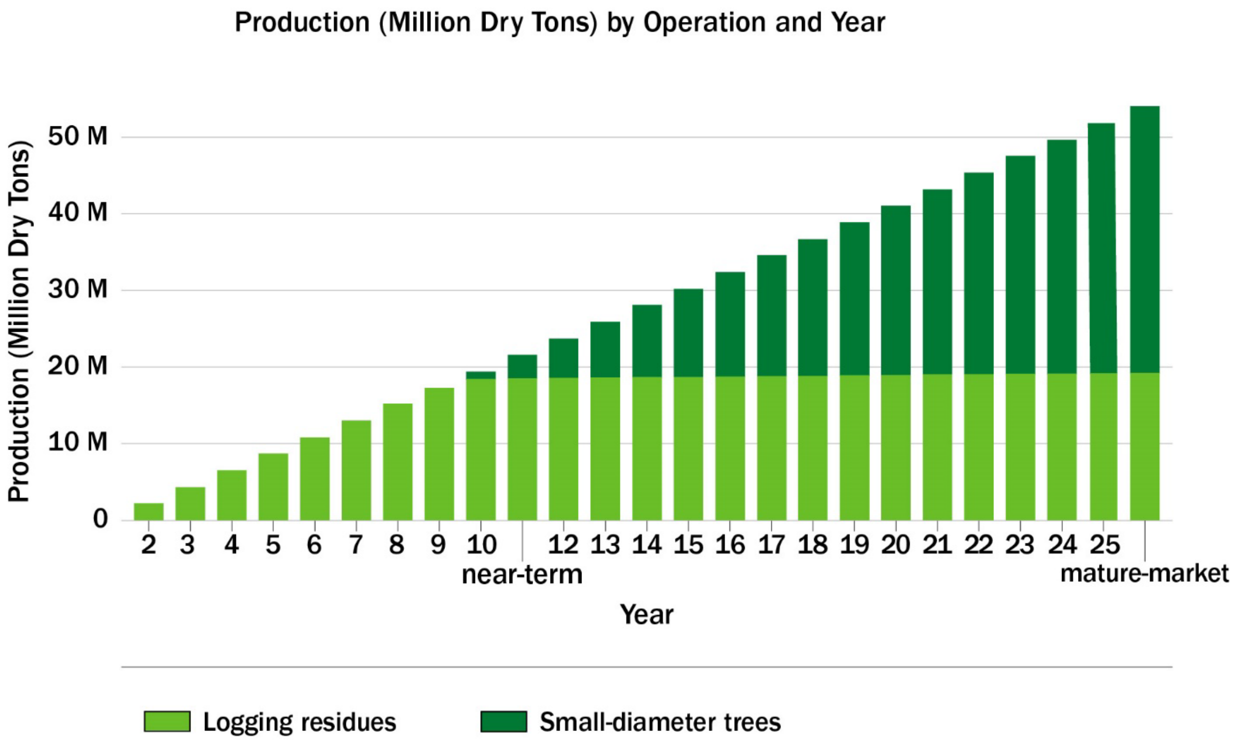

Figure 4.5. Production (million dry tons) by operation and year of the analysis, including highlighted near-term and mature-market scenarios. Biomass production trajectory used in this this analysis adds incremental biomass demand, beginning in Year 2 of the simulation at less than 5 million dry tons per year and culminating in more than 54 million dry tons per year of total biomass. Biomass production potential shows sustained logging residues (about 19 million dry tons per year) between near-term scenario years with the addition of small-diameter trees to meet demand quantities simulated (about 3–35 million dry tons per year) by the mature-market scenario year.

4.5.1.5 Discussion

More than 8 million dry tons per year of biomass are simulated to be available from small-diameter trees in hardwood (lowland) stands across the CONUS in a mature-market scenario (up to $70 per dry ton shadow price), with hardwood (upland) stands providing up to an additional 8 million dry tons annually. This analysis recognizes that hardwood thinning is not a common practice and that clearcutting may be an employed practice to harvest these resources. Lowland hardwoods should have additional considerations applied based on site-specific characteristics that were not modeled in this CONUS analysis, including site-specific sustainability priorities that may limit harvesting (see Chapter 6) and seasonal constraints that would naturally limit harvests (e.g., wet conditions making timber operations inefficient or damaging).

Small-diameter trees from softwood (natural regeneration) also contribute nearly 8 million dry tons per year in a near-term time frame and then decrease to less than 2 million dry tons per year by the mature-market scenario. Small-diameter trees from softwood (planted) stands do not contribute significant biomass until a mature-market scenario in this analysis. Mixedwood stands contribute sustained amounts of logging residues from Class 1–3 stands at more than 2 million dry tons annually throughout the simulation period, prior to a near-term scenario and extending beyond a mature-market scenario. Results indicate logging residues can be sustained at a level of 18.5 million dry tons per year across regions and resource types from a near-term scenario through to a mature-market scenario near the end of the simulation period.

Biomass production is presented as shadow price, representing cost of biomass at the roadside, at up to $70 per dry ton in the final year (mature-market scenario) of the simulation. The price point should be thought of as a breakeven price for the last ton harvested. The initial approximately 19 million dry tons of logging residues cost significantly less than $70, depending on regional markets and conditions.

Southeast Market-Driven Timberlands Modeled with SRTS Illustrate Regional Variation

SRTS is an empirical bioeconomic model that relies on the FIA data and analyst-defined changes in annual quantities of roundwood demand. This information is used to compute future forest growth, harvest rates, and roundwood prices across the South under a range of demand scenarios to provide context for this specific region to the CONUS assessments discussed in this section. In this analysis, SRTS considers relevant timber market projections in a spatially explicit simulation of growth, removals, and prices across 58 separate wood basins spanning the South. The South provides 99% of U.S. wood pellet export value to the European Union (USDA 2022), and renewable energy policy can have a significant impact on forest resources in this region (Chudy et al. 2013). Therefore, the South was chosen for this case study to provide additional data on regional variations in biomass markets relevant to industry managers and policymakers working in forest biomass markets.

This analysis specifically explores trajectories of available biomass feedstocks to the wood pellet industry, as well as the market consequences of emerging bioenergy with carbon capture and storage (BECCS) technology. Expected wood consumption needed to power a BECCS facility was modeled, and the sensitivity of forest biomass availability as a feedstock to wood pellet production was examined. This model assessed these market dynamics in the context of interactions between (1) pine sawtimber demand, which is the primary source of rent for timberland owners and drives changes in both the extent and management intensity of private timberlands; (2) pulp and paper demand, which is the primary consumer of small roundwood and mill residues; and (3) bioenergy demand, which competes with the pulp and paper sector for both small roundwood and mill residue feedstocks. A carbon price was not assumed in this analysis, but assumed changes in timber demand reflect current carbon market conditions. Additional background on previous work (e.g., BT16) and conditions, as well as information on domestic wood pellet production and exports, can be found in BT16 Chapter 3, appendices to this report, and the accompanying USFS report (Rossi et al. n.d.).

Key Findings

- Southern lumber production capacity increases are expected to increase demand for pine sawtimber and generate more byproducts (e.g., mill residue) from lumber production than observed historically.
- Sawmill capacity expansions are also projected to raise the availability of logging residues, which may be substituted for some mill residues in areas where demand for mill residues from the pulp and paper sector is especially high.
- Preferences for mill residues by the wood pellet sector could increase the capture and utilization of mill residues as sawmills see additional revenue opportunities from this byproduct to their lumber production.
- Higher preferences for mill residues as a feedstock to pellets places upward pressure on mill residue prices. However, the expanded capacity of sawmills to generate these byproducts places downward pressure on mill residue prices as supply expands. The net effect on mill residue prices from these two forces is uncertain and is likely to vary across wood basins in the South.
- When technological and cost limitations are overcome, BECCS should be expected to raise demand for small-diameter roundwood, pushing up prices in wood basins where investment in this technology grows. Utilizing greater proportions of dry mill residues as a feedstock to BECCS and pellet production can minimize associated increases in timber prices.
- Under a baseline scenario, softwood non-sawtimber harvests in the South (including pulpwood, chip-n-saw, and small-diameter whole-tree biomass) will exceed the projected harvests found in the BT16 SRTS analysis. Still, softwood pulpwood inventory is projected to expand through 2060.

Discussion

This SRTS case study has investigated how forest biomass may be used differently as market conditions change in the South, including as BECCS technology develops. Sawmill capacity changes critically impact the utilization of forest biomass for pellet production, particularly the availability of dry sawmill residues. Likewise, competition for sawmill residues from other sectors, harvests of small-diameter roundwood, availability of logging residues, and potential BECCS use of roundwood can impact forest biomass utilization for pellet production.

Future forest woody biomass availability in the South depends on the development of the pine sawtimber markets and the capacity for sawmills to generate byproducts from lumber and veneer sheet production. Lumber production and pine sawmills have had significant growth impacts, with additional growth expected (RISI 2023; Lang 2022). Projected increases in the harvest of pine sawtimber across the South could drive up consumption to around 70 million dry tons in a near-term scenario and about 72 million dry tons in a mature-market scenario. The potential for increased utilization of sawmill residues and logging residues by pellet manufacturers is enhanced by expected expansions in lumber production.

U.S. exports have gained an increasing share of the global trade of wood pellets, and the United States is the worldwide leader in densified biomass production capacity (EIA 2023). Nearly all domestically manufactured wood pellets are exported (Mendell 2019), and annual exports have increased 9% per year, on average, over the last decade (Ekström 2023). Valued at more than $1 billion in 2021, nearly all exported volumes of pellets are shipped to a European market. Japan also represents a growing source of demand for U.S. wood pellets; in the fourth quarter of 2022, Japanese markets received 13% of total U.S. pellet exports (Food and Agriculture Organization of the United Nations 2023).

4.5.2 Waste Biomass: Current Availability, Potential Forest Fire Biomass Case Study

Current forestland woody biomass can also be acquired from sawtimber operations at the mill, as discussed in the textbox "Southeast Market-Driven Timberlands Modeled with SRTS Illustrate Regional Variation," as well as land conversion from forestland to other uses. Lumber production capacity influences these sources of biomass; high production can result in additional availability of mill residues, and low production can mean high land conversion for other uses. Mill efficiency gains can reduce sawtimber waste streams, and on-site utilization of this biomass can reduce potential for external market use but may also offset the demand for energy from the power grid to supply these mills. This section provides an analysis of current availability of these waste resources as a foundation for potential annual supply, assumed consistent across near-term and mature-market scenarios. Additionally, a case study on potential forest fire biomass availability is provided in the textbox "Byproducts of Fire-Focused Management." Many regional- and industry-specific factors will determine annual biomass waste availability from these sources, and so specific market analyses should be conducted to determine actual potential from these projections.

4.5.2.1 Methods: TPO

This assessment drew on USFS TPO datasets for county-level estimates of wood residue volumes from primary wood processing facilities and timber harvest operations in the United States (USFS 2023e). The USFS National Resource Use Monitoring program includes two data collection efforts: an annual survey of primary wood processing facilities (i.e., TPO) and regular surveys of active logging sites (i.e., harvest utilization studies). Program information, as well as aggregated data currently available, can be found online (USFS 2023e). This analysis used a customized dataset available on the Bioenergy KDF data download for this report (https://bioenergykdf.ornl.gov/bt23-data-portal/).

The National Resource Use Monitoring county estimates on mill residues are for 2018, or the most recent year when 2018 data were unavailable. Mill residues are produced at a mill's site and directly linked to a mill's annual receipts to protect mill confidentiality. FIA's county-level mill residues are provided only for counties that have at least three active primary wood processing facilities during the survey year. Mill residue from mills in counties that do not meet the mill count threshold are allocated to a neighboring county. In this way, reported mill residues at the county level always represent, at a minimum, three mills. Green tons were converted to dry tons assuming a 50% moisture content.

4.5.2.2 Waste Results for Woody Biomass Available at the Mill

This dataset demonstrates an underutilized feedstock distributed across the United States, with more than 100,000 dry tons available annually for utilization in Arkansas, Tennessee, and North Carolina. Production of mill residues by state that are left unutilized total 1.1 million dry tons annually across the CONUS. Softwood has slightly more available biomass, at 0.6 million dry tons annually, with the highest production levels in Arkansas, North Carolina, Virginia, and Florida (Figure 4.6). Annually, 66.7 million dry tons of mill residues are already reported as used biomass in the dataset. Used biomass can supply on-site energy needs to mills, and has the potential to supply remaining energy to nearby communities when a connection to the power grid is established.

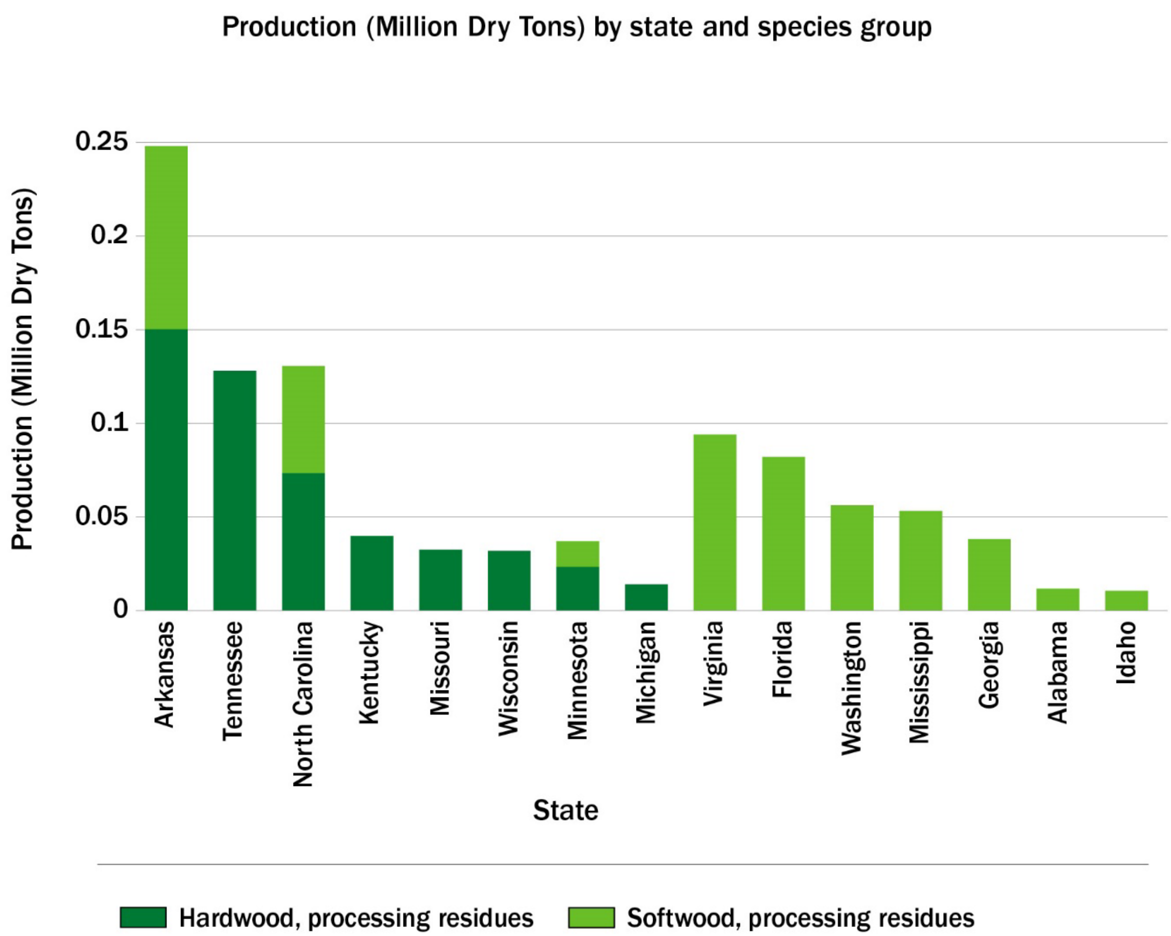

Figure 4.6. States producing more than 10,000 dry tons per year of mill residues that are left unused. Mill residues that are left unutilized total 1.1 million dry tons annually, with a concentration of residues unused in the South, with growth expected in softwood (e.g., pine) sawmills. Additional growth is expected, as discussed in the textbox "Southeast Market-Driven Timberlands Modeled with SRTS Illustrate Regional Variation."

4.5.2.3 Methods: Other Removals

This assessment again drew on USFS datasets for county-level estimates of wood volumes from land conversion in the United States. The USFS FIA program tracks forestland that upon resampling has been found to be converted to a non-forest use. The USFS categorizes these land conversions as “other removals,” meaning that they were removed from the forested land base. Relevant factors are catalogued and reported out with the FIA plot-level information.

The FIA data were queried at a county level to estimate the potential biomass available annually from these activities. This analysis excluded trees that were found to be alive upon resampling (e.g., a developed area with intact tree cover, but which no longer qualifies as forestland). Standing dead trees, meaning those that were dead at the plot visit but were still standing, were assumed to be an available source of biomass. Removed biomass are trees that had been cut and removed prior to the FIA sample and are assumed by the USFS as utilized. In this analysis, we assume 50% of this biomass to be potentially available for a near-term scenario, with a market for this biomass. Given the absence of information on why the land conversion occurred or the state of the timber that was removed, it would be difficult to estimate a per-ton price for this biomass by land conversion category. However, we assume a price similar to hog fuel of $50 per dry ton and assume that haul distance would be a significant factor in mobilizing this biomass. Biomass beyond 3 miles to a road is not included in our analysis, being cost-prohibitive for this low-value waste resource. Further, we have constrained our analysis to forestland land conversion to agricultural land, cropland, pasture, idle farmland, a maintained wildlife opening, rangeland, other human activity (e.g., business developments), right-of-way, or other nonhuman activity.

4.5.2.4 Results for Waste Biomass Available from Land Conversion

Other removals of woody material from the forested land base total 7.5 million dry tons per year. Primarily from development activity such as commercial development on previously forested lands or clearing for right-of-way, this biomass source includes accessible material within 1,000 feet of a road. Additional biomass is available from conversion to agricultural purposes, although the majority of this biomass may require longer-haul distances of up to 3 miles (Figure 4.7).

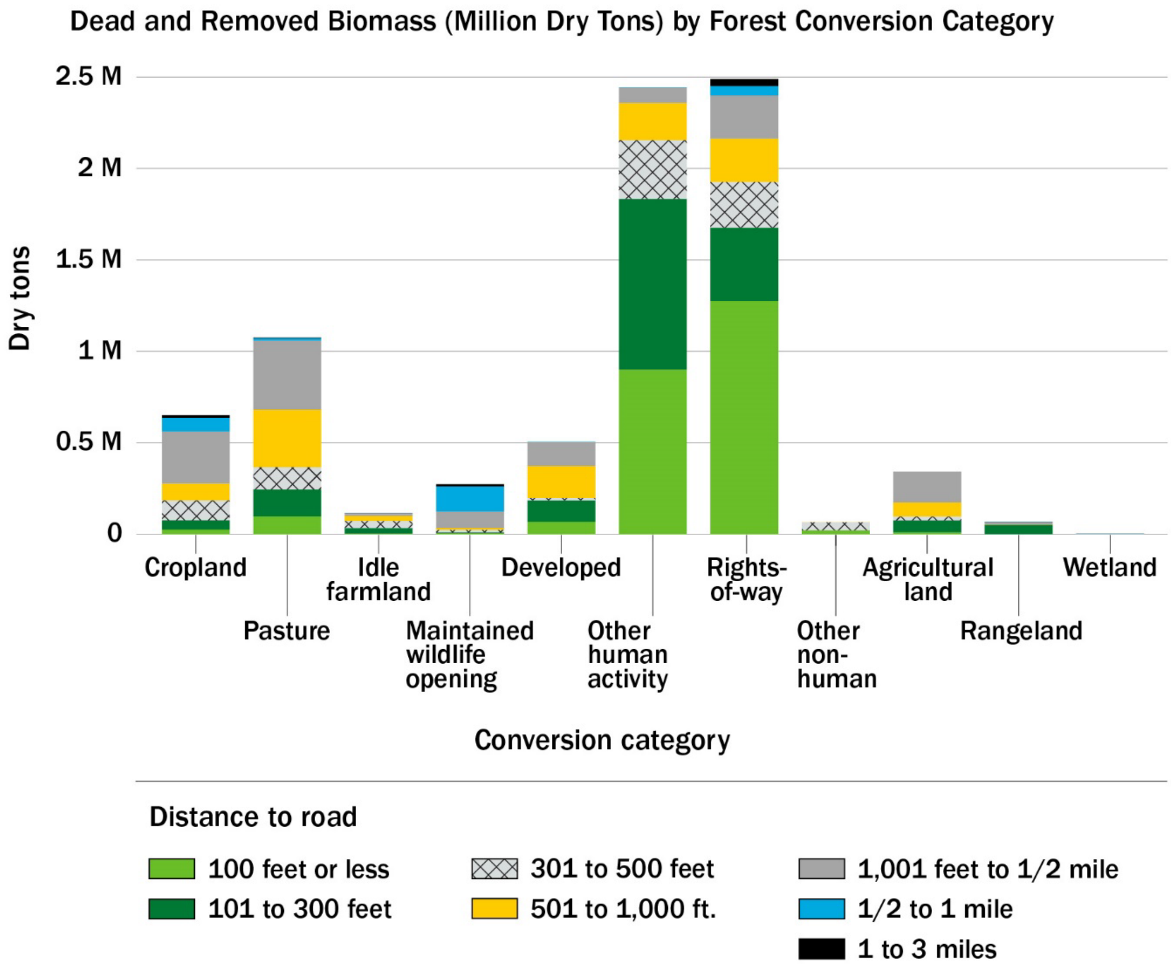

Figure 4.7. Potential forest waste from land conversion to various non-forest uses that are potentially left unutilized totals 7.5 million dry tons annually. Haul distance is expected to limit availability of biomass beyond 3 miles to a road. A price similar to hog fuel of $50 per dry ton is assumed because biomass quality is unknown for these resources.

Byproducts of Fire-Focused Management: A BioSum Analysis of Two PILs

The USFS announced the WCS in 2022, aiming to reduce catastrophic wildfire risk on 50 million acres of PILs via fuels management (USFS 2023a). When such management is implemented as mechanical fuel treatments, it may produce both merchantable wood, such as what can be utilized to manufacture conventional wood products, and biomass feedstocks, potentially suitable for other uses. This assessment evaluates the potential scope of woody biomass feedstock that could be generated as a byproduct of fire-focused management of Western forests via a case study. This study applied the USFS research and development analysis framework known as BioSum to predict biomass yield in the near-term and mature-market summaries discussed earlier. Detailed modeling assumptions are described in the appendix and summarized below.

Methods: BioSum Case Study

Two of the 10 initial PILs (USFS 2022a) were analyzed: Arizona's 4.4 million acres of forest within the Four Forests Restoration Initiative (4FRI) and 2.3 million acres of forest within the Central Washington Initiative (CWI). Together, these comprise half the anticipated treatment area opportunity of the initial PILs. The WCS seeks to treat 350,000 acres of the Okanogan-Wenatchee National Forest in the CWI and 355,707 acres of central and northern Arizona forests over approximately 10 years. Six of the 10 communities at greatest risk in Washington can be found on the CWI landscape, and six of Arizona's highest-risk firesheds are within 4FRI (USFS 2022b). Biomass feedstock felled and yarded to the roadside as a result of WCS implementation can be thought as a waste byproduct of fire-resistance-enhancing fuel treatments paid for by congressionally appropriated funds and revenues from sales of merchantable wood. Collection of this byproduct material from the roadside for utilization can benefit an owner or agency by avoiding the cost of disposal they would otherwise incur (e.g., via air curtain destruction). Delivery cost from the roadside to a utilization facility can thus be seen as a proxy for a biomass purchase price at the facility gate that leaves forest owners better off by removing disposal liability. Timber of merchantable size and species that is removed by fire resistance enhancing treatments is assumed to be sold and utilized, where markets exist, so that wood is not accounted in the biomass results discussed below. The authors acknowledge that some harvested merchantable timber may be left in the forest as residue or removed as additional biomass where local conditions (e.g., low timber value, high recovery and delivery costs) are barriers to removal. Although additional woody-material may be available on the landscape, some of this material may be retained in the forest while still meeting the goals of local land managers for fire resilience.

BioSum Results for Case Studies in the West

Based on the most likely silvicultural alternatives and currently articulated fire resistance goals, the 4FRI landscape could deliver 0.13 million dry tons per year of woody biomass feedstocks over the initial 20 years of treatments, assuming the availability of up to $70 per dry ton to cover haul costs to the nearest facility. Up to 0.14 million dry tons per year could be delivered with $110 per dry ton available to cover such costs, although as of 2023, prices for delivered, chipped biomass may not yet reach this price. Treatment could enhance resistance in 55% of targeted high-priority stands in the 4FRI region, as assessed by elevating canopy base height and reducing canopy bulk density. The CWI landscape can deliver up to 0.30 million dry tons per year of biomass feedstock over the 20-year assumed treatment installation period at a delivered price of up to $70 per dry ton, or 0.31 million dry tons per year at up to $110 per dry ton. Bioenergy feedstock availability declines markedly in the 4FRI landscape, where we modeled retreatment as early as 20 years following the first treatment. The CWI analysis did not include reentry treatments, and so assumes all management activities occur in the first 20 years. Treatment in this landscape would enhance resistance in 68% of targeted high-priority stands, as indicated by an increase in the 20-year mean composite resistance score (Fried et al. 2017). The remaining 32% of that landscape may be left untreated, while still achieving landscape-level fire resistance objectives over the initial 20 years of WCS.

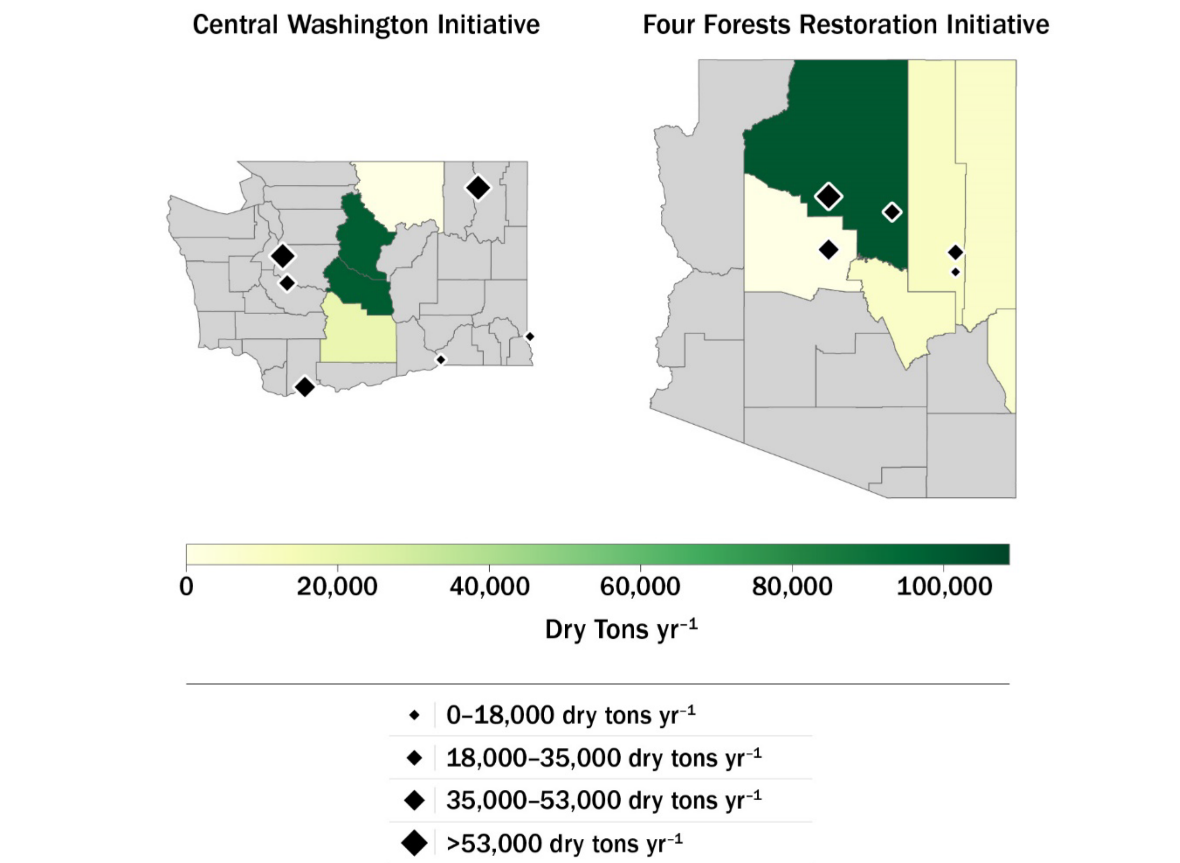

Figure 4.8. County-level woody biomass feedstock quantities produced, and facilities receiving those feedstocks (sized by quantity delivered), for the 0.13 million dry tons per year generated by the 4FRI PIL and the 0.3 million dry tons per year generated by the CWI PIL at a facility gate price payment of up to $70 dry per dry ton. Haul distances for biomass extracted from the CWI PIL are quite far, owing to a dearth of nearby facilities, suggesting the potential to site a facility in or near this PIL.

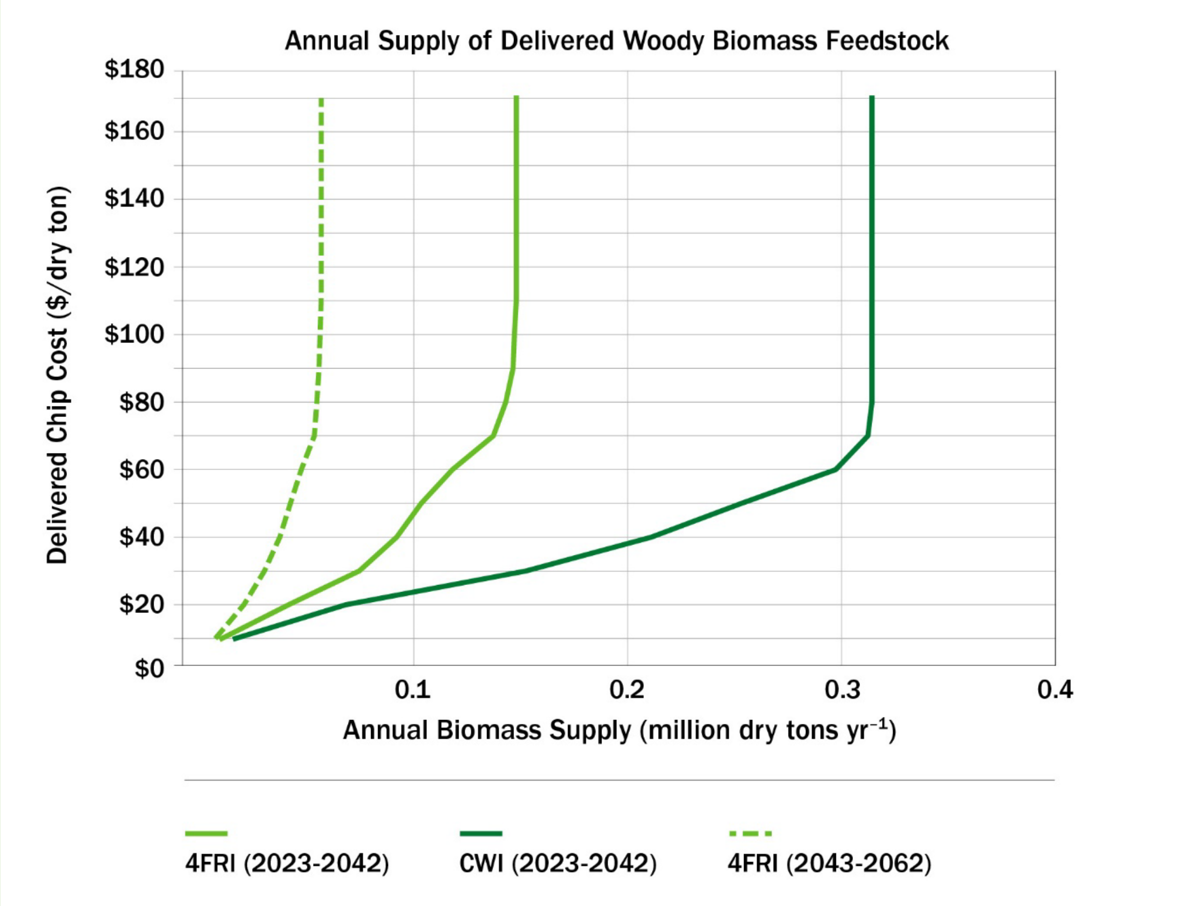

Figure 4.9. The 4FRI PIL's supply curve for woody biomass feedstock indicates considerably greater supply in both two-decade periods than the CWI PIL in 2023–2042. In both landscapes, prices over $70 generate very little additional feedstock, and prices above $110 per dry ton deliver no increase in additional feedstock.

Discussion

With 11 new WCS PILs targeted for treatment by the Inflation Reduction Act in 2023, adding to the 10 identified under the Bipartisan Infrastructure Law in 2022, 19 PILs remain to be analyzed in depth to understand their prospects for delivering additional benefits to the bioeconomy via woody biomass feedstock and the extent to which resistance to stand-replacing fire can be achieved. Modeling parameters and assumptions behind the two landscapes analyzed here are documented in the appendices. In both landscapes, we assumed treatments would be implemented only if effective. For 4FRI and CWI, this means, respectively, 45% and 32% of these landscapes may remain untreated for lack of an effective option. USFS (2022b) estimates that even with only one funded opportunity to manage a stand, managing 40%–60% of landscape will yield 80% of desired results by segmenting landscapes into mosaics of stands with differing fuel loadings and time since management.

Treatment in the other 19 PILs would certainly generate additional biomass; however, we do not yet have the parameters needed to conduct BioSum analyses. Extrapolation from the two PILs we did model can provide a rough first approximation of what might be expected, with the caveat that ecological, political, and economic factors, as well as management goals and constraints, vary a great deal among PILs. For example, PILs vary as to the relative proportion of treatment area accomplished via thinning, which can yield biomass, versus prescribed fire operations, which do not. Noticing some consistency among the two analyzed PILs (plus one more that was analyzed in part) in yield factors (the forecasted biomass yield as a percent of live biomass within the PIL), we applied the lowest and highest yield factors to all PILs to estimate annual recoverable biomass potential. For the 28.2 million forested acres within the 43.2-million-acre area of all 21 PILs combined, this rough extrapolation predicts 1.8–2.9 million dry tons per year of biomass feedstock availability associated with treatment on the 556,000 acres set in 2023 as the initial annual WCS treatment area goal, which most likely includes acres that would have received treatment without the WCS. These estimates almost certainly overstate biomass yield because at least some management and treatment operations were already occurring in these PILs before the WCS. Even at the high end of the range, mean biomass yield (5.2 dry tons per acre) is low because in many of the areas (nearly all, in some PILs), treatment acres are accomplished via burning operations that yield no biomass.

4.5.3 Discussion of Waste Biomass Available in the CONUS

Per Table 4.3, 11.5-12.6 million dry tons of waste from the forested land base are potentially available in the CONUS. This quantity could easily increase if interannually variable resources from extreme weather or other disturbance events are included. Two case studies have modeled potential biomass and merchantable timber generation from USDA-FS WCS treatments of up to 0.4 million dry tons annually in a near-term scenario. Additional biomass would certainly be generated from treatment in the other 19 PILs, and a rough extrapolation predicts 1.8–2.9 million dry tons per year may be available, but estimation requires additional modeling under future work by the USDA-FS. Overall, this analysis showed fewer resources available in this conservative analysis than in BT16 for waste-based biomass (e.g., “other removals” decreased). However, significant opportunities exist to leverage these resources at a minimized cost. For example, there is still capacity to utilize mill residues, and existing unused mill residues are already collected and accessible at the mill gate in many cases. We assume a cost of $54 per dry ton for mill residues and $50 per dry ton for waste biomass from conversion of forestland, which reflects recent industry price increases since BT16 was published (TimberMart-South 2023).

Table 4.3. Biomass Production Potential by Resource Type Totals 11.5–12.6 Million Dry Tons per Year Available in a Near-Term Scenario and 65 Million Dry Tons Available in a Mature-Market Scenario. A Shadow Price of up to $50 per Dry Ton for Other Forest Waste across Both Scenarios Is Assumed, and up to $54 per Dry Ton for Mill Residues Is Assumed for the Near-Term and Mature-Market Scenarios.

Waste Type	All Scenarios (Million Dry Tons/Year)
Forest processing waste	1.1
Hardwood, processing residues	0.5
Softwood, processing residues	0.6
Other forest waste	7.5

Mixedwood thinning residues[5]	1.8–2.9
Grand total	11.5–12.6

4.6 Discussion: Potential Availability Depends on Developing Markets and Could Scale To Be Larger than Reported

Leveraging massive, untapped volumes of woody biomass currently available on the landscape and projected to be available in the future depends on technological innovation, policies, and developing markets. If these opportunities are realized, woody biomass utilization could scale beyond what is reported in this analysis. The modeled supplies presented above are limited by environmental and economic constraints, which will vary with site-specific management. Thus, these results may not represent the full potential of resources for specific areas with an overabundance of forest biomass and threat of natural hazards (e.g., wildfire). These factors may motivate land managers to remove additional biomass, and specific market mechanisms (e.g, payments for ecosystem services, PES) may enable additional removal.

The authors acknowledge that there is opportunity to expand wood manufacturing in the Western and Northern Resources Planning Act regions based on FIA forest growth-to-harvest ratios and necessary hazardous fuel treatment. For example, a reported challenge for the WCS and for most forest landowners is the lack of a market (i.e., demand, corresponding prices) to move available wood from the site of biomass production to end-use facilities. Therefore, this modeling exercise discussed in the CONUS section (See section 4.5.1, "National Timberland Resources Modeled with ForSEAM") could be expanded to include residues available from future market harvests to capture additional biomass in these regions. Benefits to reducing fuel loads include reducing catastrophic wildfire, which in turn improves water quality; protects homes, wildlife habitat, historic and sacred sites; protects established and future recreation, lives, infrastructure; and avoids carbon release from burning. Developing markets (e.g., PES) and removing more biomass from forested stands that are threatened by wildfire and other disturbances can benefit society. Additional biomass from disturbances such as dead and diseased trees or waste timber generated from a one-time hazardous event (e.g., storm debris) would increase supply for biomass markets but vary annually and are hard to predict. Future research areas include: further analyses of WCS PILs for woody biomass potential; monitoring extreme weather events for woody biomass that could be harvested; opportunities for market development by recognizing the ecosystem service that biomass removal provides in some landscapes (e.g., fire-prone areas); and continued technological innovation to make biomass removal cheaper and easier, while reducing ecological impacts of biomass removal (e.g., compaction).

[5] This analysis includes a rough extrapolation of two WCS case studies and estimates of additional material, such as merchantable timber, are not included. Although additional woody-material may be available on the landscape, some of this material may be retained in the forest while still meeting the goals of local land managers for fire resilience.

4.7 Conclusion

CONUS resources in near-term and mature-market scenarios show a base of logging residues from the near-term scenario to the mature-market scenario of our analysis. Biomass production potential shows 30.3 million dry tons per year available in a near-term scenario and 62.7 million dry tons available in a mature-market scenario. Across both scenarios, shadow prices of up to $40 per dry ton for logging residues, $50 for other forest wastes, and $54 for mill residues are assumed (Table 4.4). Up to $58.5 per dry ton in a near-term market and $70.1 per dry ton in a mature market is assumed as a shadow price for small-diameter trees. Beyond the mature-market scenario assumption of a biomass price reaching $70.11 for small-diameter trees, and beyond sustainability constraints of our analysis, additional biomass is potentially available but excluded in this assessment. Risks of deviating from the constraints in this analysis are discussed in Chapter 6 and should be used to inform decision-making on biomass market development.

Table 4.4. Biomass Prices by Resource Type Include a Range from $40 per Dry Ton (Near Term) to $70.11 per Dry Ton (Mature Market)

Row Labels	Near Term	Mature Market
Fire reduction thinnings	$70.00	$70.00
Logging residues	$40.00	$40.00
Other forest waste	$50.00	$50.00
Mill residues	$54.00	$54.00
Small-diameter trees	$58.54	$70.11

Under an assumption of harvesting within a half-mile of a road, and under the development of a sustained market for biomass production reaching prices shown in Table 4.4, potential resources for a developing bioeconomy total 21.7 million dry tons per year available in a near-term scenario and 54.1 million dry tons available in a mature-market scenario under the ForSEAM analysis across logging residues and small-diameter trees. Distribution of this potential biomass across resource types shows softwood natural logging residues to be a major contributor to this market in both scenarios, and softwood natural small-diameter trees as a significant source of biomass in a near-term scenario. In a mature-market scenario, the ForSEAM analysis showed hardwood upland small-diameter trees contribute a majority of modeled resources. The production trajectory for biomass used in this analysis showed incremental increases in biomass demand, starting at less than 5 million dry tons per year and sustaining this growth into a mature-market scenario that can be thought of as before 2050. This analysis projects that more than 35 million dry tons per year of small-diameter trees would be available from the timberland base alone by 2050, after conventional timber demands are met. The harvest for conventional forest products is about 219 million dry tons per year, leaving about 14,000 million tons of tree biomass unharvested on timberland across the CONUS annually. Sustained logging residues of about 19 million dry tons per year are the foundation on which a bioeconomy can grow, with an additional 23 million tons per year of additional unharvested logging residues available annually.

The analysis of timberlands in the Southeast provided additional information on biomass from byproduct sources that can be impacted by announced expansions of lumber capacity, as well as potential impacts to conventional product demand in the Southeast. This expansion reflects an assumption that additional mill or logging residues become available for bioenergy, or reduced biomass prices are realized with mill or timber production expansion. Southeast timberland acreage changes reflect plantation expansion (above 1950 levels) and a doubling of growth rates that have had positive financial returns for timberland managers in less time. Recent analyses have shown the potential for expanded use of wood for bioenergy to maintain or contribute carbon benefits (e.g., as a net-zero decarbonization pathway), with policies that regulate forest carbon sequestration (Favero, Daigneault, and Sohngen 2020). Externalities (e.g., environmental) of a growing biomass industry are outside the scope of this analysis and should be considered in future research.

Additionally, there are more than 15 states producing more than 10,000 dry tons per year of mill residues that are left unused, with a heavy concentration in the South. Unutilized material totals 1.1 million dry tons annually, with growth expected in softwood (e.g., pine) sawmills, as discussed in the textbox "Southeast Market-Driven Timberlands Modeled with SRTS Illustrate Regional Variation." Used mill residues currently total 66.7 million dry tons annually, showing significant utilization of this resource already. Additional potential forest waste from land conversion to various non-forest uses that may not be fully utilized also totals 7.5 million dry tons annually. Haul distance is expected to limit availability of biomass beyond 3 miles to a road, and many of the resources shown in this analysis are within a few hundred yards of the nearest road. These land conversion activities span human activity such as development and clearings for right-of-way, as well as conversion to other land uses such as agricultural land. A price similar to hog fuel of $50 per dry ton is assumed for this biomass because quality is unknown for these resources and assumed to be low for anything left unutilized.

Additional accessible waste-based resources, including 0.4 million dry tons of additional biomass available annually from the two wildfire reduction select case studies in Arizona and Washington, are available in a near-term scenario and assumed to be sustained across the analysis time frame. As discussed above, additional biomass would likely be available from other PILs and is difficult to estimate, but an extrapolation has been made of 1.8–2.9 million dry tons per year of biomass feedstock availability associated with treatment on the 556,000 acres set in 2023 as the initial annual WCS treatment area goal. A facility gate price payment of up to $70 per dry ton was assumed, with very little additional biomass available beyond this price in the two case studies of 4FRI and CWI. Haul distances for biomass extracted from the CWI PIL show an opportunity to site a biomass handling facility in or near this PIL. The 4FRI PIL's supply curve for woody biomass feedstock indicates considerably greater supply in each two-decade period, as compared to the CWI PIL. In both landscapes, prices above $110 per dry ton deliver no increase in additional feedstock. However, this analysis has demonstrated potential biomass that is currently underutilized and at risk of resulting in carbon emissions and further damage from wildfire in the Western United States.

This analysis has again demonstrated available biomass across the forested land base at economically accessible prices for a developing bioeconomy. Consistent with BT16, ForSEAM and SRTS provide market analyses and illustrate regional variation in these markets. BioSum modeling provides more detail on regional biomass, primarily on federal lands. Wood wastes in land converted from forests and at mills shows additional biomass potential for a growing bioeconomy.

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Chapter 05 | Biomass from Agriculture

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5 Biomass from Agriculture

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This report and supporting documentation, data, and analysis tools are available online:

Report landing page: https://www.energy.gov/eere/bioenergy/2023-billion-ton-report-assessment-us-renewable-carbon-resources

Data portal: https://bioenergykdf.ornl.gov/bt23-data-portal

Summary

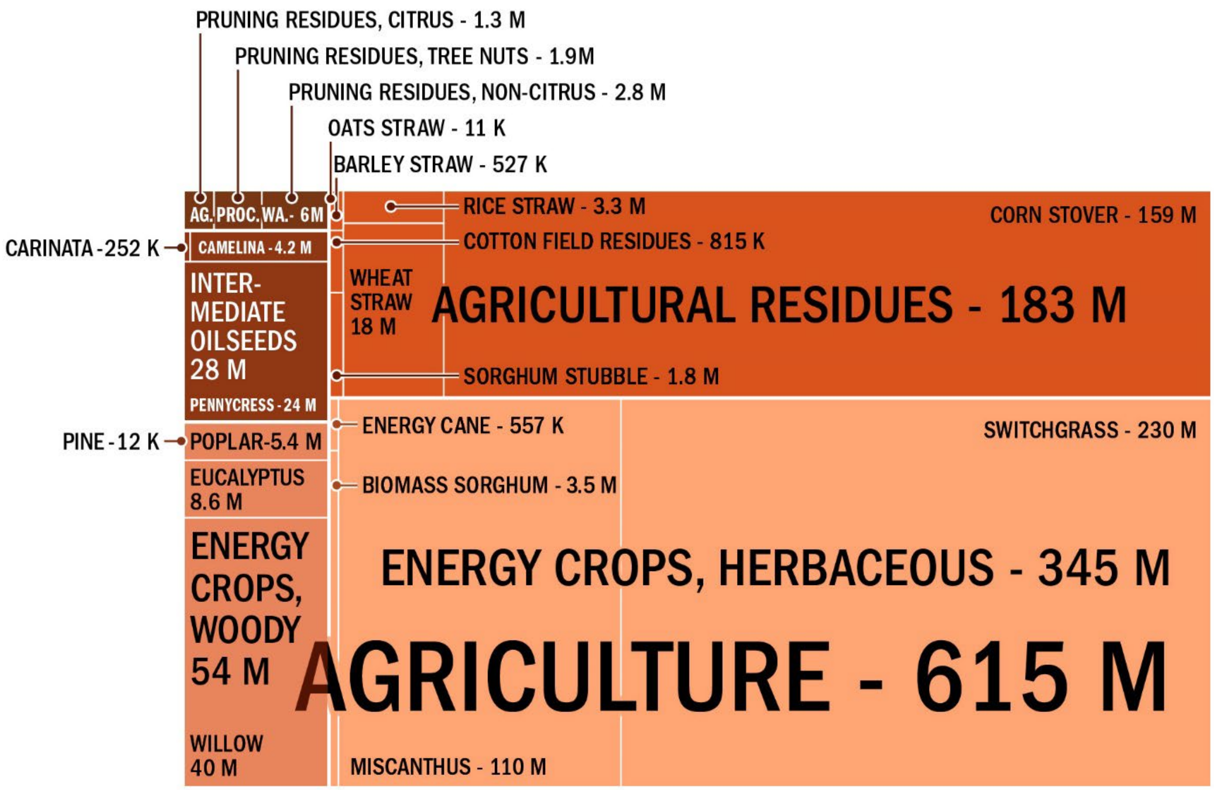

Figure 5.1. National biomass resources from agricultural lands, mature-market medium scenario, $70 per dry ton for cellulosic resources, $400 per dry ton of seed for intermediate oilseed resources. Units in dry tons of biomass except for carinata, camelina, and pennycress, which are in units of tons of oilseed.

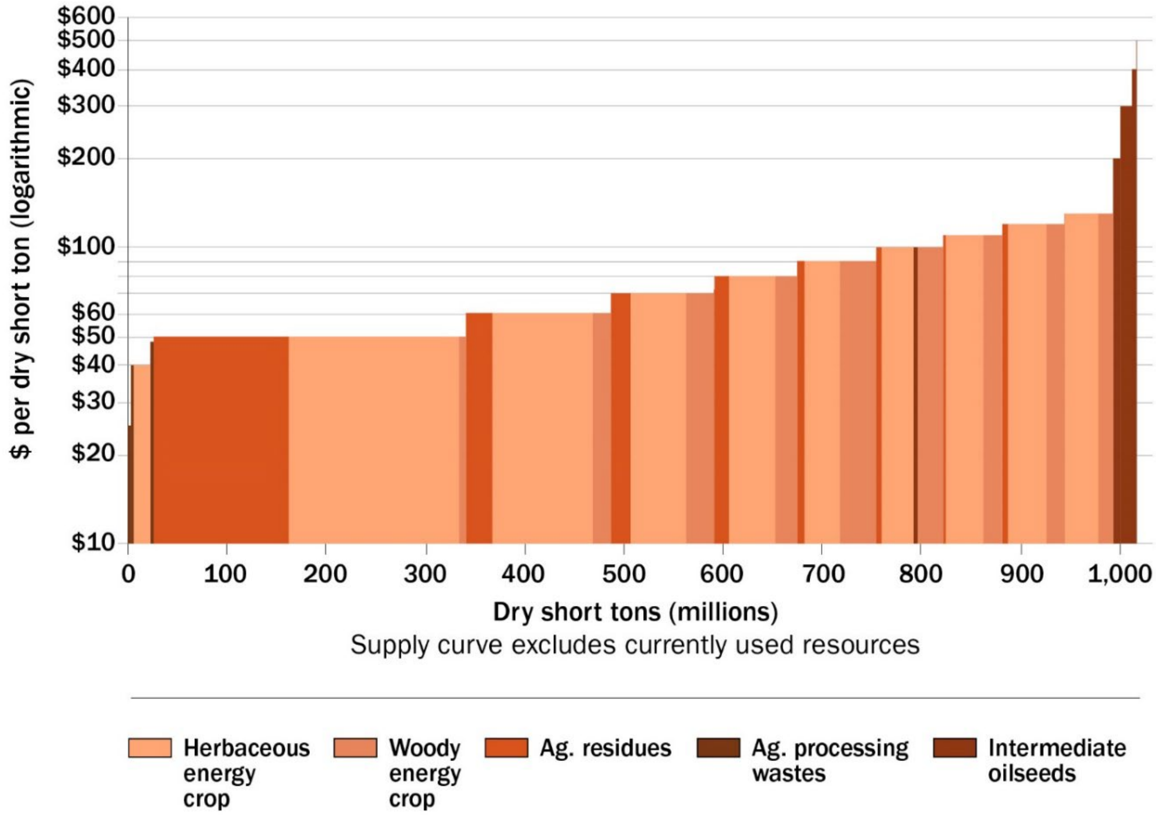

Figure 5.2. Stepwise supply curve of agricultural resources, mature-market medium scenario

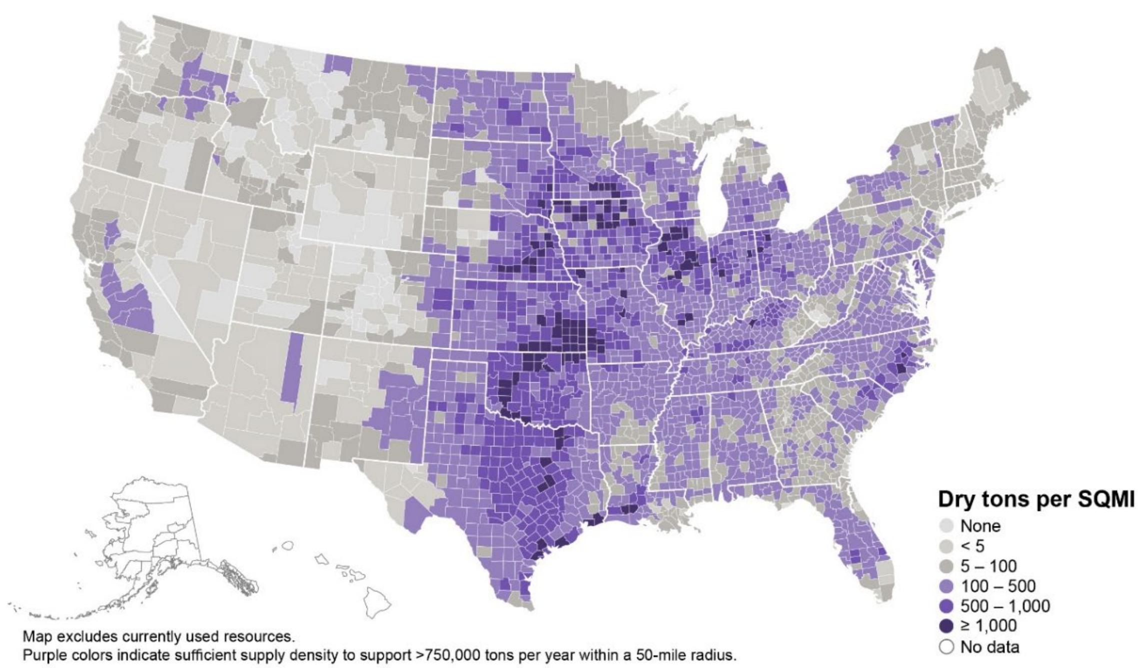

Figure 5.3. Spatial distribution of agricultural resources, mature-market medium scenario, cellulosic resources at $70 per dry ton, intermediate oilseed crops at $400 per ton of seed

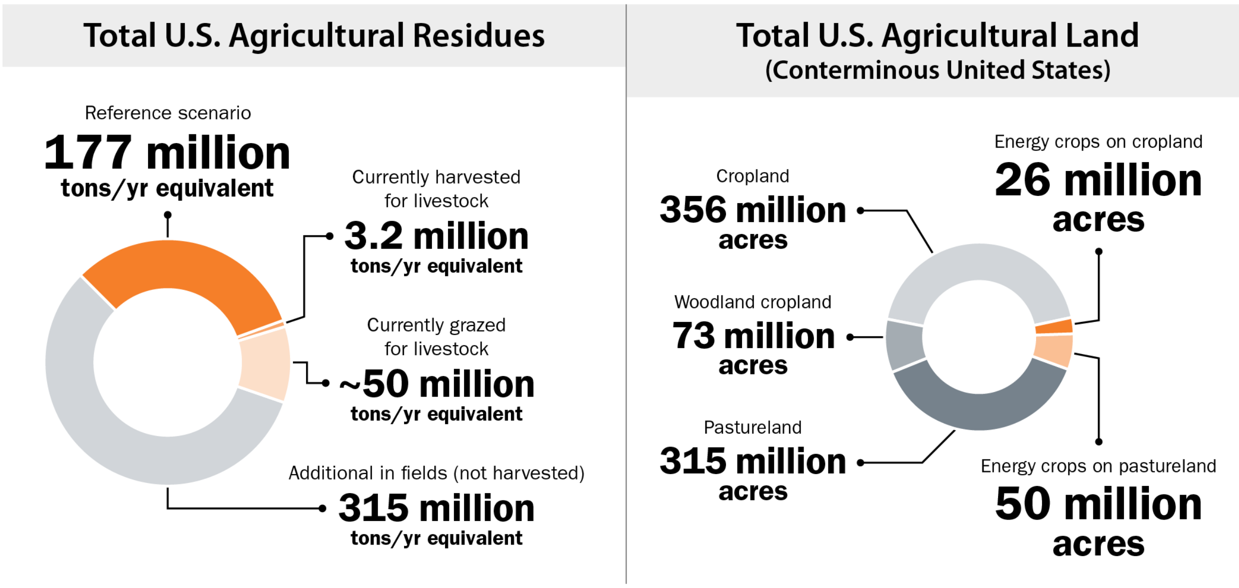

Figure 5.4. Agricultural residues (corn stover and wheat straw) reported as available in mature-market medium scenario at $70 per dry ton in proportion to total in-field production; agricultural land allocated to purposed-grown energy crops in the mature-market medium scenario at $70 per dry ton in proportion to total U.S. agricultural lands

- Sustainability constraints of this analysis are summarized in Table 1.4, and risks of deviating from these constraints are discussed in Chapter 6.
- Biomass resources from agricultural lands explored in this chapter provide the major share of biomass in future market scenarios. At a reference price of $70/dry ton (2022 $), this includes about 140–180 million tons per year of agricultural residues, and roughly 300–500 million tons of purpose-grown energy crops on about 9% of total U.S. agricultural lands, depending on scenario assumptions. Agricultural residue removal is constrained for soil conservation and adoption rates as described below, resulting in less than one-third of residues being removed nationally in the mature-market medium scenario.
- Purpose-grown energy crops are shown to have comparative advantages in regions of less intensive conventional crop production (e.g., the southern Plains, as compared to the Corn Belt). Other studies have sometimes restricted purpose-grown energy crop siting *a priori* to tracts of land with lower yields, higher vulnerability to degradation, or other biophysical characteristics that make sustained production of conventional crops challenging (Khanna et al. 2021). However, farmers make crop production and land allocation decisions based on a variety of factors, and we believe that allocating purpose-grown energy crop production to tracts of low-yielding lands in isolation of economic interactions would fail to reflect realistic futures and inevitable economic interactions among crop markets (Skevas et al. 2016; Swinton et al. 2017). As with previous reports, we instead evaluate purpose-grown energy crop production potential within an economic context of other crop options.

- About 587 million dry tons per year of cellulosic biomass resources can be produced in the United States under a mature-market medium scenario price of $70/dry ton. Of this, 183 million tons is sourced from crop residues and 398 million tons is from purpose-grown energy crops grown on cropland and pastureland, with the remainder from agricultural processing wastes. In this scenario, major grains and soybean commodity prices are estimated to increase by 5% to 20% over business as usual as biomass markets reach maturity, which is well within recent historic annual variability. This translates to up to a 0.7% weighted average finished food price increase. The combined impact is modeled to increase in total farm market net revenues of 31% over business as usual.
- A mature cellulosic market would result in the uptake of 32 million metric tons of CO_2 in soils growing perennial purpose-grown energy crops. Assuming one vehicle emits 4.6 metric tons of CO_2 per year, this is the equivalent of displacing emissions from nearly 7 million cars.
- Intermediate oilseed crops grown in winter as part of a rotation with summer-grown crops can provide 21 billion lbs. (10.5 million tons) of lipid oil per year. Commodity price impacts due to intermediate crops are minimal due to no land use competition for off-season crops.

5.1 Background

5.1.1 Introduction

We present an updated estimate of potential biomass supplies from agricultural lands. The potential for farmers to respond to new markets for biomass has been assessed with the Policy Analysis System Model (POLYSYS) in previous versions of the billion-ton report (DOE 2017, 2016, 2011) and other studies (Oyedeji et al. 2021; Davis et al. 2020; Langholtz et al. 2019; Woodbury et al. 2018; Eaton, Langholtz, and Davis 2018; Langholtz et al. 2014; Langholtz et al. 2012; Jensen et al. 2007; De la Torre Ugarte and Ray 2000; Hellwinckel et al. 2015). Building on previous analyses, POLYSYS was used to update estimates of biomass supplies and prices from agricultural lands given environmental, land use, and technical constraints. The POLYSYS model, methods, and constraints are summarized below and detailed in the appendix.[1] Model dynamics are illustrated in Figure 5.5.

Changes from previous billion-ton reports include the use of the new 2023 USDA baseline, reporting of mature-market biomass supplies (see Section 5.2: Methods Summary), oilseed supply estimates, and reporting of changes to carbon emissions and soil sequestration.

5.1.2 Agricultural Land Potential

U.S. agricultural lands consist of 382 million acres of cropland and 415 million acres of pastureland; 80% of cropland is planted to only eight annual crops. Corn is the largest crop in the United States with 95 million acres in 2023 (USDA-NASS 2023b); 37% of corn production goes

[1] Access BT23 appendices at www.energy.gov/eere/2023-billion-ton-report.html.

directly to feeding livestock and 35% is processed for ethanol production while coproducing high-protein feed ingredient (dried distillers grains with solubles). Soybeans are the second-largest crop in the United States with 87 million acres, where 51% of production is crushed to coproduce meal and oil. Almost 100% of the meal is fed to livestock, and 39% of the oil is used to produce biofuels. The majority of pastureland is devoted to low-intensity grazing of livestock. The introduction of perennial purpose-grown energy crops can be a net energy resource for the nation while also playing a role in crop diversification, soil conservation, and improving farm income. Sustainably harvesting agricultural residues and winter intermediate oilseeds from annual cropland can also be a major source of bioenergy feedstock while simultaneously ensuring soil health.

5.2 Methods Summary

- Quantifying biomass resources from agricultural lands must account for sustainability constraints, alternative land use options, operational costs, spatially explicit crop productivity potential, and competing demands for conventional agricultural products. These are quantified with POLYSYS, a partial equilibrium socioeconomic model. As a starting point, POLYSYS determines land use at the county level based on USDA-projected national acreage yield and prices and demands for food, feed, fiber, and exports for conventional crops.[2] Then it models land allocation, introducing purpose-grown energy crop demands, and reports changes in supply, demand, and price effects of traditional and energy purpose-grown crops.
- The USDA baseline and its extension to 2041 does not make any explicit assumptions on impacts of climate change in U.S. or international crop yields. Neither makes any explicit reference to wide interventions toward reducing the economy's carbon footprint—e.g., changes in corn ethanol demand driven by electrification of the light-duty vehicle fleet. Regarding biofuels, corn ethanol demand is projected at 15 billion gallons per year and biodiesel from soybeans at 1.5 billion gallons per year throughout the period of 2023–2041.
- Crop residue removals cannot exceed the tolerable soil loss limit as recommended by the USDA's Natural Resources Conservation Service.
- Crop residue removal cannot result in long-term loss of soil organic matter as estimated by the Revised Universal Soil Loss Equation and the Wind Erosion Prediction System.
- A 60% limit was put on residue removal. Based on current surveys, 40% of farmers will want to keep residues in field and not harvest them (Schmer et al. 2017).

[2] USDA baseline contains national projections for the agricultural sector through the 2032/2033 crop year, then POLYSYS uses its own parameters and exogenous projections for population and yields to extend the USDA baseline to the year 2040.

- For the number of local livestock to not be impacted by pastureland conversion to purpose-grown energy crops, pastureland needs to be managed more intensively through timed rotations using paddocks that increase sustainable stocking density. We assume that 1.5 acres of pasture need intensified management for every acre of purpose-grown energy crop in non-arid regions, and in arid regions we assume 2.5 acres of pasture need intensified management per acre of pasture converted to purpose-grown energy crops. The cost of intensified management is a first-year cost of $50 per acre for pasture (fencing, water, and management) and $15 per acre for future years (management). The cost of pastureland intensification, as defined above, to sustain livestock numbers must be paid by the new purpose-grown energy crops.

Annual production quantities for each traditional crop (corn, sorghum, oats, barley, wheat, soybeans, cotton, and rice) are summed to the national level, where crop supply and demand interact to determine crop prices simultaneously. POLYSYS solves every year for 20 years, starting in 2023, where crop prices of the previous year determine land use decisions for the next year. POLYSYS models the eight major commodity crops and also the purpose-grown energy crops—switchgrass, miscanthus, poplars, willows, energy sorghum, and energy cane, as well as crop residue collection. The same model is used to illustrate the contribution of the intermediate oilseed winter crops. A conceptual illustration of the POLYSYS model is shown in Figure 5.5 and detailed in the appendix.

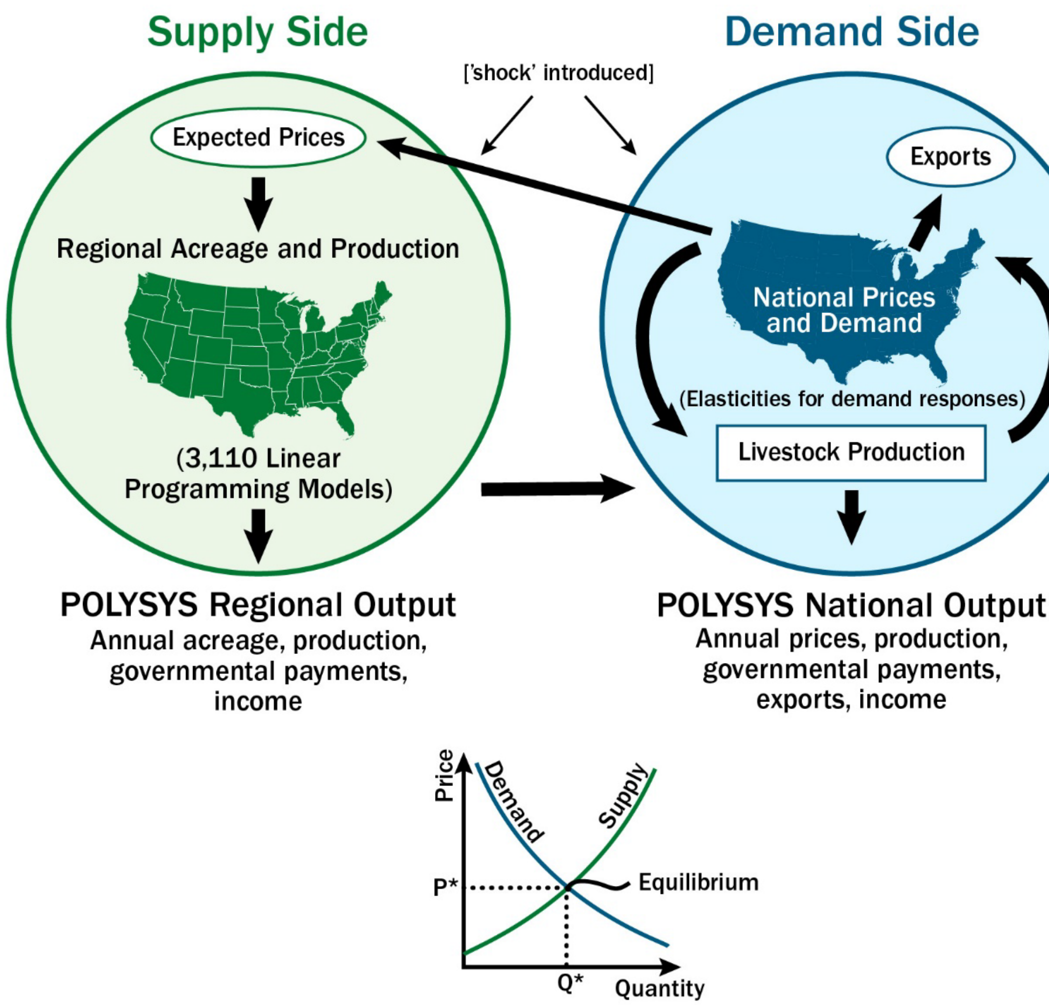

Figure 5.5. POLYSYS model iterative flow; county-level supplies are estimated and summed to the national level, where demands and prices are solved simultaneously to clear available supplies. The new prices are used in the next year to estimate supplies.

5.2.1 Biomass Scenarios

There is uncertainty in how future crop yields will improve and how quickly harvesting technology will advance. We estimate biomass potential under three different market conditions that reflect differing crop yields, designated as low, medium, or high (Table 5.1). All scenarios reflect mature-market conditions, where we assume there will be an active national biomass market for 20 years. The medium scenario assumes conventional crop yields improve following the USDA baseline, energy crop yields increase at the rate of 1% per year, and residues machinery harvest technologies improve from 50% to 90% efficiency. The low scenario assumes progress lags, and the high scenario assumes improvements in yields and technologies exceed expectations. We constrain residue harvest estimates based on current surveys that 40% of farmers will want to keep residues in the field and not harvest them (Schmer et al. 2017). We run all scenarios under a range of biomass prices to determine implications on biomass supply.

Table 5.1. Descriptions of Biomass Supply Scenarios Simulated in POLYSYS, at Prices from $40 to $130 per Dry Ton in $10 Increments (2022 $)

Scenario	Assumptions
Near term	Near term (simulated as 7 years after 2023) Only crop residues (corn, wheat, sorghum, barley, and oat) No harvest technology improvements
Low	Mature market (simulated as 18 years after 2023) No energy crop yield improvements Conventional crop yield improvements assume USDA baseline No harvest technology improvements
Medium	Mature market (simulated as 18 years after 2023) 1% per year energy crop yield improvements Conventional crop yield improvements assume USDA baseline Harvest technology improves from 50% to 90% efficiency
High	Mature market (simulated as 18 years after 2023) 3% per year energy crop yield improvements Conventional crop yields improve 1.5 times the USDA trend Harvest technology improves from 50% to 90% efficiency

5.2.2 Intermediate Non-Food Oilseed Crop Scenarios

The White House's SAF Grand Challenge has set a goal of using 3 billion gallons of SAF by 2030 and 35 billion gallons by 2050. The contribution to soybean oil as feedstock for biodiesel is around 70%, while canola and corn oil contribute 10% and 19%, respectively. All three are also well-established food crops for vegetable oil. In this analysis we focus on the introduction of non-food oilseeds or intermediate oilseeds as an independent scenario. We exclude canola from the analysis because it typically has higher costs and lower yields than the other brassica oilseeds. Consequently, we estimate future oilseed supply potential of three intermediate winter-grown oilseed crops—pennycress, camelina, and carinata—in rotation with conventional summer crops and along with the use of conventional soybeans. The intermediate oilseed crops grow in the winter between corn (or cotton) and soybeans when fields are typically fallow, but alternating production only every other winter to allow earlier corn planting and to minimize crop pest pressure by leaving fields fallow after soybeans. Oilseed crop supply scenario assumptions are shown in Table 5.2. Herbaceous intermediate crops (e.g., winter rye, alfalfa) are widely adopted for soil conservation. In one estimate they have the potential to increase biomass supply by approximately 20 million tons per year while providing environmental services (Malone et al. 2023). At this time we are excluding herbaceous intermediate crops from the analysis and focusing on lipid oil production. They will be included in ongoing follow-up analyses to this report.

Table 5.2. Descriptions of Oilseed Supply Scenarios as Simulated in POLYSYS

Scenarios	Assumptions
Intermediate oilseeds	Mature market (simulated as 18 years after 2023) Intermediate oilseed crops (pennycress, carinata, and camelina) In 2-year rotation corn (or cotton) and soybean Run farm gate prices at $0.05–$0.25/lb. oilseed
Soybean oilseed	Mature market (simulated as 18 years after 2023) Soybeans as oilseed crops Run at increasing oilseed demand levels

5.2.3 Other Agricultural Residues and Processing Wastes

Additional crop residues (rice straw and cotton field residues) and agricultural processing wastes (orchard prunings) are estimated as fractions of county-level production, totaling 10.1 million tons per year. Additional supplies for rice hulls and cotton gin trash, totaling about 10 million tons per year, are not reported here but data are provided at https://bioenergykdf.ornl.gov/bt23-data-portal. Assumptions for estimating these additional resources, totaling 21 million tons per year, are provided in the appendix.

5.3 Results

5.3.1 Biomass Supply

The general results of the simulations are summarized in Table 5.3, showing results of mature-market low, medium, and high scenarios simulated at $70 per dry ton. The table displays production of energy crops and agricultural residues, percent reduction from baseline in the total production of the three major traditional crops (corn, wheat, and soybeans), corresponding change in their weighted average price, change in food prices, and finally percentage change in total market returns from traditional crop production and residue collection. These indicators show that the production in biomass feedstock from cropland implied a small reduction in production, a small increase in crop and food prices, but a significant increase in total market returns from the baseline that ranges from 26% in the low scenario and more than 30% in the medium and high scenarios. The key message is that the shift of a small portion of acres to the production of energy crops and the added income contribution of collecting residues for energy have large returns for corn, wheat, and soybeans producers. A detailed analysis of these impacts follows.

Regenerative Grasses Benefit Farmers, Consumers, and the Environment

Regenerative grasses, with their deep root systems, have the power to improve soil health, sequester carbon, and prevent soil erosion. Cultivated annually, they can minimize environmental impact and help restore degraded land. Also, fibers from regenerative grasses such as switchgrass and giant miscanthus can benefit rural agricultural communities while offering sustainable alternatives to single-use plastics. Agricultural fiber manufacturers can help farmers produce high-yielding, carbon-negative regenerative grasses on underutilized farmland not suitable for most crops.

One company, Genera, is doing just that. Locally sourced agricultural feedstocks supply Genera's East Tennessee non-wood fiber and converting facility, where it transforms fibers into a variety of packaging products, from corrugated cardboard to biodegradable trays and containers. These materials are not only renewable but also compostable, making them an environmentally responsible choice for consumer packaging for food service and retail uses. The process uses a fraction of the energy, water, and harsh chemicals required for other types of recycled fibers.

Such products are cost-competitive and domestically sourced alternatives to single-use plastics, foam, and imported fiber products. The industry can respond to this high demand with new fiber-based products, including SAF, that benefits farmers, consumers, and the environment. Farmers get an additional source of income through the cultivation of these grasses, the packaging industry gains access to a sustainable supply of raw materials, and the environment benefits from soil conservation and carbon capture. Thus, the use of these grasses in consumer packaging demonstrates that a more sustainable future is rooted in agricultural regenerative practices with promise for a greener world for generations.

Photos from Sam Jackson, Genera Inc.

Table 5.3. Modeled Impacts of Energy Crop Scenarios on U.S. Commodity Crop Production, Commodity Crop Prices, Food Prices, and Farm Revenues. Future Yield Improvements Simulated in the Mature-Market High Scenario Mitigate Impacts on Conventional Production and Increase Biomass Production.

Scenario [a]	Energy Crops Produced (Million Dry Tons) [a,b]	Agricultural Residues Harvested (Million Dry Tons) [a,c]	Production of Corn, Soy, and Wheat	Change in Commodity Price [d]	Change in Finished Food Price [d,e]	Total Farm Market Net Revenues [f]
			(% Change from Baseline, Mature Market)			
Mature-market low	318	152	−3%	+5%	+0.6%	+26%
Mature-market medium	398	177	−3%	+6%	+0.7%	+31%
Mature-market high	638	200	−1%	+1%	+0.1%	+31%

[a] Simulated biomass price of $70 per dry ton, selected as modeling year 2041 as described in this chapter and summarized in Figure ES.1.
[b] Sum of modeled cellulosic terrestrial (i.e., intermediate oilseeds and excluding algae) purpose-grown energy crops within modeling constraints as summarized in Figure ES.1.
[c] Sum of corn stover and wheat straw within modeling constraints as summarized in Figure ES.1.
[d] Weighted average of corn, soy, and wheat.
[e] Assumes raw food commodities comprise 16.6% of the price of finished food prices based on average from 1993–2022 .
[f] Total market revenues minus total variable costs on cropland, as compared to the USDA baseline simulation without energy crop production, 2041. Excludes government payments.

Detailed simulation results indicate that biomass supplies from agricultural lands (i.e., crop residues [excluding rice and cotton] and purpose-grown energy crops) come into production at prices over $50 per dry ton and increase as the offered biomass price increases. At the reference price of $70 per dry ton, 471, 577, and 839 million dry tons are estimated to be produced under the low-, medium-, and high-yield assumptions, respectively (Table 5.4 and Figure 5.6). At the high price of $130 per dry ton, quantities increase to 788, 973, and 1,365 million dry tons under low-, medium-, and high-yield assumptions, respectively (Figure 5.7). An additional 10.2 million tons per year of rice straw, cotton field residues, and orchard prunings is accounted for separately, as described in the appendix.

Table 5.4. Biomass Supply Potential per Year from Agricultural Lands for Residues and Purpose-Grown Energy Crops at Increasing Biomass Prices under Low, Medium, and High Mature-Market Scenario Assumptions

	Low				Medium				High			
Price	Crop Residues	Herbaceous Energy Crops	Woody Energy Crops	Total (Residues + All Energy Crops)	Crop Residues	Herbaceous Energy Crops	Dedicated Woody	Total (Residues + All Energy Crops)	Crop Residues	Herbaceous Energy Crops	Woody Energy Crops	Total (Residues + All Energy Crops)
($/dt)	(million dry tons)				(million dry tons)				(million dry tons)			
$-	0	0	0	0	0	0	0	0	0	0	0	0
$30	0	0	0	0	0	0	0	0	0	0	0	0
$40	0	7	0	7	0	17	0	17	0	97	3	99
$50	121	123	3	247	136	188	7	331	169	337	30	536
$60	136	226	16	379	158	289	26	473	187	454	63	704
$70	**153**	**284**	**34**	**471**	**179**	**345**	**54**	**577**	**201**	**535**	**103**	**839**
$80	163	317	57	538	192	391	76	658	208	606	148	962
$90	172	353	79	603	199	427	113	738	214	664	185	1,064
$100	176	376	109	661	205	459	138	801	218	731	211	1,160
$110	181	396	129	707	208	496	157	861	221	788	235	1,244
$120	183	420	146	749	213	535	176	924	221	832	253	1,306
$130	186	443	159	788	214	569	191	973	219	871	275	1,365

Estimated residue harvest quantities are considerably below total residues available in the field (harvest approximately one-third of total residues) due to model limits that (1) ensure adequate quantities remain in the field to prevent erosion; (2) account for harvesting equipment efficiency limits, which currently can only capture 50% of total residues; and (3) ensure quantities remain for livestock uses (see the appendix for details). Corn and wheat residues comprise 89% and 10% of total harvestable residues, respectively, with sorghum, oat, and barley residues making up less than 1% of total residues.

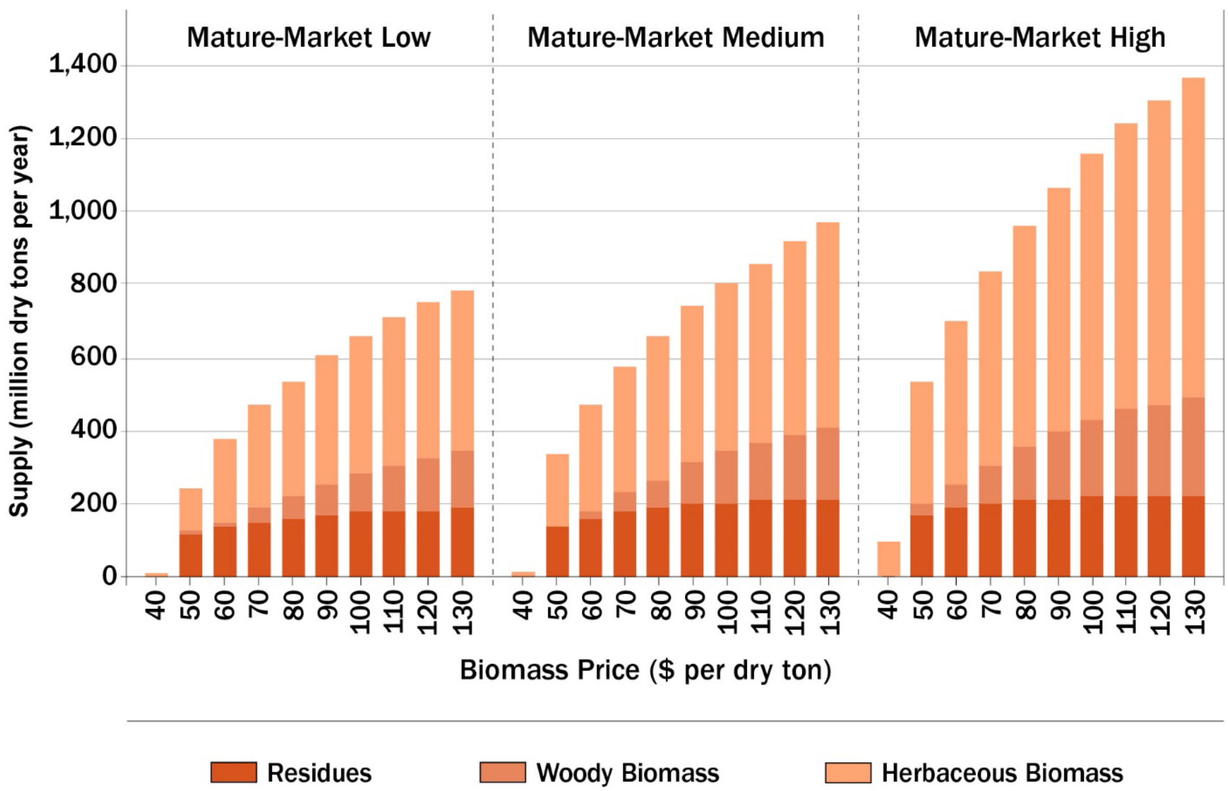

Figure 5.6. Modeled biomass production by scenario, price, and subclass

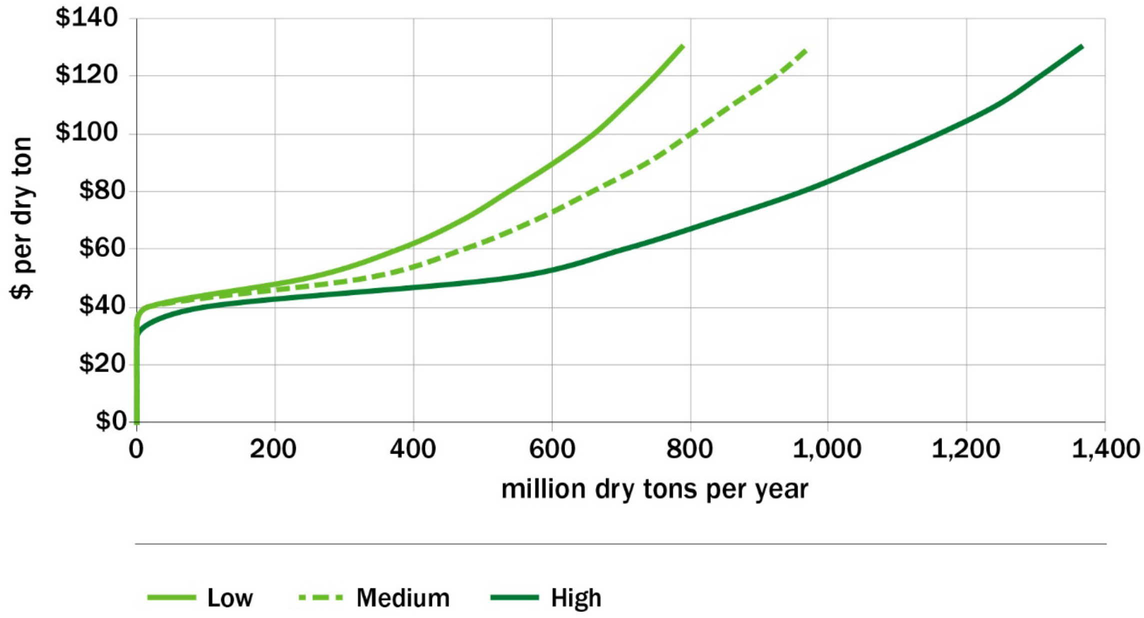

Figure 5.7. Biomass supply potential per year from agricultural lands (i.e., crop residues and purpose-grown energy crops combined) at increasing biomass prices under low, medium, and high mature-market scenario assumptions

5.3.2 Agricultural Land Competition for Purpose-Grown Energy Crops

Key points of agricultural land use competition:

- In this analysis, we do not presuppose that farmers are constrained to purpose-grown energy crop production on marginal lands, because future practices could be expected to deviate from this assumption (Skevas et al. 2016; Swinton et al. 2017). Rather, we model for an economic solution to simulate expected farmer production decisions in a free market. Modeled results suggest that conventional crops (e.g., corn and soy) maintain their position of economic competitive advantage on prime cropland (e.g., the Corn Belt), and purpose-grown energy crops are allocated to regions of less intensive conventional crop production outside the Corn Belt, and to pasturelands largely in the southern Plains (Figure 5.8).
- Under simulated mature-market conditions at a reference price of $70 per dry ton, approximately 398 million tons of purpose-grown energy crops are produced on 76 million acres planted to purpose-grown energy crops, including 26 million acres of cropland and 50 million acres of pastureland (Figure 5.9). The total land planted to purpose-gown energy crops represents about 9% of agricultural lands (Figure 5.10), while meeting demands for food, feed, fiber, and exports.

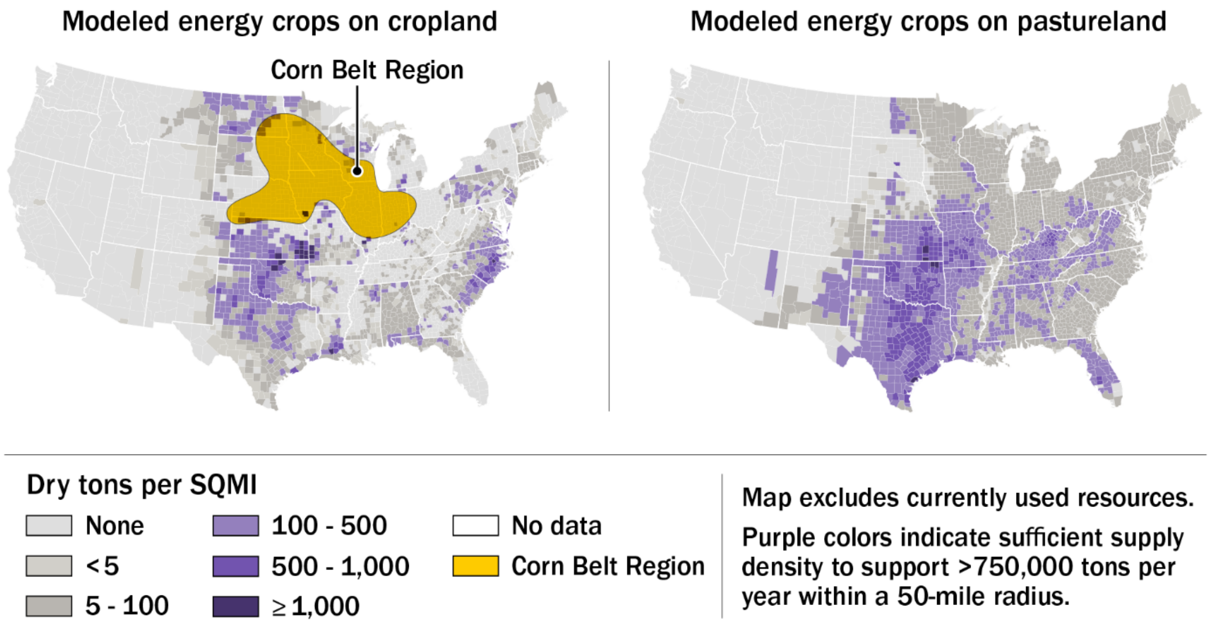

Figure 5.8. Energy crop production density on cropland and pastureland in the simulated mature-market medium scenario under a biomass price of $70 per dry ton. Orange region indicates corn/soy production region as indicated by the USDA National Agricultural Statistics Service (2023a). Little purpose-grown energy crop production is modeled on cropland in the Corn Belt, but rather is concentrated in the southern Plains.

Estimated agricultural land allocation to purpose-grown energy crop production as a function of biomass price is shown in Figure 5.9. As biomass prices rise, pasture converts rapidly in the East but slows in the West, where purpose-grown energy crop yields decline and pasture intensification costs increase. Cropland conversion steadily increases as biomass prices increase. For the mature-market medium scenario at the reference price of $70 per dry ton, 76 million acres are planted to purpose-grown energy crops, including 26 million acres of cropland and 50 million acres of pastureland. An additional 70 million acres are harvested for crop residues. Prime farmland in the Midwest does not convert to purpose-grown energy crops because of economic comparative advantages of commodity crops in that region (i.e., the Prairie Gateway Farm Resource Region [USDA-ERS 2000]). Land tends to convert to purpose-grown crops in regions of less intensive production, where cultivated cropland area grows or shrinks depending on commodity prices (Swinton et al. 2011; Lark, Salmon, and Gibbs 2015). Inclusion of other parameters such as soil conservation, water quality, or regional cooling could result in a different spatial distribution of purpose-grown energy crop potential (e.g., Uludere Aragon et al. 2023). Similarly, subcounty and subfield optimization could increase biomass production, reduce biomass price, and enhance ecosystem services (Abodeely et al. 2013; Brandes et al. 2016, 2018; Griffel et al. 2022). This could lead to more optimistic results than those presented here and provide opportunities for subcounty optimization of county-level outputs provided here.

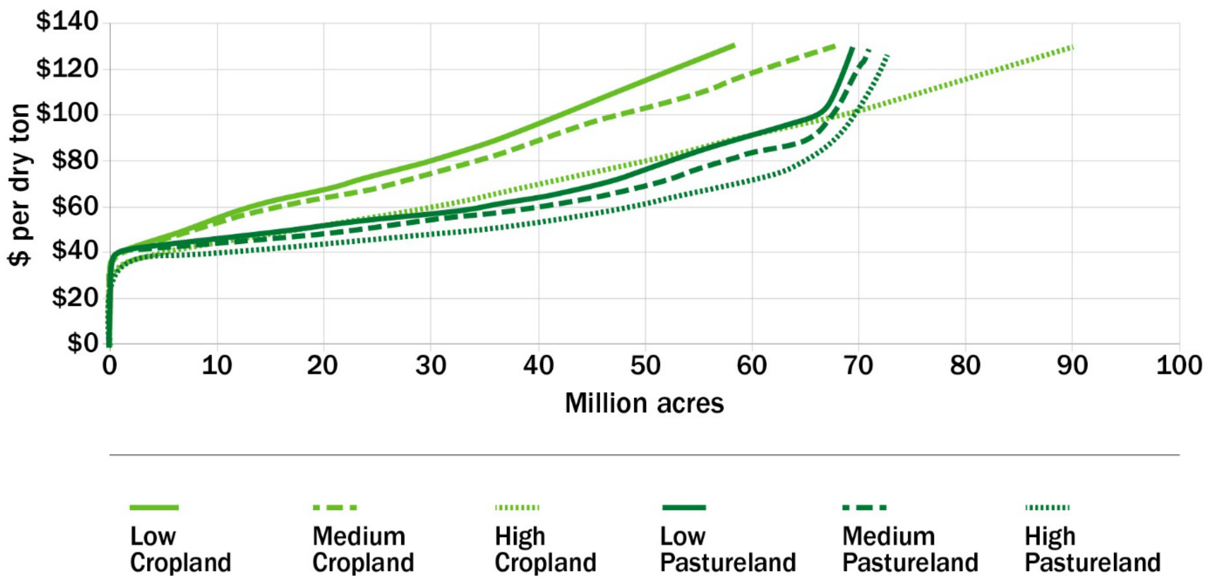

Figure 5.9. Land transitions to purpose-grown energy crops at increasing biomass prices for cropland and pastureland

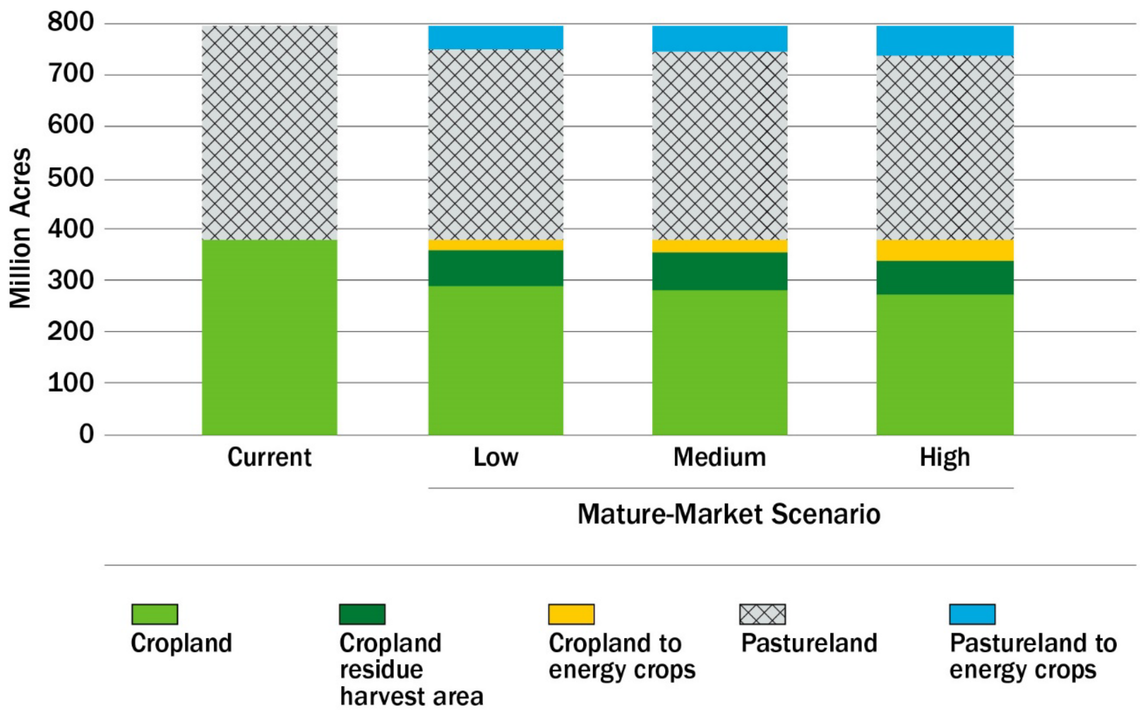

Figure 5.10. Current agricultural land area (CONUS) and land area of modeled low, medium, and high mature-market scenarios at the reference price of $70 per dry ton

5.3.3 Commodity Crop Price Impacts

Purpose-grown energy crops face scrutiny over concerns of food security. The mature-market scenarios were analyzed at biomass prices ranging from $30 to $130 per ton. As biomass prices increase and purpose-grown energy crops outbid conventional commodity crops for land use, commodity prices are estimated to increase. For example, the mature-market medium scenario with a reference price of $70 per dry ton incentivizes the production of 398 million dry tons of purpose-grown energy crops, corn prices increase 5%, wheat increases 19%, and soy increases 9% (Figure 5.11).

In relation to recent market price spikes, these increases are relatively low. For example, during the three most recent price spikes, wheat prices rose from the year before by 127%, 48%, and 64%; corn by 120%, 124%, and 128%; and soybeans by 89%, 50%, and 84% for 2008, 2012, and 2022, respectively. Given that raw food commodities comprised an average of 16.6% of the price of finished food prices from 1993–2022 , commodity price increases in the range of 5%–20% would correspond to finished food price increases of 0.8% to 3.3%. In Chapter 6 we discuss how the demand for purpose-grown energy crops can play a role in chronic oversupply issues in agriculture.

As purpose-grown energy crops expand and market prices increase, U.S. exports of commodities decrease. In our modeling analysis, prices and demand levels, including exports, are determined simultaneously using demand and income elasticities. In the medium scenario at $70 per dry ton, exports of corn, wheat, and soybeans decrease by 8%, 12%, and 11%, respectively. However, due to the higher commodity prices, the value of exports for corn decline by 3.7%, for wheat increase by 2.2%, and for soybeans decline by 2.8%. The impact of the reduction in export volume must be put in the context that according to the USDA 2023 baseline, the average U.S. share of global markets is 31%, 11%, and 28% for corn, wheat, and soybeans, respectively. Consequently, the reductions in the U.S. export volumes represent only 2.5%, 1.3%, and 3% of the global market (global trade) in the case of corn, wheat, and soybeans.

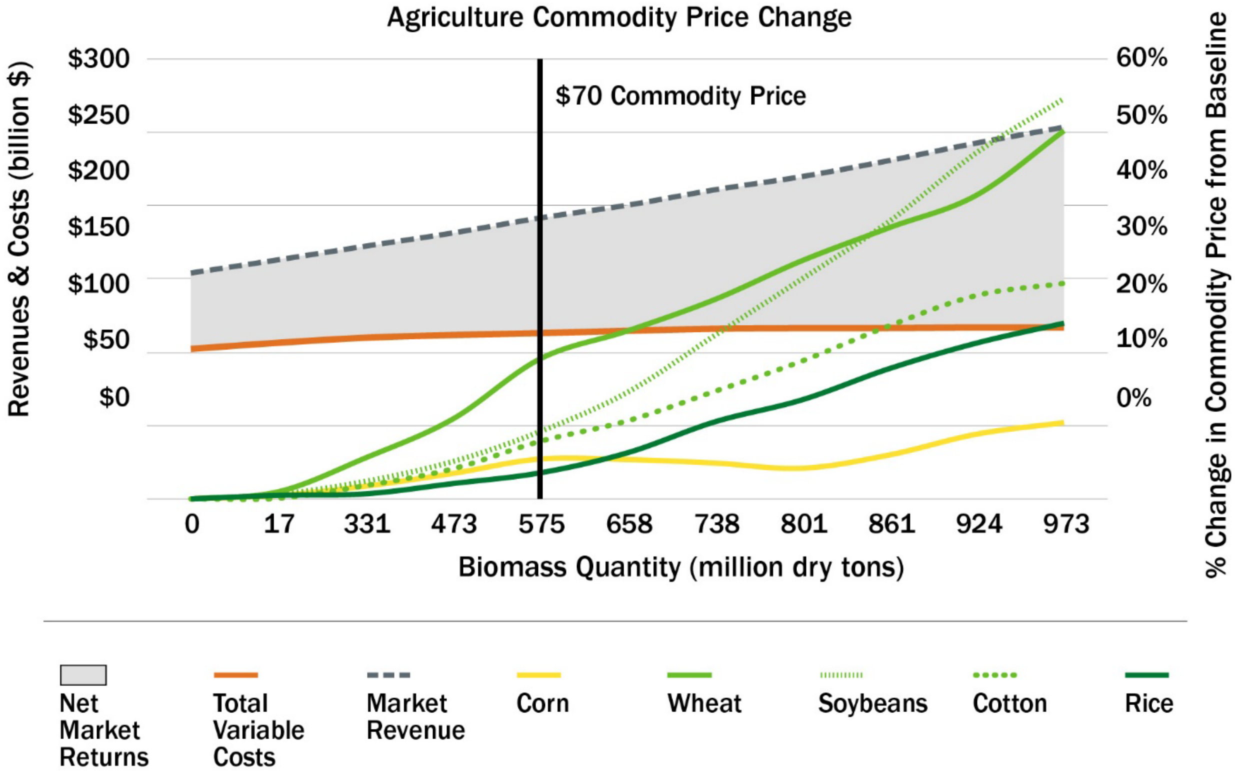

Figure 5.11. Increase in net market returns and percentage increase in commodity prices at increasing quantities of biomass produced from U.S. agriculture under medium scenario assumptions. At $70 per dry ton, approximately 577 million dry tons of biomass can be produced. Commodity prices increase by less than 20%. Increasing commodity prices increases U.S. farmer net market returns by $23 billion per year from baseline.

Nationally, total net market returns to crop agriculture increase by 43%, or $23 billion per year, over baseline in the mature-market medium scenario at $70 per dry ton. Of the total net increase in returns, conventional grains and oilseeds comprise 26% of the increase ($13.5 billion), energy crop returns 18% ($9 billion), and residue returns an additional 8% ($4 billion). Livestock returns are not estimated, but will likely decline due to increased feed prices. Figure 5.12 indicates the regional increases in market net returns to crop agriculture. Commodity price increases and residue returns lead to the greatest increases in returns in the prime agriculture regions in the Midwest, but energy crops grown in the Southeast and Western Plains act to increase regional net returns as well.

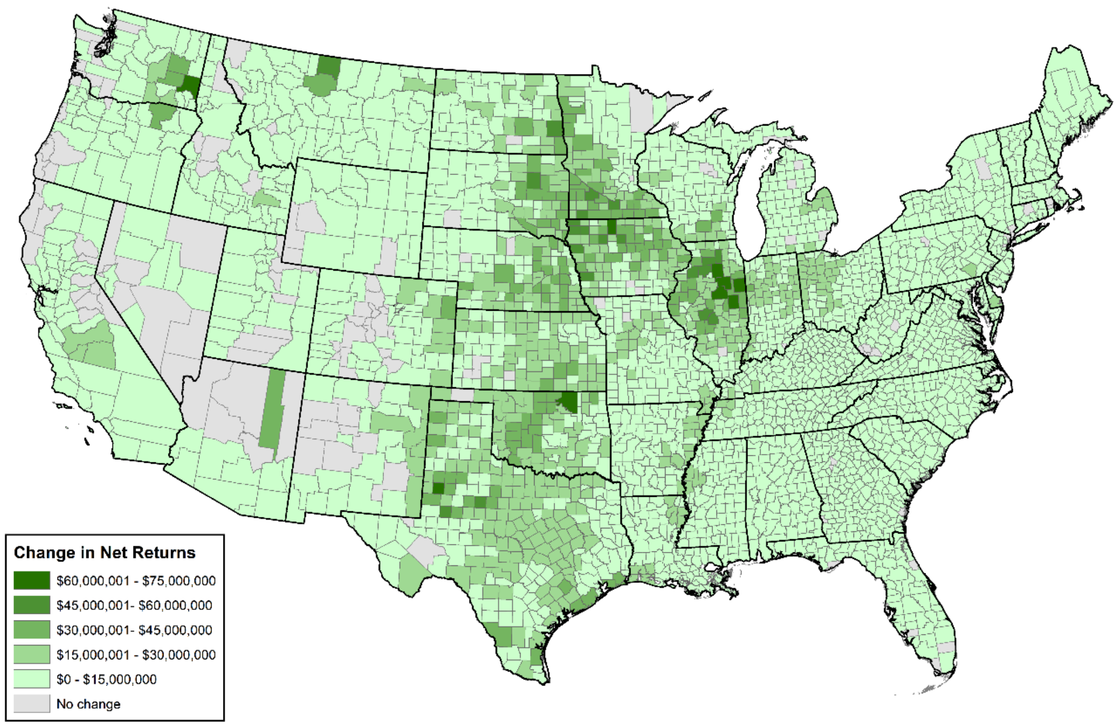

Figure 5.12. Farm net income changes of the mature-market medium reference case scenario over baseline

The higher market returns reduce government payments nationally and act to reduce the percent of U.S. agricultural commodities dumped at below the cost of production, hence improving global prices received by farmers throughout the world (Murphy and Hansen-Kuhn 2020). There has been a century-long problem of overproduction in agriculture, forcing commodity prices below the cost to produce them, and therefore costing about $2 billion in federal expenditures annually to keep farmers out of bankruptcy (USDA-FSA 2023). Purpose-grown energy crops can play a role in helping the chronic oversupply problem in agriculture (De La Torre Ugarte and Hellwinckel 2010). Since the mid-20th century, when technology, education, and new seeds quickly increased yields, U.S. agriculture has faced recurrent oversupply problems where the prices of commodities are most often below the cost of production. For example, Murphy and Hansen-Kuhn (2020) show dumping rates from 1990–2017. Low prices have set off cycles of farmer bankruptcies and have institutionalized large government support payments to keep remaining farmers economically viable. Farmers in developing countries have been harmed by oversupply problems as well by having to compete with cheap imports from the United States. This has driven rural flight to urban areas, underinvestment in agricultural sectors of developing nations, and associated environmental and social problems (Murphy and Hansen-Kuhn 2020). Production of purpose-grown energy crops can be part of a strategy to keep prices within an acceptable range, where they are equal to or above the cost of production for farmers, but low enough to avoid hardship for consumers (De La Torre Ugarte and Hellwinckel 2010; Ray and Schaffer 2018; De La Torre Ugarte et al. 2012).

5.3.4 Carbon Sequestration

Purpose-grown perennial energy crops pull carbon out of the atmosphere and sequester carbon in the soil as they grow, but growing purpose-grown energy crops also requires some GHG emissions of carbon during production (e.g., establishment, maintenance, harvest) and upstream emissions associated with fertilizer production. The balance of sequestration and emissions equals the net GHG flux from agriculture to the atmosphere. Here we give a simplified estimate of the soil sequestration impacts of purpose-grown perennial energy crops, but we do not quantify the direct or upstream life cycle GHG emissions. We assume purpose-grown perennial energy crops increase soil carbon levels annually by approximately 5%, 3.8%, and 0.17% for switchgrass, miscanthus, and short-rotation woody crops, respectively, on land previously growing annual crops (Agostini, Gregory, and Richter 2015; Qin et al. 2016b) (see the appendix for more detail). We assume no soil carbon change on pastureland converting to purpose-grown energy crops (Chamberlain, Miller, and Frederick 2011; Qin et al. 2016b, 2016a). In the baseline case we assume soils have reached a steady state and no carbon is being sequestered or removed per year in U.S. crop agriculture.[3] There is great uncertainty around carbon sequestration estimation; future studies should estimate impacts in more detail using dedicated soils models.

In the medium scenario and at a reference price of $70 per dry ton, we estimate that soils under perennial purpose-grown energy crops can sequester 32 million metric tons of CO_2 per year. At higher prices, the additional sequestration from purpose-grown energy crops would lead to greater reductions in carbon from agriculture to the atmosphere, reaching a maximum reduction of 75 million metric tons of CO_2. Assuming a typical passenger vehicle emits 4.6 metric tons of CO_2 per year, this is the equivalent of removing more than 16 million vehicles. In comparison, it has been estimated that universal adoption of cover crops across the major cropping regions of the United States would sequester approximately 100 million metric tons of CO_2 per year (Fargione et al. 2018), and adoption of all practically achievable agricultural soil carbon measures could sequester 250 million metric tons of CO_2 per year (National Academies of Sciences, Engineering, and Medicine 2019). We are not estimating changes in emissions of carbon during production, which would likely increase moderately with the production of purpose-grown energy crops and harvesting of residues, and consequently decrease the net atmospheric carbon impact of the soil carbon changes.

5.3.5 Intermediate Non-Food Oilseed Crops

Brassica oilseed intermediate crops, including pennycress, camelina, and carinata, can be grown in the winter fallow season between a typical corn (or cotton) and soybean rotation. The oilseed can be grown in between summer crops every other winter, hence becoming an "intermediate" crop with no need for additional land and therefore little impact on production capacity of agricultural lands (see the appendix for modeling assumptions). Oilseed intermediate crops can also provide ecosystem benefits while producing a secondary product (Karami 2021;

[3] Recent studies have placed uncertainty upon whether no-tillage increases soil carbon; therefore, we assume no net soil carbon accumulation under no-till.

McClelland, Paustian, and Schipanski 2021). Figure 5.13 shows intermediate crop oilseed production potential as a function of offered price. Intermediate oilseeds can produce up to 21 billion lbs. of lipid oil from oilseeds per year from 47 million acres, which, once converted, can produce 1.4 billion gallons of SAF.[4] From the pressing of oilseeds to produce 21 billion lbs. of lipid oil, 16 million tons of meal are coproduced, which can be used to feed livestock. This amounts to 20% of current soybean meal demand. We assume the meal coproduct of intermediate oilseeds can be used for animal feed through pre-crush processing, hence impacting the soy meal market (Alhotan et al. 2017). At $0.15/lb, the additional meal entering the market from oilseeds meal coproduct lowers meal prices by 17%, reducing soybean feed demand and lowering soybean prices by 4% below baseline. Based on current assumptions on yields and costs of production, pennycress is the largest potential intermediate oilseed producer with 87% of the total, followed by camelina with 13% and carinata with less than 1%. Figure 5.14 shows that the geographic range of potential intermediate oilseed crops extends north and south. Camelina and carinata dominate in southern warmer regions, but their yields decline as the probability of freezing increases at more northern latitudes where pennycress, a cold-tolerant species, dominates projections.

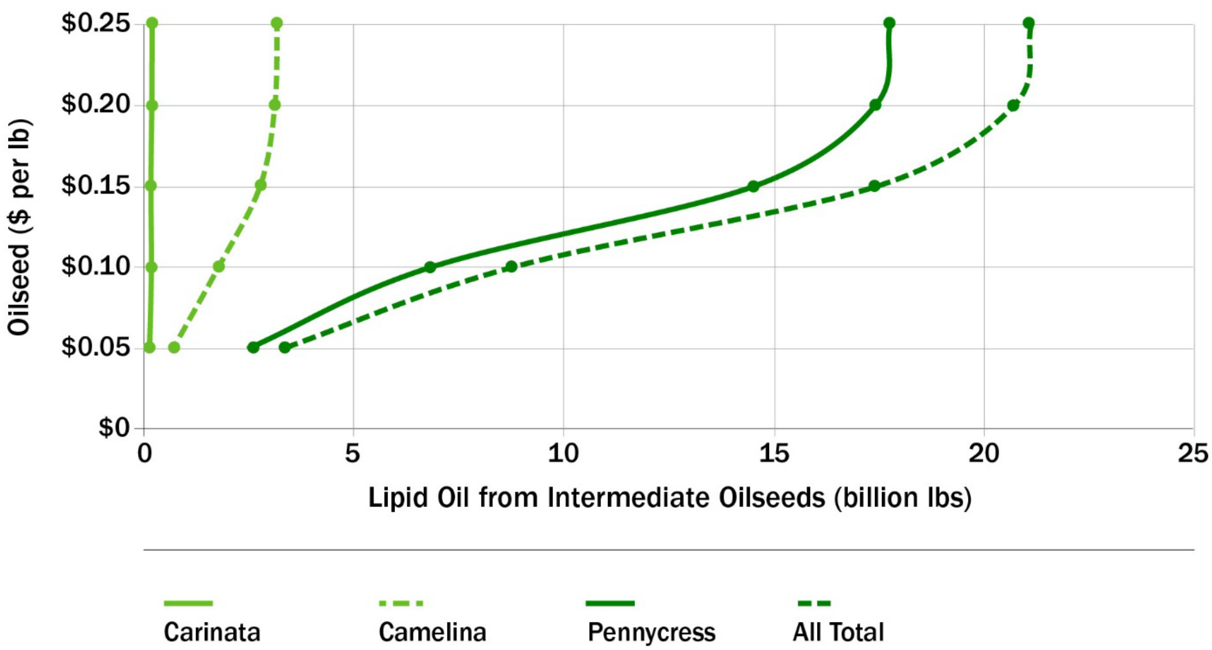

Figure 5.13. Intermediate oilseed supplies per year at increasing oilseed prices at mature market

[4] We assume pennycress, camelina, and carinata are 38%, 37%, and 47% lipid oil, respectively. We assume a conversion rate of 0.0722 gallons of SAF per pound of lipid oil.

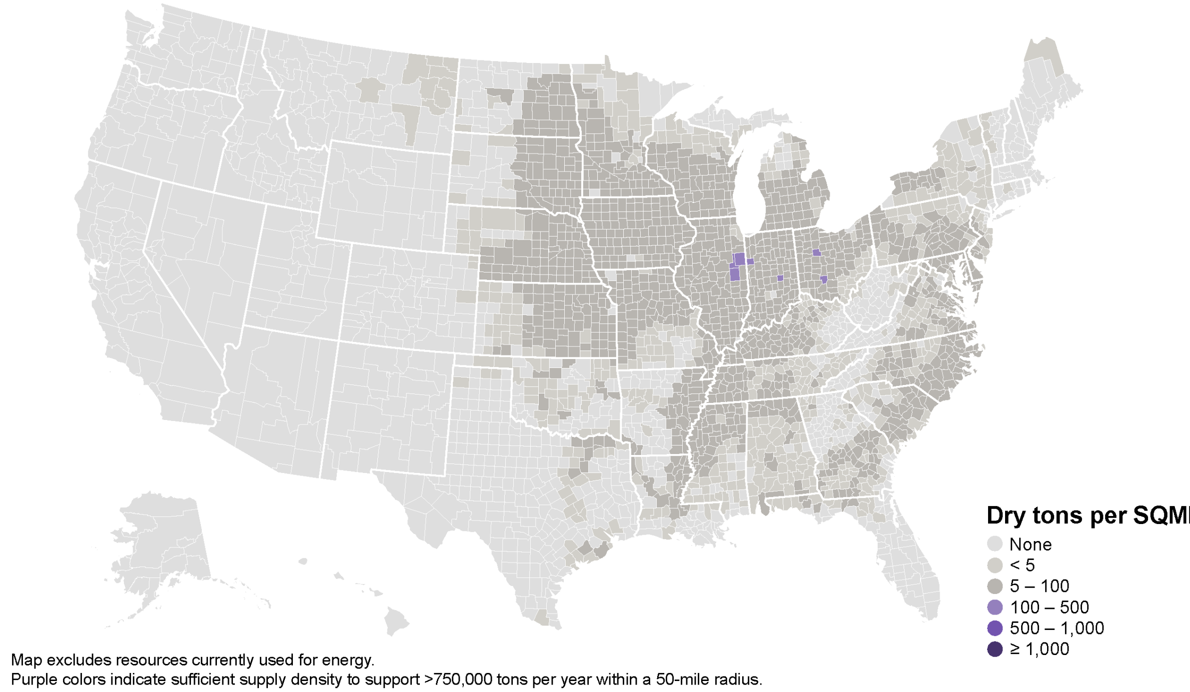

Figure 5.14. Geographic distribution of mature-market intermediate oilseed crop production

To show the market differences between meeting future oilseed demand from intermediate crops compared to soybeans, we develop a supply curve for soybeans meeting equivalent SAF demands as intermediate crops. If additional soybeans were used for aviation fuels, it would be another demand for soybeans that would compete with other uses. Currently, 6.3 billion lbs. of soybean lipid oil are used for bioenergy at a market price of $0.17/lb. for soybeans. We simulated increasing demand levels for soybeans for energy oilseed in POLYSYS, with resulting price impacts associated with increased production shown in Figure 5.15. As demand increases, competition for soybeans increases. As prices increase, soybeans gain acreage and land use competition increases the price of other crops simultaneously. For soybeans to provide 21 billion lbs. of lipid oil, 2 billion bushels of soybeans would be needed. This additional demand for soybeans would increase prices of soybean, corn, and wheat by 16%, 13%, and 23%, respectively. Soybean exports also decline as oilseed demand increases. An average acre of soybeans can produce about 73 gallons of biodiesel (or 39 gallons of SAF).[5] In comparison, an acre of corn can produce about 470 gallons of ethanol. This illustrates the differences in meeting future energy demand from conventional soybeans versus intermediate crops.

[5] We assume conversion rates of 0.7579 gallons of SAF per bushel of soybeans, 1.4 gallons of biodiesel per bushel of soybeans, and 3 gallons of ethanol per bushel of corn.

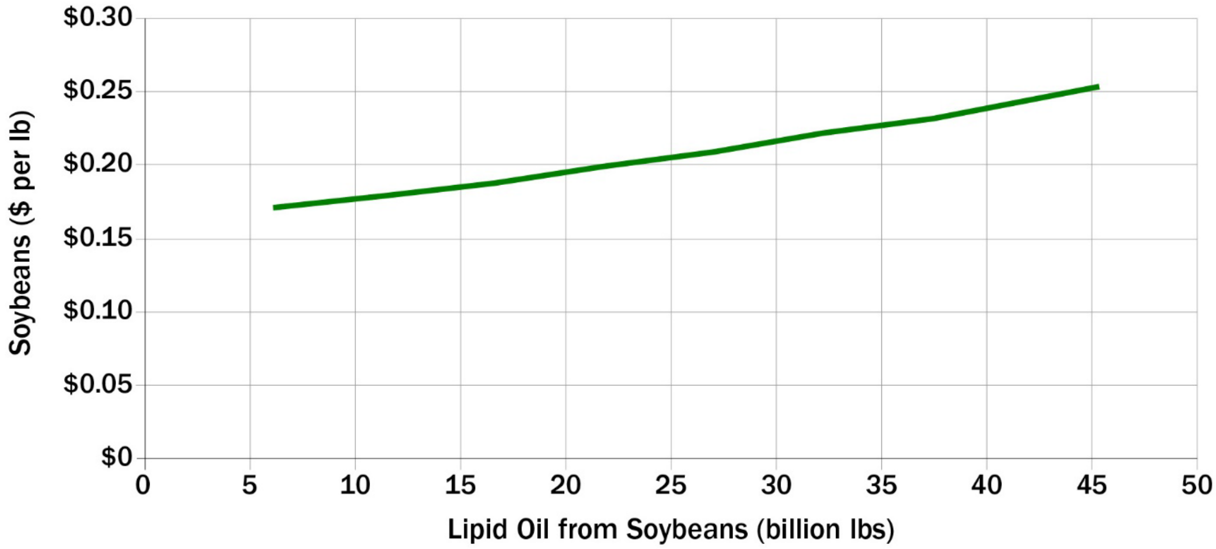

Figure 5.15. Supply of soybeans for energy oilseed per year at increasing prices. In 2022, the United States used 6.3 billion lbs. of oil from soybeans for energy uses.

Conclusions

- Agricultural lands are the greatest single source of biomass production potential explored in this report. By harvesting about one-third of agricultural residues and integrating about 9% of agricultural land into purpose-grown energy crop production, agricultural lands can provide about 179 (major residues), 398 (purpose-grown energy crops), and 10 (msc. residues and processing wastes) million tons of cellulosic biomass per year, for a total of 587 million tons per year, in a mature-market reference scenario and price, within specified economic and environmental constraints.
- Modeling commodity prices rise by 6%–18% in a mature-market reference scenario for a mid-range of bioenergy production. Modeled exports decline by approximately 10% as prices rise, but the value of exports decline by about half, or less than the volume decline. These price rises contribute to a 1%–3% increase in U.S. food costs. This modeling does not account for the potential increase in yield due to the higher prices, which would mitigate the impact on consumer prices.
- Estimates of oilseed supplies are new in this report. Intermediate oilseeds can produce more than 21 billion lbs. (10.5 million tons) of lipid oil per year.

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Chapter 06 | Sustainability and Good Practices

Table of Contents

6 Sustainability and Good Practices

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Data portal: https://bioenergykdf.ornl.gov/bt23-data-portal

Summary

Sustainability constraints applied to the biomass modeled in this report illustrate how the United States can increase biomass supplies in ways that support net carbon sequestration, water conservation, and other ecosystem services through land management practices, or what some modelers might describe as beneficial land use change (LUC). Whereas the report identifies specific sustainable supply opportunities, one cannot be certain that land management for biomass production will evolve following the assumed constraints. Thus, consistent monitoring, assessment, and good management practices are necessary for avoiding or minimizing detrimental effects on soil, water, and ecosystem services. This chapter:

- Describes the impact of relaxing select sustainability constraints on estimates of potential biomass.
- Estimates carbon intensity.
- Reviews LUC concepts, potential effects of BT23 biomass supply scenarios on the environment, and potential good management practices that can improve environmental sustainability of biomass.

The supply estimates and analyses are independent of a specific policy or end use. In contrast, the EPA publishes a triennial report to Congress on biofuels that estimates specific environmental effects of a policy, the Renewable Fuel Standard (Clark et al. 2022). Other

environmental analyses of biofuel are tied to specific current or future policies (e.g., Chen et al. 2021; Austin et al. 2022), whereas potential biomass and related analyses in this report are not.

Key points:

- Broad agreement exists on the essential role for biomass to achieve climate and circular economy goals. Agricultural and forest scenarios in other chapters of this report estimate sustainable U.S. biomass supplies under assumptions (sustainability constraints) that reflect good practices to protect the environment and mitigate impacts on food and forest product markets. This chapter considers the range of potential impacts that might result if specific constraints are relaxed or removed.
- Removing the sustainability constraints from model assumptions (e.g., residue removal limits, timberland clearcut restrictions, tree diameter limits, distance from roads, harvest intensities for timberlands) increases potential biomass production from agriculture and timberlands[1] but adds risk of adverse environmental effects.
    - Relaxing sustainability constraints for corn stover suggests that removals to maximize profit could approximately double the stover removal rates, going from about one-third of national supply to about two-thirds of national supply.
    - Relaxing sustainability constraints for logging residues increases overall collection rates from about 45% of total logging residues to about 60%, but about 40% remains unharvested after relaxing the constraints.
    - Removal of larger-diameter (i.e., >11-inch-DBH) trees is constrained by the biomass price of $70 per dry ton. If prices increase to $75 per dry ton, approximately 30 million tons per year of trees greater than 11-inch DBH could be added to the harvested quantity. For reference, about 30 million tons represents less than 1% of timberland growing stock.
- Some sustainability constraints applied in the report (e.g., residue removal limits in many forests) are aligned with prevailing management practices, historic trends, and economic and biophysical feasibility, and thus are likely to be implemented. However, due to limited market experience and social science research, data are not available to determine whether agricultural residue retention recommendations will be followed.
- Effects of biomass production on crop prices and food security may be beneficial for some groups (rural producers), detrimental for others (urban consumers), or, most likely, negligible relative to other factors. Harvesting forest biomass does not affect food security.

[1] Timberlands are defined as forestlands with potential to produce more than 20 cubic feet of industrial wood per acre per year. Timberlands exclude reserved forests (e.g., National Park Service forests and other protected forests).

- Under BT23 mature-market scenarios, many environmental benefits, such as improved water quality in streams (nutrients and pesticides) and carbon sequestration, could increase because of increased perennial and cover crop acreage. Benefits could be enhanced with more efficient and precision management practices at the field or subfield scale.
- Uncertainties in future land management scenarios are unavoidable and would affect any environmental projection. Differences in LUC projections are large and have potentially significant impacts on estimates of biomass greenhouse gas (GHG) emissions intensity and sustainability. Monitoring and responsive decision-making are important to mitigate potential negative effects associated with land cover and management practices.
- Common sustainability concerns about producing and harvesting biomass could be mitigated by using good management and siting practices and mechanisms for increasing their adoption.
- Biomass resource estimates could be lower or higher depending on criteria applied to support sustainability.

GHG emissions, primarily from the combustion of fossil fuels, are causing temperature increases, increased frequencies and magnitudes of extreme events, and associated health and environmental impacts. Applying good practices for the production and use of biomass is essential to advancing sustainability goals, such as reducing fossil emissions associated with power, transportation, fuel, chemicals, and materials (IEA 2021, 2022). The important role of biomass in achieving national climate goals is driving global efforts to identify and develop sustainable biomass supply chains (IEA 2023). *The U.S. National Blueprint for Transportation Decarbonization* (DOE, USDOT, EPA, and HUD 2023) and a National Academies report on accelerating decarbonization (National Academies of Sciences, Engineering, and Medicine 2023) target GHG emissions reductions from aviation and other hard-to-electrify sectors with biofuels.

As with any energy technology, and particularly any production system based on land management, trade-offs among social, economic, and environmental objectives are necessary (Robertson et al. 2017; Dale et al. 2018). An evaluation of the environmental sustainability effects and potential trade-offs associated with the U.S. biomass potential estimated in BT16 was the subject of a companion report (DOE 2017), herein called BT16 Volume 2, that includes supporting analyses, glossaries, and datasets. BT16 Volume 2 evaluated changes in land cover and management, soil carbon, water quality, water availability, air emissions, and biodiversity for many biomass feedstocks as a function of production and harvest scenarios and prices. It also considered potential changes in biomass production based on a set of climate change projections. The BT16 Volume 2 analyses remain relevant and applicable to BT23. Rather than repeat those analyses, here we focus on questions raised by stakeholders:

1. Which aspects of sustainability were incorporated in estimates of national biomass potential and potentially serve as constraints or guardrails?

2. How might the sustainability attributes of biomass supply vary if producers do not follow these assumed sustainability constraints or guardrails?
3. How would biomass supply potential change if sustainability constraints were relaxed?
4. Which aspects of sustainability have not yet been explicitly considered in these estimates of biomass potential but are important for siting or managing biomass?
5. Which management practices can promote more sustainable biomass production?

The first question is addressed in the report's introduction and in individual biomass supply chapters. The remaining questions are addressed in this chapter and focus on agriculture and forestry. Expected benefits associated with the biomass supply scenarios are discussed, followed by analyses of expected effects of relaxing specific sustainability constraints associated with BT23 supplies. Environmental and other effects of potential production and harvesting of biomass are also discussed, including LUC, potential impacts on food security, forest conservation, biodiversity, water, and air quality.

6.1 Key Benefits of Producing and Harvesting Biomass

6.1.1 Climate Change Services, Carbon Management, and Carbon Intensities

Broad agreement exists on the essential role for biomass to achieve climate and circular economy goals. Production of biofuel, biopower, and bioproducts can mitigate climate change by avoiding combustion of fossil fuels, accumulating soil carbon, and displacing more carbon-intensive products and materials (IEA 2022). Net benefits depend on proper resource management, including minimization of GHG emissions during the biomass production stage (Robertson et al. 2017; Dale et al. 2014). As described in Chapter 5, purpose-grown energy crops (hereafter "energy crops") in the mature-market medium scenario reference price can achieve a net flux reduction of about 18 million metric tons of CO_2.

Carbon emissions intensity (i.e., carbon intensity) is CO_2-equivalent (CO_2e) emissions per unit of energy or product. Carbon intensities are typically measured for products rather than feedstocks, but some general principles pertain to biomass. Modeled carbon intensity estimates for crops used for bioenergy and bioproducts vary widely depending on baseline land allocation and assumed emission profiles (Wise et al. 2015). Other factors being equal, the biomass carbon intensity declines as annual yields increase because of better seed varietals and growing conditions such as soil and climate (Wise et al. 2015). However, if yield improvements are achieved by using more emissions-intense production practices, such as greater applications of fertilizer or pesticides, carbon intensity may not improve with higher yields.

Carbon intensities were calculated for major biomass feedstocks in this study (Table 6.1) using Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) model (Wang, Elgowainy, et al. 2022). The model captures upstream impacts, including fuels and chemicals manufacturing for biomass that requires fertilizer or pesticide. In Table 6.1, carbon uptake is the CO_2 absorbed by the plant during growth, treated as biogenic. It does not include LUC-related emissions, which can release soil organic carbon

(SOC). The supply chain emissions include biomass production, harvest or collection, and handling prior to transportation to the biorefinery. Transportation emissions and end use emissions are not included. Also not included are estimates of indirect emissions such as indirect LUC emissions, as have been assessed by the EPA for the RFS program or the California Air Resources Board for the Low Carbon Fuel Standard program. Differences between these estimates can be large and can have significant impacts on the overall carbon intensity estimates. A general discussion of LUC concepts is in Section 6.3.2. The carbon intensity values for petroleum include only crude oil recovery. Upstream emissions from exploration and related activities, as well as indirect effects, can be significant (Parish et al. 2013; National Research Council 2003).

Table 6.1. Example Carbon Intensity Values of Key Biomass and Fossil Resources, Based on GREET 2022 Revision 1

Category	Examples	Carbon Uptake [a]	Supply Chain Emissions [b]	Feedstock Total [c]	Unit (Short Tons)
Agricultural residues, primary	Corn stover	1,600,000	28,000	−1,572,000	g CO_2e/dry ton
	Wheat straw	1,300,000	240,000	−1,060,000	g CO_2e/dry ton
Primary forest residues	Logging residues	1,700,000	13,000	−1,687,000	g CO_2e/dry ton
	Hardwood	1,700,000	21,000	−1,679,000	g CO_2e/ton
	Softwood	1,700,000	21,000	−1,679,000	g CO_2e/ton
Herbaceous energy crops [d]	Miscanthus	1,600,000	67,000	−1,533,000	g CO_2e/dry ton
	Switchgrass	1,600,000	73,000	−1,527,000	g CO_2e/dry ton
Woody energy crops	Willow	1,600,000	36,000 [e]	−1,564,000	g CO_2e/dry ton
	Poplar	1,700,000	55,000	−1,645,000	g CO_2e/dry ton
	Pine	1,700,000	51,000	−1,649,000	g CO_2e/dry ton
Animal manures [f]	Hog manure	1,500,000	−1,100,000 [g]	−2,600,000	g CO_2e/ton solids
	Cow manure	1,600,000	5,500	−1,594,000	g CO_2e/ton solids
Municipal solid waste [f]	Food waste	460,000	−250,000	−710,000	g CO_2e/wet ton
	Paper and paperboard	540,000	250,000	−290,000	g CO_2e/wet ton
	Yard waste	270,000	−53,000	−323,000	g CO_2e/wet ton
Range for crude oils [h]	Conventional crude oil, sand recovery values, shale oil, U.S. average crude		200,000–1,300,000		g CO_2e/ton

[a] Based on biogenic carbon content of each feedstock, per dry ton.
[b] Includes everything up to the "edge of field"/forest road.
[c] Credits feedstock with carbon uptake.
[d] Energy cane and eucalyptus are not parameterized in GREET.
[e] GHG emissions are lower for willow than for poplar and pine because trucks with higher fuel efficiency are assumed to be used for transport of the former.
[f] Avoided "BAU" emissions are incorporated in supply chain results. However, the practice of allocating credits based on reductions relative to counterfactual BAU emissions is currently under review by the California Air Resources Board.

[g] Scientific and policy consensus on allocating credits for reductions in BAU emissions from historical manure management has not been reached; therefore, this credit may be eliminated by carbon intensity scoring systems or by the California Air Resources Board.
[h] The supply chain emissions range (g CO_2e/ton) for crude oils includes conventional crude oil (230,000), oil sand recovery values (surface mining, 520,000; *in situ* production, 830,000; surface mining + bitumen, 1,100,000; or synthetic crude oil, 1,300,000), shale oil (Bakken, 370,000; or Eagle Ford, 310,000), and U.S. average crude, 310,000. Notably, much more processing is needed for biomass than for crude oils.
Note: These values do not include estimates of indirect land use changes.

Carbon uptake values are large for all crops and residues in Table 6.1. The supply chain carbon intensity for hog manure is shown as large and negative in the table because in this case, unlike other biogenic feedstocks, the value reflects an assumed avoidance of methane emissions relative to a counterfactual fate of the manure. Carbon intensity values for the biomass production and supply chains are consistently lower than for fossil fuel supply chains, though, as noted, the estimates presented in Table 6.1 exclude certain categories of potentially substantial emissions.

6.1.2 Other Agricultural Ecosystem Services

Energy crops can generate ecosystem services beyond the carbon uptake benefits described above and carbon sequestration benefits in Chapter 5. People who consume water or use waterways for recreation can benefit from water purification and soil conservation services offered by lands managed for energy crops (Cacho et al. 2017; Jager et al. 2022). Additional ecosystem services provided by energy crops include wildlife habitat and pollination (Robertson et al. 2017). Growing these energy crops, as well as harvesting residues, also provides pest protection for adjacent crops (Robertson et al. 2017; Helms et al. 2020; Sindelar et al. 2013). Furthermore, energy crops can be used to restore abandoned mine land (Quinkenstein et al. 2012).

Ecosystem services provided by energy crops may have substantial economic value that could decrease net costs if realized through incentives. Riparian buffers planted with perennial energy crops can provide targeted water quality benefits, many of which could be monetized (Jager et al. 2023). Nitrate and sediment removal services of energy crops have been valued or monetized in previous studies (Mishra et al. 2019; Jager et al. 2022; Ssegane et al. 2016). Services include water-based recreation, as well as wildlife viewing and pheasant hunting. Supporting pollinators could be of economic value to farmers (Donnison et al. 2021), even if these services are not monetized. Research projects funded through USDA conservation programs with Inflation Reduction Act funds may produce more data on the value of good management practices in the future (USDA 2023).

However, estimating the magnitude of ecosystem services generated under specific planting and harvesting scenarios is challenging because of a lack of empirical data and models adapted to local conditions and energy crop opportunities (Ventura et al. 2012). An exception and example of this future research direction is a recent study in Iowa that was able to use subfield data to show landscape- and watershed-scale differences in soil carbon sequestration and water quality indicators under different combinations of agricultural management practices related to corn stover harvesting and switchgrass plantings (Parish et al. 2023).

Cover crops and “intermediate” crop rotations, as described in Chapter 5, also provide ecosystem services (Daryanto et al. 2018). Cover crops are grasses, legumes, or small grains grown between the harvest and planting season of traditional commodity crops like corn, soybeans, and cotton. Cover crops provide soil conservation and conditioning services by providing cover to reduce erosion and through incorporation into soils when a field is ready for the next crop. By USDA definition, “cover crops” are unharvested. If a cover crop is harvested it becomes an “intermediate crop,” which may also be described as double cropping or adding another crop into the rotation. Planting intermediate crops may improve conditions for the primary crop. Herbaceous cover crops such as rye, winter wheat, and hairy vetch offer ecosystem services including reductions in soil erosion and increased soil organic matter, improved water quality, weed suppression, and increased wildlife and pollinator habitat, along with increased yields of the main crop (Blanco-Canqui et al. 2015; Darysanto et al. 2018). Cover and intermediate crops can mitigate adverse environmental impacts of crop residue removal for biofuel production (Blanco-Canqui et al. 2015). However, lignocellulosic cover crops are more costly and difficult to refine into useful fuels than oilseeds. Oilseed intermediate crops such as pennycress, camelina, and carinata (Chapter 5) produce oil that can be converted to SAF, for example, without expanding the land base used for production of other products. However, cover and intermediate crops are not widely grown in the United States, comprising less than 6% of total cropland in 2017 (Wallander et al. 2021). Thus, the ecosystem services of these cover crops (Cubins et al. 2019) and effects of harvesting on ecosystem services (Blanco-Canqui et al. 2020) are less well studied. Recent studies (Taheripour, Sajedinia, and Karami 2022; Field et al. 2022) offer insight into opportunities to generate biomass from integrated production systems that incorporate cover and intermediate crops for multiple markets and services, generating climate benefits and biomass without reducing traditional commodity production.

6.1.3 Benefits of Woody Biomass Harvest in Forests

Mechanically thinning trees is a common wildfire fuel reduction treatment (i.e., “fuel treatment”). Mechanical thinning is intended to open the forest structure and reduce fire intensity, severity, and frequency by removing surface fuels and increasing the vertical distance to the canopy (Kalies and Kent 2016; Graham 2003; Reinhardt et al. 2008). As a fuel treatment, mechanical thinning is an alternative to prescribed burns, mastication, or manual pile and burn. Skog and Barbour (2006) identified timberland areas in Western states where thinning treatments would be needed to reduce fire hazard and could make forest products economically feasible. Kline (2004) summarizes many benefits or services promoted by reducing wildfire risk, including carbon sequestration, timber products, and recreation. Additional benefits of reduced wildfire risk would be improved water quality and reduced risk to homes, wildlife habitat, historic places, and sacred sites.

Benefits in addition to reduced wildfire risk can result. Collecting forest biomass for biofuel or bioproducts can reduce GHG emissions and air pollutant emissions from open pile burning of woody residues from logging operations. Furthermore, bioenergy market demand can help retain or increase forest area and productivity (Duden et al. 2023; Jonker et al. 2018).

6.1.4 Benefits of Waste Collection and Utilization

Collecting waste products and transforming them to a resource for energy and other uses has benefits and value (Tuck et al. 2012) that depend on the waste resource, including reducing demand on disposal facilities (e.g., landfills, waste treatment facilities), protecting water quality, improving air quality (e.g., reduction in field burning of residues, reduced emissions from raw manure), and controlling odor (from manure).

Managing MSW can reduce GHG emissions, with several potential options: capturing biogas from landfills, composting organic waste, anaerobically digesting organic waste, and reducing MSW generation (Hoy et al. 2023; Cuéllar and Webber 2008; Powell, Pons, and Chertow 2016). Reducing solid waste upstream (e.g., less consumption) and downstream through recycling and other means may be environmentally preferable and would reduce waste-based feedstock for bioenergy and bioproducts. The use of MSW for bioenergy may alleviate some concerns related to conventional disposal pathways such as limited landfill space for disposal and significant methane emissions from landfills (Powell, Pons, and Chertow 2016).

The collection of manures for biogas or other uses has environmental benefits that include protecting water quality by destroying potentially pathogenic bacteria and reducing biological oxygen demand, which can improve water quality and protect aquatic biodiversity. Reducing storage of livestock waste in lagoons can also reduce odors and emissions of methane and nitrous oxide (N_2O) from those lagoons.

6.2 Relaxing Sustainability Constraints

“With the proper safeguards, the likelihood of environmental payoff [of producing biomass] appears high” (Robertson et al. 2017). As discussed in Chapter 1, constraints on potential biomass supply (Figure 6.1) were implemented in the models to move toward the sourcing of more sustainable biomass (See Table 1.3, agriculture, and Table 1.4, forestry). Thus, the model scenarios reflected areas where new biomass could not be grown, harvested, or collected, as well as assumptions on sustainable management practices or restrictions on unsustainable management practices.

Transitions to or from forest or agricultural land cover were not options in the simulations, nor were transitions to or from other land cover types, including many grasslands. These constraints could not be relaxed because they are endogenous to the POLYSYS and ForSEAM models.

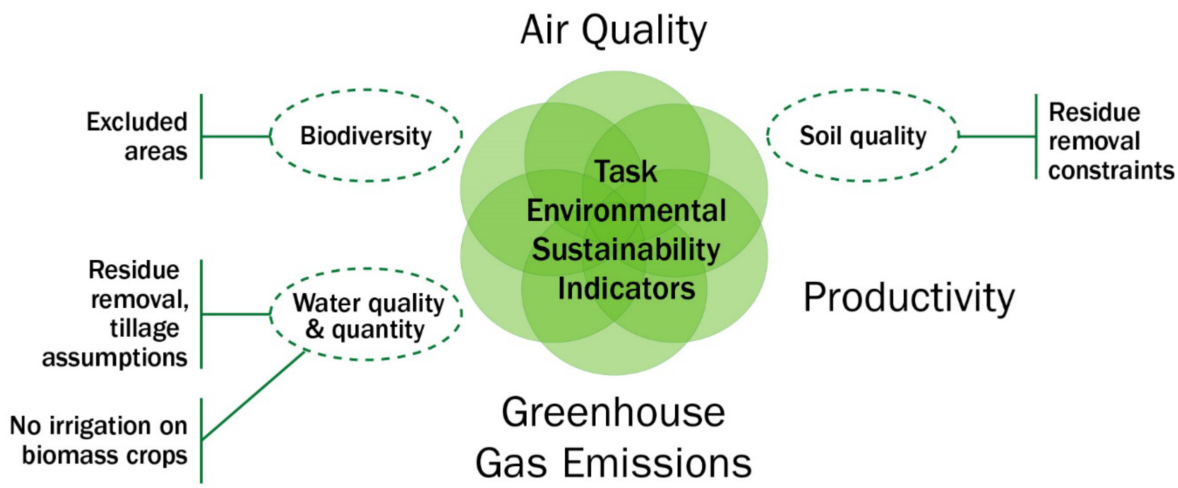

Figure 6.1. Sustainability constraints and sustainability indicator categories (green dashed circles) implemented in this report

This report illustrates how much and where different types of biomass *could* be supplied while attempting to minimize significant adverse environmental or food crop impacts. However, model simulations do not attempt to predict what *will* happen. For example, model results provide no guarantee that competition for biomass will not occur among different potential market demands (food, feed, fiber, bioenergy, and other bioproducts). Model simulations of what could be supplied sustainably do not preclude potential for adverse environmental effects if safeguards are not in place. If good management practices are not followed and excessive residue is removed, leaving soils unprotected, for example, accelerated soil erosion and nutrient loss could result (Hawks et al. 2023).

To address concerns about the effects of sustainability constraints assumed in this study, we tested scenarios in which certain constraints were relaxed. Results of the sensitivity analyses differ slightly from final results presented in Chapters 1, 4, and 5, but are presented to indicate directionality and magnitude. Thus, POLYSYS (used for agricultural lands) relaxed the residues collection constraint, and ForSEAM (used for timberlands) "freed up" timberland resources to supply biomass in addition to the quantity that could be supplied with these specific sustainability constraints in place. The new simulations illustrate how potential biomass supplies, prices, and locations change when residue retention limits and forestry demands are modified. We also consulted literature on farmer behavior and economic and physical harvesting constraints to begin to examine the likelihood that the sustainability constraints would be employed.

6.2.1 Relaxing Sustainability Constraints: Agriculture

To explore the effects of relaxing sustainability constraints on agricultural production of biomass, we altered the POLYSYS modeling runs to allow residues to be removed from conventionally tilled acres without regard to wind and water erosion or soil carbon loss. This meant relaxing the following constraints from Table 1.3:

- Crop residue removal prohibited in conventionally tilled acres.
- Crop residue removal limited based on wind and water erosion estimates and soil carbon loss.
- Acceptable residue removal different for reduced and no-till acres.

At current residue harvest machinery efficiency, a maximum of 50% of residues can be collected, but as machinery efficiency improves, up to 90% of residues could theoretically be removed if unconstrained by erosion and carbon limits. Relaxing the sustainability constraints (and applying only economic constraints and an operational efficiency constraint of up to 90%) led to a 140% increase in biomass from agricultural residues—from 174 million to 419 million dry tons at a reference price of $70 per dry ton. Thus, implementing the residue removal constraints in POLYSYS leads to a conservative estimate of the supply potential, which meets a specified environmental target (that may itself be conservative; see Khanna and Paulson 2016). However, if the machinery were available to cost-effectively remove higher volumes, and if contracts or regulations did not prevent it, operators could remove higher volumes of residues, and incentives to exceed assumed removal constraints increase with higher biomass prices. In one study, southern Illinois producers were willing to supply over 40% of their corn stover and wheat straw for bioenergy or bioproducts (Altman and Sanders 2012). The authors found a difference between maximum willingness to supply residues for bioenergy and willingness to supply at a given price.

A salient question is: Are farmers likely to harvest residues within the constraints assumed in this report, or are they likely to harvest more biomass than would meet sustainability targets? The risk of harvesting beyond sustainable targets is influenced by economic, technical, and social factors. Farmers could overharvest corn stover and other residues for short-term economic gain. Some who lease rather than own land may be less motivated to retain the nutrients from residues for long-term soil productivity. However, a 90% removal rate may not be technically, socially, or economically feasible in many contexts because it would require collection of smaller, less dense, and soil-contaminated residues that are costly to collect and transport, and that require additional advanced processing. A U.S. effort to commercialize cellulosic ethanol using corn stover shows the importance of technical constraints. Harvest guidelines were supported by machinery designed to collect and remove only the top 30% of the dried corn plant along with the cobs and husks from the sheller, thereby reducing dirt and ash content and ensuring high levels of residue remained on soils (BETO 2023; Slupska and Bushong 2019).

Constraints related to residue retention are included in POLYSYS at county-level resolution. However, many good practices for farmers harvesting residues are best determined at the subfield scale, based on grain yield data, slope, and soil characteristics (Muth et al. 2012; Parish et al. 2023). Precision agriculture applied to biomass production holds promise to reduce soil erosion, increase SOC, and improve profitability for the grower. In addition, smart combines can ensure that residue removal is limited to subfield-level sustainability constraints (see textbox).

However, data are not available for many locations to populate POLYSYS with good residue removal practices at the subfield scale. As noted above, actual residue retention for agriculture or forestry could be lower or higher than sustainable targets.

Site-specific sustainability targets that prevent erosion and protect health, such as residue removal limits, could be built into operations of cellulosic biofuels producers (i.e., energy crop users) (Kemp 2015). Economic incentives or regulations could increase the likelihood that sustainable quantities of residues are harvested (Searle and Bitnere 2017). Biorefineries have an interest in documenting that resources are sustainably managed, and contractual conditions to limit residue collection rates can be established with stover suppliers.

Energy crops are another important biomass resource, but sustainability constraints for these feedstocks, such as the prohibition of production in regions where irrigation would be required, were not relaxed in this chapter. In this report, potential biomass from energy crops is constrained economically, as discussed in Chapter 5.

Smart Technology Enables More Sustainable Farming

Software and state-of-the-art technology are making it easier for farmers to produce crops in an energy-efficient, cost-effective, and sustainable manner. Maintaining or improving soil conditions, harvesting only what's needed, and making use of biomass that otherwise would be wasted are some of the areas where new technology can enable efficiencies.

For example, a new kind of harvester header, the Straeter Cornrower Header, named for its inventor, Jim Straeter, can enable sustainable corn stover removal. Such a machine provides variable-rate harvest controls that respond to changing topography and soil conditions. This allows sustainable stover removal of about 1.5–2 tons of corn stover per acre in fields producing an average of 200 bushels of corn.

The process relies on a unique header that takes material off the field while leaving enough corn stover to maintain or improve soil carbon and keep the soil condition in shape for the next crop or cover crop. Using software developed at Iowa State University, algorithms determine when the door under the combine should be opened to let the farmer leave more or less stover on the field. A conveyor under the combine takes the biomass and puts it straight into a baler so it never hits the ground. Thus, the header eliminates the need for the farmer to make an additional pass over the field, as the machine combines two steps in one. Eliminating that extra pass saves labor, time, fuel, and overall costs.

The resulting stover bales contain 20% more biomass, which translates to less storage space required for the user. The farmer doesn't need shredders or rakes and gets more volume in a bale and a variable harvest rate. This is one example of smart technologies that promote more energy-efficient, cost-efficient, and sustainable ways to do agriculture.

Photo from William Belden, ANTARES Group Inc.

6.2.2 Relaxing Sustainability Constraints: Forestry

To explore the effects of relaxing sustainability constraints in ForSEAM on production of biomass from timberlands, we altered the following assumptions from the analysis in Chapter 4 to the description in parentheses:

- Exclude Class 1 trees—i.e., >11-inch DBH (relaxed to include Class 1 trees).
- Retain 30% of logging residues on slopes less than 40% (21.8°) (relaxed to 10% retention rate).
- Limit to land access within half-mile of roads, including USFS roads, where applicable (relaxed to within 3 miles of roads).
- Constrain maximum harvest intensity to 5% (relaxed to 10%).
- Constrain region-specific historic clearcut (relaxed to 100%).

Relaxing the above modeling constraints explores the risk of harvesting large trees for biomass, harvesting a greater percentage of logging residues than is recommended in many regions of the country (Titus et al. 2021), harvesting timberland biomass at a greater distance from roads, harvesting a larger area within each region within a year, or harvesting all biomass with clearcuts.

In addition, forest and cropland area are held constant in scenarios with sustainability constraints and in those where constraints are relaxed. What would happen to the areas of those land cover types without the constraints is uncertain, and the literature provides mixed assessments of what is possible (Rose et al. 2020). Historic evidence and modeling indicate that strong forest product markets can contribute to retention of or expansion of forest area (Galik and Abt 2016; Wear et al. 2013). For example, even though biomass demand for energy or bioproducts represents a relatively small part of total forest sector production, the impact of this demand on forest area is expected to be positive (i.e., contributing to an expanding forest area) if scenarios with and without bioenergy demand are compared in the Southeastern United States (Duden et al. 2023). Nonetheless, commodity prices and land rents can influence whether intensification or extensification occurs to meet market demand (Tian et al. 2018). The evidence from USFS FIA data and research to date suggest that the impact of bioenergy demand on total forest area is likely to be marginal relative to other drivers that determine forest area (Dale et al. 2017). If there is a notable effect, increasing woody biomass demand for energy is expected to facilitate small increases in forest area in the long term. Thus, whereas there is uncertainty, the assumption to keep forest area constant is probably somewhat conservative.

ForSEAM solves for national price and regional harvest distribution under a specified biomass demand pathway (e.g., a linear increase from 0 to 65 million tons per year from 2021 to 2050). A concern is that increased demand for biomass could drive prices up to the point that harvests could exceed the sustainability constraints specified in Table 1.4. For this report, the highest level of demand for which prices for woody biomass do not exceed $70 per dry ton (in 2022 dollars) was selected to be consistent with the national mature-market reference price for energy crops (comparable to the reference price of $60 per dry ton in 2014 dollars used in BT16). The resulting ForSEAM demand pathway is to harvest up to 54 million tons from timberlands in mature-market conditions (simulated as 2045). Relaxing this constraint to simulate biomass prices up to $75 per dry ton suggest about an additional 30 million tons per year of Class 1 trees could be harvested, as shown in Figure 6.2. Risk associated with increased demand or deviating from the sustainability constraints modeled in ForSEAM is explored below.

Relaxing the assumption of exclusion of Class 1 trees (largest diameter) and increasing the demand pathway were simulated simultaneously. ForSEAM models tree sizes as Class 1, 2, or 3. A Class 1 forest stand has an average DBH >11 inches, Class 2 has a DBH of 5–11 inches, and Class 3 has a DBH <5 inches. Results from the mature-market reference scenario suggest that increasing the mature-market demand target above 54 million tons per year (including 19 million and 35 million from logging residues and small-diameter trees, respectively) could drive market-equilibrium roadside prices above $70 per dry ton, which could incentivize harvest of Class 1 forest stands for biomass. Figure 6.2 illustrates a scenario targeting 75 million tons per year of biomass from timberlands by 2050. This scenario drives prices high enough to incentivize the harvest of Class 1 trees for biomass after demand surpasses 60 million tons per year in 2044. Class 1 trees generally have two to three times the market value of Class 2 trees due to their suitability for higher-value dimension lumber products and longer growth period to maturity. Thus, using Class 1 trees is likely to be cost prohibitive for biofuel uses.[2] For context, 35 million tons per year of small-diameter trees is about 11% of approximately 314 million tons per year of U.S. roundwood harvests for conventional forest products in 2019 (estimated from USFS 2023a).

While not incorporated in current ForSEAM scenarios, management of naturally regenerating forests using selective harvesting to maintain an uneven stand age with canopy structural complexity has been shown to be advantageous for carbon uptake rates, carbon storage, and the maintenance of ecological functions (Gough et al. 2021; Hardiman et al. 2011; Toda et al. 2023; Scheuermann et al. 2018; Murphy et al. 2022; Crockett et al. 2023). The research suggests that good management for some temperate forests can support increased harvests for both conventional timber markets and residual biomass, while maintaining net carbon uptake relative to unmanaged sites. The profitability of uneven-aged management of forests and plantations depends on tree species, residual basal area, and length of cutting cycle (Suseata et al. 2023), among other variables.

[2] For illustration, assuming $70 per ton and a biofuel yield of 60 gallons per ton indicates a feedstock cost of over $1 per gallon of biofuel, before logistics and conversion costs. Historical sawtimber stumpage prices in the range of $50–$60 per dry ton (timbermart-south.com, assuming 50% moisture content), plus an estimated $20 per dry ton harvest cost, exceed $70 per dry ton.

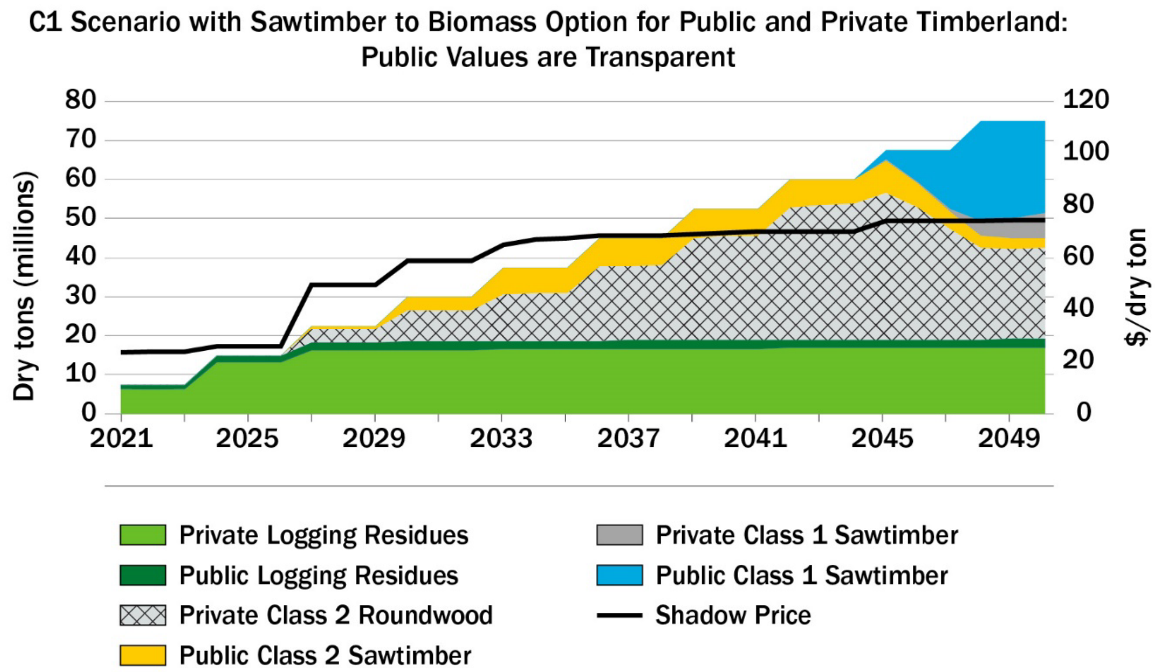

Figure 6.2. Example forest modeling results illustrating risk of exceeding $70 per dry ton roadside. Producing more than 60 million tons of biomass from timberlands risks driving market prices higher than $70 per dry ton at roadside and incentivizing production of Class 1 (C1) trees (i.e., >11-inch DBH) for bioenergy.

Relaxing the other forestry sustainability constraints under the base case also provided insights. For example, relaxing the logging residue constraint increased residue harvesting from 19 million to 25 million tons in 2050. For context, this is about 45% and 58% of the estimated 42 million tons per year of logging residues currently left in forests, respectively (USFS 2023b). Relaxing distance to roads or harvest intensity had little impact on production but decreased price in some outyears by up to $4 per ton. Relaxing the constraint on clearcutting also had little impact on production or price but resulted in up to 3.4 million additional tons of biomass from Class 1 plantations. In sum, these results suggest that if biomass prices exceed $70 per ton (dry basis, before delivery), biomass supplies from timberland could exceed about 55 million tons per year, and pressure could increase to deviate from sustainability constraints assumed in this analysis. For context, 55 million tons per year is less than 1% of about 22 billion tons of U.S. timberland growing stock (estimated from USFS 2023a). Given recent growth of woody biomass production in other nations, global competition is a key factor that is likely to moderate prices for woody biomass over the long term (e.g., Johnston and Kooten 2016; Aguilar et al. 2022).

As with agriculture, an important question is: Are forest managers likely to harvest residues within the constraints assumed in this report, or might they harvest beyond sustainable targets? Here we show that (1) sustainable residue retention and related good practices vary depending on environment and jurisdiction, (2) regionally limited field studies suggest that residues are not overharvested, and (3) mechanical and economic constraints generally prevent foresters from harvesting biomass beyond sustainable limits. Still, more studies are needed.

Several states are developing or have developed good management practices for residual biomass retention (Dirkswager et al. 2011; Titus et al. 2021). Residue retention targets range from at least 10% retained (Wisconsin) to 100% (part of Massachusetts), with most targets ranging from at least 20% to 33% (Titus et al. 2021, supplemental information). Notably, state retention targets are reported for the Pacific Northwest but not for other Western states or regions where rainfall is sparse (Titus et al. 2021). In fire-prone Western forests, rather than targets for residue retention, targets for biomass removals are set to bring total forest biomass down to recommended forest biomass density or stocking rates to improve productivity and fire resilience (North et al. 2022; USFS 2022).

Spatially explicit residue removal constraints could be imposed in forest models of biomass production, such as ForSEAM. The Forest Stewards Guild (2023) publishes regional forest biomass retention and harvesting guidelines. Some states caution harvesters against removal of biomass from specific soil types, such as poorly drained or low-nutrient soils (Benjamin 2010; Bronson et al. 2014), and this guidance could be reflected in model assumptions. The residue retention limit in this report is conservative for most environments.

Residues are not typically overharvested. Studies of effects of biomass versus conventional harvest sites in Virginia found greater residue removal at biomass sites than conventional sites but still sufficient downed woody debris and heavy slash to ensure best management practice (BMP) implementation related to erosion (Garren et al. 2022; Hawks et al. 2023; Barrett et al. 2016a). Similar results were documented in Michigan when historical records across 40 years were compared for whole-tree (including residue removal) and stem-only harvests (Premer, Froese, and Vance 2019). More importantly, whole-tree biomass removals did not impact stand productivity relative to stem-only removals. Following biomass collection, quantities of remaining downed woody debris averaged 10.98 tons/acre in the mountains (Garren et al. 2022) and 10.22 tons/acre in the Coastal Plain (Hawks et al. 2023). Residues and slash piles remaining in the Piedmont covered about 12% of the area (Barrett et al. 2016a).

Concerns about overharvesting forest residues often overlook the fact that harvesting technology and low prices, along with market requirements for clean, high-quality biomass, limit economic and technical feasibility of excessive residue removal (Premer, Froese, and Vance 2019). For example, large quantities of woody debris (about 18 tons/acre in Missouri) remain even where there are no removal restrictions (Kabrick, Goyne, and Stelzer 2019). Furthermore, methods to ensure that woody debris is retained are not specified in guidance documents, and the quantification of debris remaining is challenging (Fritts et al. 2014). Many studies show that retention recommendations are exceeded (i.e., far more debris is left following biomass collection) without deliberate effort (see references listed in Premer, Froese, and Vance 2019). In the Southeast, debris collection is limited by current operational and economic efficiencies rather than by less restrictive limits in the biomass harvest guidelines (Fritts et al. 2014). The minimum volume of residues retained in a North Carolina field study was three times the volume recommendation for the Piedmont and Coastal Plain physiographic regions (Forest Guild Southeast Biomass Working Group 2012).

Surveys find that both social and economic factors influence whether forest landowners are willing to harvest biomass (Butler et al. 2010; Gruchy et al. 2012; Hodges et al. 2019). For example, Hodges et al. (2019) find landowners consider the offered price along with other land management and conservation goals. However, information about the quantities of logging residue that forest owners and managers are willing to harvest or retain is limited, and survey results are complicated by variable interpretation of terminology. Some landowners may not be willing to harvest logging residues at all (Swinton, Dulys, and Klammer 2021). Others might be willing to collect a large quantity of residues, given an adequate price (Wolde et al. 2016). A financial analysis of forest biomass in Montana showed that harvesting can expand farther from bioenergy facilities, including along unpaved roads, if prices are high (Jones et al. 2013). Yet nonindustrial landowners may not be aware of technical constraints on residue removal, and some landowners may not be aware of applicable BMPs (Hodges et al. 2019). Forest management goals are affected by ownership tenure, history, role of hunting and other uses, whether land was purchased or inherited, size of forestland, forestland ownership objectives, and demographic features like household size and education (Hodges et al. 2019; Wolde et al. 2016).

6.3 Review of Potential Environmental Outcomes

Environmental implications of the further production and use of biomass in the economy go beyond the factors included among the sustainability constraints above. Here we present several categories of potential environmental outcomes associated with producing and harvesting agricultural and forest biomass, including plausible outcomes that may result depending on the degree to which producers choose to follow good management practices. This section addresses several specific environmental outcomes that may be affected by the adoption, or lack thereof, of sustainability practices: LUC, food availability, water consumption, air quality, and biodiversity. If products of biomass are needed for GHG reduction strategies, "what is the most effective and least harmful way of doing so?" (Pierrehumbert 2022).

6.3.1 Good Management Practices

Good management practices are recommended approaches that contribute to progress toward environmental sustainability of biomass production and harvesting. Management practices included in the modeling of potential biomass and termed "sustainability constraints" (Section 1.3) are a first step. Good management practices balance multiple societal goals such as improving environmental conditions or food security with the economic and productivity goals of producers.

Good management practices are sometimes documented as "BMPs" and may be officially designated by cognizant organizations. BMPs aim to be cost-effective, practical, and generally accepted. Some guidelines and certification processes are voluntary, context-specific, and just one way to do things (Lattimore, Smith, and Richardson 2010). Numerous good practices are available for agriculture and forestry, as well as for microalgae (Efroymson et al. 2021). Most BMPs are designed to protect water quality, but good management practices go beyond water quality. General good practices to ensure sustainable biomass production and use were recently developed under the Clean Energy Ministerial (Biofuture CEM 2023), emphasizing the importance of local context and engagement of local stakeholders. We use the general term "good management practice," except where BMPs are published and clearly recognized in the context of a specific activity and jurisdiction.

Good management practices can be used to refine model assumptions and outputs. Some practices may increase the price or reduce the quantity of potential biomass. On the other hand, some management practices, like the use of irrigation where sufficient water is available, could increase the quantity of potential biomass compared to quantities in this report. Some good management practices could serve as future sustainability constraints for modeling biomass or lead to biomass that is even more sustainable than the biomass in this study. Some practices are implemented at spatial scales much smaller than county-level simulations. The management practices highlighted below are examples, not a comprehensive review.

6.3.2 LUC

Land can provide simultaneous services (e.g., food, energy, species habitat), but land is a limited resource, and concerns about competition for land are growing (Searchinger et al. 2023). Therefore, research including biomass and bioenergy studies attempts to identify and apportion causes of LUC (Oladosu et al. 2012; Efroymson et al. 2016) and to quantify its environmental and human impacts (Robertson et al. 2017; Dunn et al. 2017). Land use, which typically includes land cover and land management, is defined by the IPCC (2022) as "the total of arrangements, activities and inputs applied to a parcel of land," and any change in these arrangements, including governance and zoning, is considered LUC.[3] Sustainability constraints applied to biomass models in this report are intended to support changes in land cover and management that are beneficial for societal goals and environmental outcomes. In other words, the biomass production is based on beneficial LUC.

The primary type of land change associated with the potential biomass supply estimates in this report consists of changes in agricultural land management practices, with modeling results indicating increases in land area under perennial crop cover and in productivity. The results show that energy crops are economically competitive only where conventional agricultural crops offer marginal returns (Figure 6.3). Change is minimal in areas where conventional crops have a comparative advantage, such as in the Corn Belt. It would be unreasonable to assume that most corn fields will transition to perennial grasses if it is not profitable to do so (Clark et al. 2013).

To model compensation for displaced forage production on pastureland, the agricultural modeling with POLYSYS includes assumptions of management-intensive grazing (described in

[3] LUC includes any change in land cover, management, or function associated with human activities. In this report, indirect or induced LUC is considered a part of total LUC.

the appendix to Chapter 5).[4] To estimate sustainable supply potential, change in primary land use was not permitted, and thus interactions between land in agricultural use and forestland were not modeled. Agricultural land available for biomass may depend on crop yields, livestock yields, and trends in dietary patterns and consumption of animal products (Donnison et al. 2021).

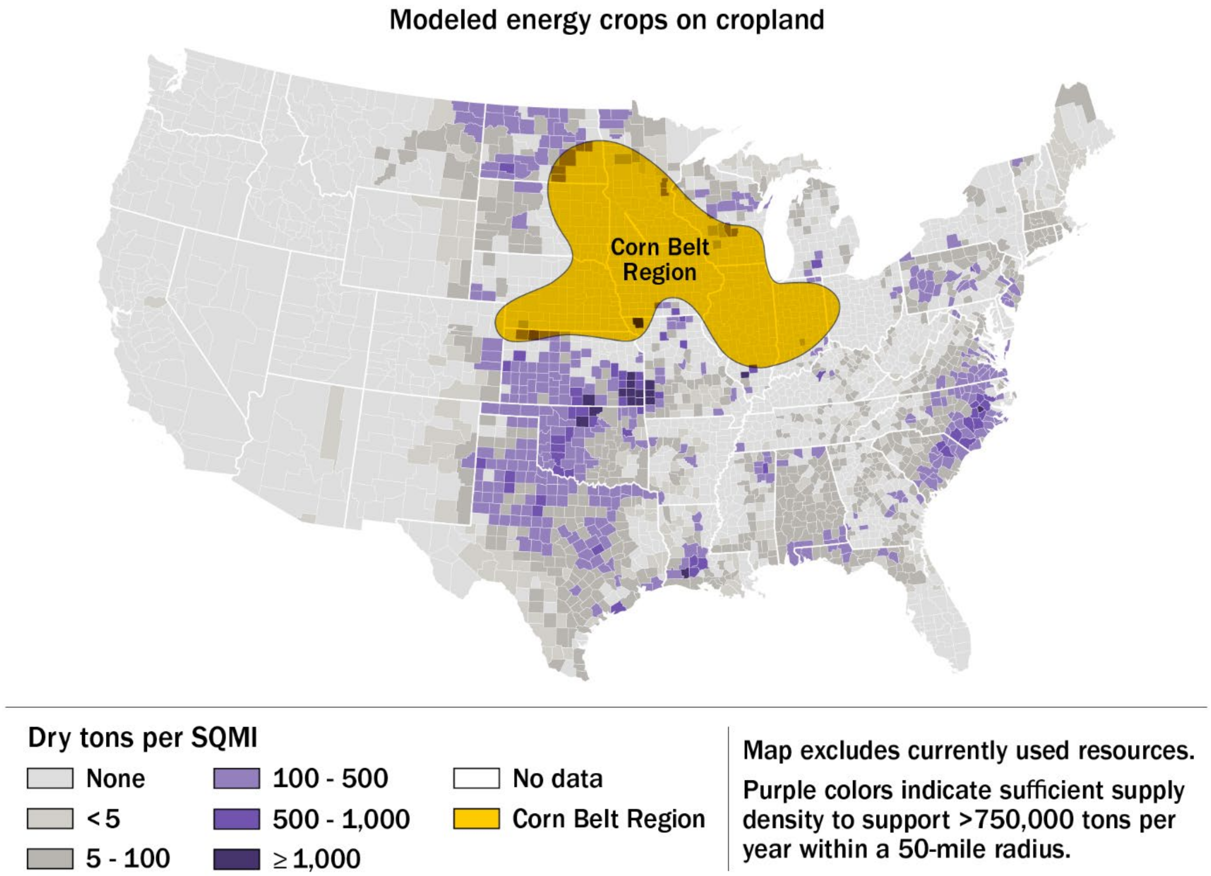

Figure 6.3. Spatial distribution of purpose-grown energy crops under the mature-market medium reference scenario on cropland, illustrating the comparative economic advantage of commodity crops in the Corn Belt

6.3.2.1 LUC-Related Concerns and Analytic Approaches

A specific concern about LUC is that expanded biomass production for bioenergy will directly or indirectly lead to the loss of grasslands, forests, and other carbon-rich ecosystems. Changes in land cover and management associated with biomass production can occur directly on the lands where biomass is grown and harvested or indirectly on distant lands through market-mediated effects such as higher commodity prices and shifts in trade flows. Bioenergy-induced LUC and the extent of its effects are typically estimated through modeling (Searchinger et al. 2023; Lark et al. 2022; Clark et al. 2022) and represent a great source of uncertainty regarding the carbon intensity and sustainability of biomass production. Land management and land cover influence

[4] Access BT23 appendices at www.energy.gov/eere/2023-billion-ton-report.html.

GHG emissions, food security, biodiversity, water quality, and water quantity, which are discussed later in this chapter.

Inferring and testing causal relationships between biomass and LUC may help analysts better estimate the effects of biomass production and use. However, to date, few papers have attempted to quantify causal connections between biomass production and LUC (e.g., Li, Miao, and Khanna 2019; Oladosu, Kline, and Langeveld 2021; Lee et al. 2021; Chen and Khanna 2018). The challenges of attribution analyses are discussed in *Biofuels and the Environment: Third Triennial Report to Congress* (Clark et al. 2022).

Results of LUC simulations depend on comparing a range of bioenergy scenarios with different reference or counterfactual scenarios (Koponen et al. 2018). A transparent land reference is especially important for determining results of bioenergy assessments (Koponen et al. 2018).

6.3.2.2 LUC-Related Models, Assumptions, and Data

Outputs of models of bioenergy and LUC are sensitive to assumptions (e.g., Khanna, Rajagopal, and Zilberman 2021; Oladosu et al. 2012). Some types of assumptions are unverifiable, but others can be tested empirically (Field 2021). Assumptions about the role of crop prices in LUC, for example, are in dispute (Persson 2016). Modeling is also founded on different assumptions about land ownership and management (Daioglou et al. 2020; Daioglou 2022; Efroymson et al. 2016; Kline et al. 2011). Agricultural land needs of the future are uncertain, and biomass crop yield improvements related to technology improvement and climate change are also the subject of debate (Field et al. 2020; Aggarwal et al. 2019; Zilberman 2017). Assumptions about coproducts are critical for estimating LUC attributable to biofuels and other end uses of biomass (Szabó 2023). Agricultural subsidies and programs such as the USDA Conservation Reserve Program (CRP) vary over time and are difficult to incorporate in models but are widely recognized to influence cropland area and prices in the United States (Taheripour and Tyner 2014; Frisvold 2004).

The concept and measurement of LUC are dependent on the model and user-selected parameters (e.g., land categories, definitions, time periods). Change estimates vary widely depending on the points in time being compared and specific geographic areas included in an analysis, in part because land cover and management associated with agriculture and forestry are extremely dynamic, as illustrated in Figure 6.4.

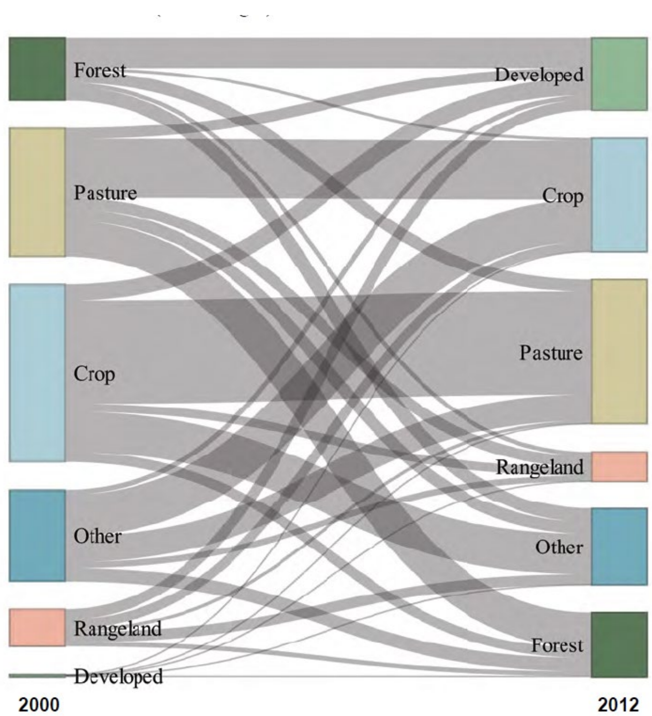

Figure 6.4. Gross LUC in the CONUS from 2000 to 2012. For land moving out of a specific land use in 2000 (bars on left), the width of the gray flows indicate the relative area moving into each new use in 2012 (bars on right).

Source: Riitters et al. 2023

Variable land cover classifications affect LUC estimates (Singh et al. 2017). Variability from year to year in reported acreage in different categories used by the USDA Census of Agriculture (USDA 2019)—including idle, summer fallow, non-cultivated, and harvested cropland—and discrepancies in classification due to field boundaries, changing remote sensing technologies, and other factors can result in a range of ±20 million acres in reported cropland in a given year (Wang, Wander, et al. 2022), further complicating LUC analyses. Independent of classification errors, the Census of Agriculture finds that harvested cropland varied by ±20 million acres around a 305-million-acre midpoint, and total cropland area decreased slightly (−10 million acres) from 2007 to 2017 (Clark et al. 2022, Figure 5.3), while harvested cropland increased slightly (+10 million acres). The increase in harvested acres reflects the expiration of contracts paid to farmers to take cropland out of production under federally funded set-asides such as the CRP. Thus, LUC estimates depend on the time periods and data sources selected for analysis, how CRP lands are classified, and how uncertainty is considered (Copenhaver et al. 2021). For example, some studies focus on the recent expansion of cultivated crops and calculate LUC for any return of CRP grassland to its prior use (cultivated crops) (Lark et al. 2020). Others focus on the persistent loss of farms and prime cropland to urban and other developments (Francis et al. 2012; Hunter et al. 2022). Further, as discussed above, literature establishing causal historical connections between cropland change and biomass or bioenergy production is preliminary and inconclusive.

The gaps and uncertainties associated with land cover and management data, aggregation, and definitions required to assign land "use" classes, as well as choices of model assumptions, illustrate why model results associated with LUC have large margins of uncertainty. For example, an analysis sponsored by the EPA estimated that between zero acres and a maximum of 2 million acres of new cropland (or 0%–0.5% of total cropland) are attributable to the RFS (Clark et al. 2022).

Because LUC modeling is dependent on multiple assumed relationships and general land use classifications, minor differences in approach lead to widely disparate estimates of LUC impacts of biomass and bioenergy production (e.g., Scully et al. 2021; Broch, Hoekman, and Unnasch 2013) with contrasting conclusions—i.e., that highly detrimental (Searchinger et al. 2008) or beneficial (Donnison et al. 2021; Oladosu et al. 2012) effects associated with land and GHG emissions are likely. Modeled estimates of indirect LUC attributable to bioenergy production are unverifiable (Babcock 2009; Smith et al. 2014; Scarlat and Dallemand 2019). A recent EPA literature review of biofuel carbon intensity modeling found widely varying LUC, as well as overall GHG emissions results, varying with study, modeling framework, and scenario assumptions for both corn starch ethanol and soybean oil biodiesel (EPA 2023b).

6.3.2.3 Cropland, Forest, and Grassland Areas and Interactions with Commodity Prices

Crop price and acreage responses in models are influenced by elements that impact extensive and intensive responses. The extensive response is the addition of new land, and the intensive response is the intensification of existing agricultural land by improvement in technology, the introduction of double cropping, or other practices to improve yields. Reviews by Babcock (2015) and Khanna, Rajagopal, and Zilberman (2021) present theoretical and empirical evidence of the importance of intensification in the response of prices to changes in biofuels demand and on the response of cropland.

Modeling results related to price and LUC can be sensitive to assumptions in the dynamics of the response to the extensive and intensive margin. Whereas elasticity factors have been applied to perform LUC modeling since the early 2000s (Hertel et al. 2010), the price elasticities that determine LUC responses in the models are based on sparse data (Lambin and Meyfroidt 2011).

One limitation of this billion-ton report is the assumption that agricultural prices have zero impact on the intensification of land use, and therefore on increasing yields. Consequently, model results could overestimate the increase in crop prices. However, the crop yield improvement assumptions in the low, medium, and high mature-market scenarios in POLYSYS could represent future crop intensification (DOE 2009), and the management-intensive grazing described above represents a type of intensification on pastureland.

An example of the importance of the intensification can be obtained by looking at the commodity crop price increase in the $70/dry-ton, mature-market high scenario, in which the price of corn compared to the mature-market medium reference case drops from $4.20/bu to

$3.82/bu. As a result of this crop intensification, the quantity of the biomass produced increases from 575 million tons per year to 838 million tons per year.

Regarding causation, some studies find that U.S. biofuel policies or corn ethanol production are drivers of higher crop prices and cropland acreage expansion (Li, Miao, and Khanna 2019; Lark et al. 2022), and others find no significant influence of U.S. corn ethanol production as a driver of LUC via the causal mechanisms of higher prices or displacement of exports (Oladosu, Kline, and Langeveld 2021). The expansion of total agricultural land may be more influenced by non-price elements than by commodity prices or bioenergy markets (Zilberman 2017; Kline et al. 2011). Land tenure regimes, government development policies, agricultural subsidies, infrastructure development, existence of production contracts, policy incentives to convert nonagricultural land (i.e., primary forest and natural pasture), and other localized sociopolitical and economic factors are important drivers of LUC (Kline et al. 2009, 2015; Kline and Dale 2020).

Under the mature-market medium scenario at a biomass price of $70 per dry ton in Chapter 5, 398 million tons per year of energy crops are produced. This production is on 76 million acres of agricultural land, including 26 million acres of cropland and 50 million acres of pastureland (Figure 5.9). Farmers are expected to produce crops that have local comparative economic advantage. Thus, modeling in Chapter 5 explores likely interactions with U.S. conventional crop markets. Under modeled price impacts of the mature-market medium scenario, wheat has the largest price increase (19%), followed by soybeans (9%) and corn (5%), compared to the extended USDA baseline. This results in a weighted average price increase of 6% (Figure 5.11). In all cases, these price increases are far below the price spikes experienced in 2007–2008 and 2011–2012. These price increases, and the low total U.S. agricultural land price elasticities reported by Barr et al. (2011)[5] and Roberts and Schlenker (2013), suggest land use responses to changes in price may be relatively inelastic. Li et al. (2023) analyzed data from USDA and reported that for the last 20 years or more, the U.S. aggregate cropland remained relatively constant between 2000 and 2021. Results also suggest there is an inelastic response to price, but there is a trend of increasing acreage for corn and soy production as a replacement for other crops in the 1980s (USDA NRCS 2023b). The historical data reported in the Food and Agricultural Policy Research Institute's 2023 agricultural outlook show that annual variations in U.S. land use for major crops, hay, and CRP for the last 20 years have been in the range of ±0.3% despite significant crop price variations (FAPRI 2023).

[5] Barr et al. (2011) found that the elasticity of total land used in agriculture with respect to agricultural prices is 0.03, and in Brazil the same elasticity stabilized at 0.05 after 2000, even in the presence of soaring prices. One additional finding is that the elasticity of total land use in Brazil is much lower when pastureland is included than when only crops are considered; this indicates a significant shift from pasture to cropland and could indicate a small impact on deforestation. A later econometric study by Roberts and Schlenker (2013) found similar results for the cropland elasticity in Brazil, but significantly higher (0.28) for the United States. However, when they introduce set-asides and land retirement programs, the supply response drops sharply, and it is inconclusive. This remains an area of uncertainty in the literature.

Economic theory suggests that the risks of induced LUCs are higher as prices for commodity crops increase. These risks are uncertain and unquantified in this study. Figure 5.11 shows that commodity crop price impacts under the $70/ton, mature-market medium scenario are in the range of approximately 5% to 19%, a wide range that varies both by crop and the level of biomass demanded. These simulated price responses reflect the effects of changes in the demand for agricultural land, while other factors are assumed to be held constant. Despite persistently increasing global demand, long-term trends for corn, wheat, and soybean prices show declines in real terms. The fall in real prices is driven mostly by the intensification of agricultural land; 95% of global food growth has come from the increase of output per hectare (Maletta 2016). Because the current modeling approach includes only changes in land use in the United States, the global intensification or extensification of agricultural lands (including both cropland and livestock pasture) into nonagricultural lands and associated environmental impacts resulting from these price increases cannot be quantified in this study. Impacts on non-U.S. commodity consumption, production, and demand are not quantified in this study and could range from small to very substantial, although that is an area of substantial uncertainty.

Local policies, technical assistance, and financing are among factors that influence whether production intensifies and allows for expansion of conserved areas (as occurred in most high-income nations over the past 50 years), or if agriculture expands and impacts forests and potentially biodiversity (as occurred in nations with less stable governance and land tenure regimes). Characterizing potential impacts of increased commodity prices on forests is complex, as effects vary greatly depending on local context (Zabel et al. 2019; Kline et al. 2015). Global commodity prices influence crop choice, but there are various factors that lead to deforestation including local drivers (Kline and Dale 2020). The fieldwork required to determine actual causes of deforestation and changes in biodiversity is difficult, costly, and often dangerous. Thus, most published research is based on remotely sensed land cover data, correlations, and models that do not always incorporate factors such as local land acquisition customs, governance, security, property rights, illegal logging, incremental forest degradation, wildfires, or land invasions (Efroymson et al. 2016; Kline et al. 2009). A recent analysis by Brazilian researchers illustrates the critical role of local governance in Brazil, independent of agricultural commodity prices (Rochedo et al. 2018). For these reasons, it is not possible to determine with certainty how a small increase in U.S. commodity prices could affect forests, but evidence suggests that any effects, whether beneficial via intensification or detrimental via extensification, and also have uncertainty similar to other factors impacting forests, such as those related to changing climate, including sea level rise, extreme weather events, and wildfires (Kline and Dale 2020; Kline et al. 2015). Wildfire-burned areas, for example, are trending upward in the United States (Salguero et al. 2020).

Corn ethanol and, to a lesser extent, soybean oil biodiesel have been the focus of simulations of future market-mediated impacts of potential biomass-induced agricultural price increases on forest extent. This literature suggests a very wide range of potential global impacts (EPA 2023b) whose uncertainty would increase if energy crops were planted. A recent large-scale attempt to understand such impacts, the Stanford Energy Modeling Forum's EMF 33 study, also suggests a very wide range of potential LUC impacts associated with cellulosic biomass. Further research is needed to better quantify the range of potential market-mediated impacts of energy crops compared to those of corn- and soy-based bioenergy.

In addition to modeling energy crop production on cropland, results in the mature-market medium reference scenario at a price of $70 per ton of biomass include energy crop production on 50 million acres of pastureland. This represents 12% of the 415 million acres of pastureland on farmland, or 8% of the 655 million total acres classified as grassland pasture and range by the USDA's National Agricultural Statistics Service (USDA 2014).

In light of studies that attempt to quantify grassland-to-agriculture transitions in recent years (Mladenoff et al. 2016; Lark, Salmon, and Gibbs 2015; Lark et al. 2019, 2020; Comer et al. 2018; Gage, Olimb, and Nelson 2016), the question arises whether energy crop production might further threaten grasslands. Several studies document correlations between conventional biofuel production and recent transitions of grassland to cultivated cropland in the United States (e.g., Li, Miao, and Khanna 2019; Lark et al. 2020). Researchers have identified grasslands likeliest to transition to agriculture in the future (Gage, Olimb, and Nelson 2016; Olimb and Robinson 2019) based on soil, climate, and topographic variables. Others acknowledge that commodity prices and revenues are likely to influence land cover transitions as well (Rashford, Walker, and Bastian 2011). However, estimates of extents of transition have large uncertainties (Rashford, Albeke, and Lewis 2013; Singh et al. 2017). Little research, if any, projects potential effects of energy crop expansion on grasslands. Environmental consequences will depend on the types of crops, management practices, and conditions of the grasslands. Better understanding of causal relationships that influence cropland expansion could help direct future conservation and energy policy (Olimb and Robinson 2019).

6.3.2.4 Sustainability Constraints and LUC in BT23

BT23 scenarios are based on sustainability constraints applied to the agricultural (Table 1.3) and forest (Table 1.4) model parameters and land classes. The analyses attempt to minimize transformation of new lands, exclude biomass harvest in administratively reserved forestlands, and apply practices (e.g., conservation, no tillage) that support or improve important ecosystem functions and services. Agricultural and forestry lands remain fixed in the agricultural land model (POLYSYS, described in Chapter 5). The restriction that no forest or pastureland may transition to annual cropland is assumed so that estimates of potential biomass in this report do not rely on deforestation or other transition of natural land in the United States. However, this modeling restriction does not ensure that these transitions will not actually happen. The constraints could drive intensification, but that is not endogenously modeled.

Some concerns about induced LUC are addressed in BT23 scenarios by ensuring that primary demands (food feed, forage, and fiber, Table 1.3) are met in tandem with additional biomass production while demonstrating the potential to expand perennial cover in regions of lower-profit (economically marginal) pasture and croplands. The bioenergy scenarios result in higher land productivity overall. Food security is addressed in more detail in Section 6.3.3.1.

The constraint of avoiding planting energy crops, or crops in general, on nonagricultural land (Table 1.3) is consistent with observations that overall acreage in agricultural production is not sensitive to price changes in ranges considered here (Dunn et al. 2017). Cultivated agricultural area in the United States fell by 70 million acres between 1982 and 2007 and then rebounded by 10 million acres from 2007 to 2017 (USDA NRCS 2023b). Government subsidies and land set-aside programs exert large influence on crops and total area under cultivation in the United States (Frisvold 2004). Thus, while cultivated cropland area increased by 10 million acres from 2007 to 2017, more than 13 million acres were released back to farmers for potential cultivation because of expiring CRP contracts over the same period.

There is no way to ensure that biomass production will evolve following assumed constraints and land distribution illustrated in Figure 6.3. Monitoring land cover, land management, and associated environmental effects, combined with public access to transparent and consistent reporting, are important steps to help identify if problems arise that merit corrective action. Timely monitoring can support safeguards and management to minimize potential detrimental changes in land cover and management.

6.3.2.5 Moving Forward with LUC Studies and Good Practices

Additional research is needed to verify historical changes in land cover and land management, and to discern causal drivers. Quantifying LUC involves uncertainties but is nonetheless important. The uncertainties underlying LUC models are irreducible unless verifiable land cover categories are applied consistently to understand historical trends in conjunction with analyses to identify local drivers for land management decisions, focusing on areas where critical changes occur. Research is also needed to explore the potential magnitude and impacts of cropland extensification into nonagricultural lands in response to biomass production scenarios; this could involve linking POLYSYS and ForSEAM. Balboni et al. (2023) conclude that research is needed to go beyond traditional economic modeling approaches, to employ rapidly improving remotely sensed data on land cover and carbon stocks, and to collect field data on local variables that influence LUC such as local political cycles, accountability, subsidies, enforcement capabilities, and land insecurity.

In addition, constructive resolution of questions about LUC requires testing, especially place-based testing, of causal inferences related to biomass and LUC. A basic question relates to the direction of causation. Some statistical causal analysis studies based on empirical data (e.g., Katrakilidis et al. 2015; Natanelov et al. 2011; Roman, Górecka, and Domagała 2020) find that ethanol production quickly responds to, rather than causes, price changes. Monitoring land cover conditions in near real time is now technologically possible and can help distinguish effects of biomass production from effects of other agents. Understanding causation can help analysts identify effective solutions that promote beneficial changes in land management and associated ecosystem functions (Daioglou et al. 2020; Daioglou 2022; Efroymson et al. 2016; Kline et al. 2011).

Good practices can mitigate concerns associated with LUC. For example, growing perennial energy crops on degraded grassland or low-fertility lands can provide ecological benefits and reduce the likelihood that forest or grassland transition to annual cropland (Gelfland et al. 2013; Robertson et al. 2017; Daioglou et al. 2020). In a study in the Northeastern United States, landowners who owned marginal lands were more likely to plant energy crops and for a lower price than landowners who did not own these marginal lands (Jiang, Zipp, and Jacobson 2018). The use of agricultural and forest residues reduces competition for land (Calvin et al. 2020; Daioglou et al. 2020). Investments in integrated production systems, infrastructure, and technologies that improve land management and productivity can convert concerns about competition to synergies and co-benefits (Dale et al. 2014; Souza et al. 2017; Kline, Msangi, et al. 2017). Protecting lands with high carbon or biodiversity value is a good practice (Daioglou et al. 2020) that is a sustainability constraint in POLYSYS and ForSEAM. Other opportunities for beneficial LUC are not considered in BT23 but may merit additional study. Many of these add costs but could benefit from payments for ecosystem services, in addition to biomass supplied. For example, one recent study found that the technical potential of biomass from diverse sustainable sources—such as biomass grown and managed as part of land reclamation from contaminants, restoration of former mining lands, removal of invasive species to improve habitat for native or endangered species, improved regulation of runoff in catchment basins, and biomass removal (rather than mowing, herbicides, or fire) to manage vegetation in powerline and road rights-of-way—is estimated at half a billion tons per year or more (Field et al. 2023). The same study found that another 100 million metric tons of biomass could be generated by reducing wildfire risks in the West. These biomass resources do not compete for land for other productive uses. Information describing and quantifying adoption of good practices will lead to more realistic future scenarios of biomass production.

Good practices that safeguard sustainability need to be appropriate for local conditions; consider the practical, place-based opportunities and constraints; and be developed with stakeholders who are informed by reliable monitoring and evaluation data to support continual improvement. Biomass markets that provide performance-based incentives support safeguards by promoting investment in technologies for more sustainable agricultural practices that reduce supply chain emissions and other detrimental effects.

6.3.3 Good Management Practices in Agriculture

Many good management practices, including guidelines and official BMPs (usually termed conservation practices), have been developed for agriculture. The Natural Resources Conservation Service is the main source of agricultural BMPs for water and soil quality. U.S. states and researchers from the National Corn Growers Association, Water Research Foundation, and United Soybean Board have contributed to BMPs. However, the knowledge base to support the development and implementation of good practices may still be low for some energy crops.

A few studies of adoption of good management practices have been undertaken in agriculture. The USDA found that more than 80% of farm acreage has adopted tillage, nutrient management, and irrigation management practices. In the same study, cover crops were found to be adopted by only 40.5% of farmland and 61.3% of farmers (USDA NASS 2022). In contrast, Wade, Claasen, and Wallander (2015) found much lower adoption rates for good practices by farmers growing annual commodity crops (e.g., 40% of combined acreage of corn, soy, wheat, and cotton in no-till/strip-till in 2010–2011). Adoption rates differ by region and crop, with adoption rates high for some crops (e.g., soy) and some regions (e.g., Southern seaboard) (Wade, Claasen, and Wallander 2015). Factors that determine adoption by farmers include information, profits (farm income and off-farm income), land tenure, farm size, experience, and education (Liu, Bruins, and Heberling 2018). Access to good information, government subsidies, environmental consciousness, and profits associated with practices leads to greater adoption of BMPs (Liu, Bruins, and Heberling 2018), and additional social science research can increase understanding of how to increase adoption of good practices (Delaroche 2020). BMP compliance can be affected by regulatory push and community pull (Welch and Marc-Aurele 2001). The performance of certification programs has not been evaluated (Liu, Bruins, and Heberling 2018). Rates of adoption of good practices for farmers growing energy crops or harvesting crop residues (as mentioned above) are uncertain. Identifying decision makers who could increase the likelihood of compliance with good management practices and regulations for harvesting stover would be important. Decision makers could include farmers, harvesters, stover aggregators, biomass users (Kemp 2015), or policymakers.

6.3.3.1 Food Security

Food security questions in the context of biomass are not new, and guidelines have been published to build synergies between the development of biomass markets, food security, and other sustainable development goals (e.g., FAO 2014). BT23 estimates potential biomass while meeting food, feed, and fiber needs concurrently. Integrated modeling of the bioeconomy helps inform strategies to avoid unintended impacts of LUC on food crops (Daioglou et al. 2020).

As specified above and in Chapter 5, production of nearly 400 million tons of energy crops per year under the mature-market medium scenario could cause commodity crop prices to increase, raising farmer returns above the costs of production and raising corn prices 5%, wheat prices 19%, and soy prices 9%. These are modest increases compared with those observed in 2008, 2012, and 2022. Associated impacts on food prices would be low given that food commodities comprised an average of 16.6% of the price of finished food prices from 1993 to 2022 (USDA ERS 2023), with the remaining 83.4% attributed to off-farm costs. Thus, commodity price increases in the range of 5%–20% would correspond to finished food price increases of 0.8%–3.3%.

Key determinants of hunger are not commodity prices, but rather the political and governance conditions that influence access to social safety nets in times of need (e.g., crop failures, natural disasters) and, of course, poverty (Kline, Msangi, et al. 2017), with the rural poor consistently at highest risk (FAO 2017). As noted in *Enough: Why the World's Poorest Starve in an Age of Plenty*, people are at risk of food insecurity and hunger in modern times not because of a lack of global food production, but rather because of poor distribution of wealth and resources (Thurow and Kilman 2009). Changes in commodity prices have a more direct effect on income for agricultural producers than for consumers. This can be beneficial for food security because more than two-thirds of global poor live in rural areas, and their incomes strongly depend on agriculture (World Bank 2015). Economic growth in the agricultural sector has two to four times the impact of growth in any other sector in reducing poverty (World Bank 2007, 2015). Consequently, increases in commodity prices paid to farmers improve farm wages and food security, and in countries in which agriculture provides a significant proportion of rural employment, these increases are likely to reduce overall poverty rates (Headey and Hirvonen 2023).

Integrating food crop and biomass crop production improves resource management (Kline, Msangi, et al. 2017). For example, the use of cover and intermediate crops is a good management practice that integrates food cropland and energy crops without requiring more land. Food concerns are also mitigated, as scenarios target croplands that are economically marginal because of relatively low productivity and higher operational costs. Expanding marketing options and allowing flexible end use of crops can help ensure sufficient food surplus to help meet unforeseen supply disruptions, along with ecosystem services, biofuel, and bioproducts (Vural-Gursel et al. 2021).

As shown in Chapter 5, the contribution of biomass production to farmers' total net market returns is projected to be $27 billion/year, or 52% over baseline for the case of the mature-market medium scenario at $70 per dry ton. These increased returns are generated by higher crop prices (26%), residue collection (9%), and harvesting of purpose-grown energy crops (18%). This not only offers a significant increase in income for farmers and rural communities, but also implies a reduction of government support and subsidies to agricultural income. Such an increase in crop prices could be expected to reduce the level of subsidized U.S. agricultural exports and contribute to increased agricultural incomes of farmers and rural communities around the globe. Increased rural incomes contribute to improved food security for the more than 800 million poor whose incomes depend on agriculture.

6.3.3.2 GHG Emissions

The carbon benefits of growing and harvesting energy crops, including uptake of CO_2 by vegetation and carbon sequestration by soils, were described above and in Chapter 5. We revisit the GHG emissions topic here to describe good management practices and remaining concerns. We acknowledge that it is impossible to predict the extent to which producers will choose to follow all good management practices, and adoption rates are not within the scope of this study.

Many recommended practices for mitigating agricultural GHG emissions are related to fertilizer management (e.g., Langholtz et al. 2021) and soil carbon sequestration. Purpose-grown, perennial energy crops generally have lower fertilizer requirements than annual crops, as discussed below. Soil carbon can be enhanced through crop selection, harvesting practices, nutrient management, residue management, erosion control, and improved management on marginal or degraded lands. Growing perennial biomass on former cropland, for example, can improve sequestration of soil carbon (West and Post 2002). BT16 estimated SOC changes from simulated biomass, with benefits where potential deep-rooted feedstocks were simulated to grow (Canter et al. 2017). Life cycle and other analyses show that planting perennial crops provides greater GHG emissions reductions than corn (Farrell et al. 2006; Morales et al. 2015; Davis et al. 2012; Wang et al. 2012). Follett et al. (2012) describe management parameters for switchgrass that lead to increases in soil carbon in subsoil. Good management practices for residues led to many of the sustainability constraints in Table 1.3. Altering the plant microbiome for energy crops could lead to further carbon gains (Robertson et al. 2017).

More intensive crop management systems can reduce net GHG emissions, in part by allowing the succession of uncultivated lands to forests (Snyder, Bruulsema, and Jensen 2007; Barbier, Burgess, and Grainger 2010; Yeo and Huang 2013), as has occurred in the United States, especially in Eastern states (e.g., Thompson et al. 2013).

Existing literature suggests purpose-grown biomass may realize minimal to substantial net GHG benefits, depending on factors such as the initial site conditions, on-site management practices used, and the severity and direction of market-mediated impacts. Whereas market-mediated price changes for commodity crops were estimated in POLYSYS scenarios, potential impacts of price changes on net GHG emissions were not estimated. Further research will be needed to quantify these impacts. N_2O is the dominant GHG source from agriculture (on a warming potential basis) and the third-largest GHG source for the country as a whole (EPA 2023a). Thus, the question of whether biomass production scenarios will lead to higher or lower net N_2O emissions is important (Robertson et al. 2017).

N_2O emissions are highly variable and difficult to model. Fertilizer application rates and emissions factors for energy crops are among the largest uncertainties for projections of future N_2O emissions (Davidson and Kanter 2014). Therefore, additional field studies (e.g., poplar in Robertson, Paul, and Harwood [2000]) are needed to help researchers identify concerns and good management practices. However, there is strong evidence that perennial energy crops have lower N_2O emissions per area (Whitaker et al. 2018) and per unit of nitrogen applied (Field 2015) than annual cropping systems, likely due to their greater nitrogen use efficiency enabled by more developed root systems.

Few recommendations for biomass crop management are focused on N_2O. The source, application rate, timing, placement, and nutrient balance of fertilizer can affect N_2O emissions rates (Snyder, Bruulsema, and Jensen 2007), so optimizing fertilizer nitrogen use efficiency (Smeets et al. 2009; van Groenigen et al. 2011; Wang et al. 2015), increasing yield (Smeets et al. 2009), and possibly switching the form of nitrogen applied or using nitrification inhibitors (Smeets et al. 2009; Subbarao and Searchinger 2021) are good management practices. Practices that reduce N_2O currently emitted from wet soils in the Corn Belt would also be important (Lawrence et al. 2021).

Fertilizer production is a GHG emission-intensive process, and the associated CO_2e is an important component of biomass production and the bioproduct life cycle, given the fertilizer needs of energy crops (Wang et al. 2012). Energy required to produce fertilizer through the Haber-Bosch process using fossil energy sources and process emissions are sources of CO_2 emissions, while the nitric acid production process also releases N_2O, which has a substantially higher global warming potential (Camargo, Ryan, and Richard 2013). GHG emissions could be reduced by using renewable energy for the process or by planting legumes as cover crops or in rotations to meet part of the crop nitrogen requirement (Camargo, Ryan, and Richard 2013; Northrup et al. 2021).

6.3.3.3 Water Quantity

Competition for water can affect biomass production or alter the preferred feedstock and possibly the total potential biomass in this report. Groundwater storage volumes are declining rapidly in many parts of the Ogallala Aquifer (Bailey, Schipanski, and Kisekka 2020), and demand is increasing in the Apalachicola-Chattahoochee-Flint Basin in the Southeast, which includes Atlanta (Schlef, Steinschneider, and Brown 2018). Warming temperatures and declining precipitation, along with population growth, are reducing water availability, especially for new uses (Wu et al. 2020).

Could the potential energy crops in this report use more or less water than the vegetation they replace, altering groundwater and surface water flows? Crop type, climate, and management practices influence water use (Ferchaud et al. 2015; Moore et al. 2015). Some energy crops (e.g., eucalyptus) use more water than others (e.g., switchgrass); deep-rooted perennial grasses and short-rotation woody crops grow well without irrigation (Gerbens-Leenes, Hoekstra, and van der Meer 2009; Wu and Ha 2017). However, studies show similar water use by maize and perennial systems in the Midwest (Hamilton et al. 2015; Abraha et al. 2015). A review of water use efficiencies suggests that the evapotranspiration rate of energy crops would have little negative impact on water balances in temperate humid areas (Robertson et al. 2017).

Concerns about irrigation (Stenzel et al. 2021) are important but not pertinent to BT23 model outputs because energy crops are not irrigated, a sustainability constraint in POLYSYS. Groundwater consumption for irrigation in this study could decrease largely because energy crops, which would replace some irrigated crops, are assumed not to be irrigated, as in BT16 (Wu and Ha 2017). The irrigation constraint was not relaxed in model scenarios, so we do not know how potential biomass supply or prices might be affected by irrigation. Some regions, such as some watersheds in the Ogallala Aquifer (Irmak et al. 2010), restrict the amount of water available for irrigation, and cooperative, dynamic management of this common water resource can lead to low to no groundwater depletion (Steiner et al. 2021).

Water requirements for processing biomass, which are not considered in POLYSYS modeling, may influence local market demand for biomass in a region. Some regions may have high biomass potential but possibly insufficient water for a biorefinery (e.g., the Great Plains). New biorefineries could diminish limited surface water and groundwater resources, especially in the Arkansas-White-Red River basin in the Great Plains, and also in the Republican River basin in the High Plains, the California Central Valley, and the Columbia-Snake River basin in Washington (Yang, Piao, and Cai 2022). In contrast, watersheds in the Midwest, the Mississippi Delta, Appalachia, and the Northeast have abundant water and potential biomass feedstock for bioenergy and bioproducts. Existing water supply infrastructure might need to be expanded to meet processing needs (Yang, Piao, and Cai 2022).

In water-limited regions, good management practices for water conservation need to consider competing demands for water resources and associated restrictions (Berndes 2002). For example, farmers in nearby counties that lack access to Ogallala groundwater employ management practices that are less water intensive and more drought resistant (Hornbeck and Keskin 2014). Wastewater or processing water could be used in some water-competitive or arid locations (Zema et al. 2012). Good water use management practices can include irrigation scheduling (if irrigation is used), as well as crop residue management and conservation tillage (to conserve soil moisture) (Texas Water Development Board 2005), which are important for maintaining soil carbon and promoting water quality as well. Good practices on water-stressed sites can include selection for drought-tolerant genotypes (Zalesny et al. 2019).

In flood-prone agricultural areas, deep-rooted perennial energy crops, including grasses and trees, can be an adaptation strategy (Jager et al. 2020; Langholtz et al. 2014). In addition to droughts, floods will likely increase in frequency in the future climate, and perennial crops are superior to annuals for controlling erosion during flood events.

6.3.3.4 Water Quality

Water quality can represent a benefit or a risk of producing and harvesting biomass, depending on the crop, location, and previous land cover and land management. Fertilizer requirements and related nutrient runoff tend to be lower for perennials like switchgrass than for annuals like corn. Similarly, perennial energy crops do not require as much herbicide or insecticide as annual crops (e.g., *Salix* spp. in Nordberg, Cederberg, and Berndes [2014]), and pesticide runoff from perennials is lower than for annuals. In contrast, transitions of grassland to energy crops would likely increase fertilizer use and could increase the use of herbicides, which are applied during establishment, potentially decreasing water quality in streams or groundwater. Trade-offs among water quality variables (nitrate, total suspended solids, and total phosphorus) were simulated in BT16, with short-rotation woody crops, for example, offering water quality benefits (Jager, Wu, et al. 2017).

Modeling of agricultural biomass resources in this report does not include constraints for protecting water quality, other than the residue retention targets and use of cover crops. For example, in POLYSYS we do not exclude highly fertilized corn from riparian zones that exceed nutrient-related federal water quality criteria.

Good management practices would improve environmental effects by reducing the quantity of nutrients and sediments moving to streams. In biomass field and modeling studies, riparian buffers, cover crops, and switchgrass planting decreased nutrient and sediment loadings from annual cropland (Ha and Wu 2017; Brandes et al. 2018; Jager et al. 2023). These benefits, along with those of cover crops, slow-release nitrogen fertilizer, and tile-drain control, were also demonstrated in BT16 (Jager, Wu, et al. 2017). Minimizing the quantity of fertilizer is clearly a best practice. Harvest cutting height and timing can be optimized for water quality and to retain nutrients on-site (Ventura et al. 2012). For short-rotation woody crops, coppicing is typically done at the end of the growing season to retain nutrients (Ventura et al. 2012).

6.3.3.5 Air Quality

Air pollutant emissions from biomass occur at stages from field preparation through harvest, including chemical application and on-farm (or on-forest) transportation, along with transportation and preprocessing prior to the biorefinery or other end use. The full implications of the production and use of biomass will vary depending on many factors, including counterfactual assumptions and how the substitution effects are considered in terms of decreased fossil-related emissions. Inventories of seven non-GHG regulated air pollutants were estimated for BT16, not including upstream air emissions (e.g., from fertilizer production) (Warner et al. 2017). In BT16, about a quarter of U.S. counties growing the potential biomass were estimated to emit direct and precursor criteria pollutant mass emissions equivalent to 1% to 10% of the current National Emissions Inventory (Warner et al. 2017). The National Emissions Inventory is a triennial estimate of air emissions of criteria pollutants, their precursors, and hazardous air pollutants from emissions sources.

Emissions resulting from increased biomass feedstock production could pose challenges for local compliance with air quality regulations in some areas (Warner et al. 2017). Thus, Clean Air Act nonattainment areas—i.e., those with worse air quality than National Ambient Air Quality Standards—may affect if and how energy crops could be grown or harvested. In addition, an industrial facility converting biomass to fuel or other products may be collocated near biomass production and would create more air pollution (Lee et al. 2021). Current sustainability constraints in POLYSYS do not address air quality; if implemented, such model constraints could modify potential biomass quantities estimated in this report. However, locations of nonattainment areas can change as standards change and as industrial facilities are built and closed. So, whereas nonattainment areas could be excluded from the POLYSYS land base, they may be more dynamic than wilderness areas, wetlands, and other excluded areas.

Agricultural activities contribute to air quality issues in some regions of the United States, and air quality conservation measures, developed by the USDA Natural Resources Conservation Service and EPA, minimize wind erosion and machinery particulate matter generation (USDA NRCS 2012) and could be applied to biomass production. These include methods to maintain soil surface cover (e.g., residue and tillage management, mulching, cover crops); minimize in-field vehicle passes while tilling, planting, mowing, fertilizing, etc.; modify timing of operations; manage unpaved roadways; provide wind barriers; modify equipment; and manage fire and smoke. Additional good practices for farm machinery have been published, such as restrictions on idling time of farm machinery (Pennsylvania Department of Environmental Protection 2013).

Species and site selection may be important predictors of air quality in actual and potential biomass fields that represent good practices. In general, emissions for cellulosic feedstocks are lower than for corn grain (Warner et al. 2017). For example, isoprene, an ozone precursor, was not detected above a *Miscanthus* canopy (Copeland, Cape, and Heal 2012). Isoprene emissions at the scale of current poplar plantations in Europe do not significantly affect ground-level ozone concentration (Zenone et al. 2016). However, ozone was projected to increase under some conditions where the giant cane *Arundo donax* and short-rotation coppice willow, *Salix* spp., could be cultivated. (Porter et al. 2012).

Good management practices for reducing air emissions (per mass of biomass) include higher yields, lower tillage, and lower fertilizer and chemical inputs. Getting lightweight, bulky residues and grasses to a depot or biorefinery can take more truck trips than conventional crops. Using biomass more locally or using more fuel-efficient long-distance transportation methods (e.g., rail, densified biomass) could potentially decrease emissions from truck transport (Warner et al. 2017).

6.3.3.6 Biodiversity

How does biomass crop production affect the diversity of plant and animal species? The answer depends on whether and where land cover and management would be modified, as well as what land management practices are replaced. In this study, the structure of the POLYSYS model restricted the U.S. agricultural land base from changing. This study does not address the potential for impacts on biodiversity due to any biomass production-induced LUC in other nations.

Transitions to cropland from other land cover types such as grassland can reduce diversity of flora through fertilization (Werling et al. 2014) or diversity of fauna by altering landscape structure (Fletcher et al. 2011; Lark 2023). Changes from perennial cover (e.g., grasslands) to annual crops have negatively impacted biodiversity (LeDuc et al. 2022). Furthermore, the extent of fragmentation and the adjacency of cropland to valued animal species habitat are important factors determining biodiversity (Lark 2023). Crop management schedules may affect different species differently and can be designed to favor specific species of concern (Jager and Kreig 2018).

Growing energy crops on arable cropland can increase the abundance and diversity of birds and arthropods and microbial biomass and plant species richness (Werling et al. 2014; Donnison et al. 2021; Helms et al. 2020). Greater benefits were observed when land transitioned from arable land to short-rotation woody crops (e.g., poplar and willow), compared to grasses (*Miscanthus*, switchgrass, and prairie grass) (Donnison et al. 2021). The benefits may be dependent on landscape heterogeneity. Grassland birds respond negatively to corn and soy planted in a North Dakota grassland region (van der Burg, Otto, and MacDonald 2023). Simulations of birds in BT16 showed varied changes in occupancy or richness depending on feedstock, climate, land use, and land management (Jager, Wang, et al. 2017). As in many simulations, high uncertainties were associated with the lack of empirical data for many species and regions. Effects of biomass production and harvesting on mammals is a research gap (Donnison et al. 2021).

Would conserving land to protect species limit the quantity of biomass potentially available? This study employed a model constraint in which many high-biodiversity lands (wetlands, wilderness areas, and legally protected areas) were excluded from production. Regulations keep biomass from being grown on protected lands, many of which are state- or federally managed.

The Conservation Reserve Enhancement Program and several state and local programs provide incentives to employ specific management practices in productive agricultural systems to "enhance critical threatened and endangered plant and animal species survival" and restore wildlife habitats (USDA FSA 2023). The Environmental Quality Incentives Program helps producers manage habitat for targeted bird species through selective use of crop planting and harvest timing (USDA NRCS 2023a). There are also state- and local-level programs to promote biodiversity conservation on agricultural lands where biomass is produced and harvested. Avoiding cultivation of nonnative or invasive energy crops on land with conservation value would be important (Robertson et al. 2017). Integrating prairie strips (i.e., native perennial vegetation) with row crops can improve abundance and diversity of birds, insect pollinators (Schulte et al. 2017), and some arthropods (Kemmerling et al. 2022).

6.3.4 Good Management Practices in Forestry

Good management practices are common in forestry, and their implementation would maintain or increase sustainability of potential forest biomass. Relevant forestry management activities relate to timber and biomass harvesting, site preparation, stream crossings, riparian management, road construction, and fire management (Shepard 2006; Southern Group of State Foresters 2018). BMPs can be mandatory in some states (Ice et al. 2004) and voluntary in others (Ice and Stuart 2001; Kilgore and Blinn 2004; Shepard 2006). Studies of compliance with BMPs are more common in forestry than in agriculture (Wang and Goff 2008; Ice, Schilling, and Vowell 2010), including for biomass harvesting (Barrett et al. 2016b). We describe good management practices for forest biomass harvesting below.

Several sustainability categories are not addressed below. It is important to note that harvesting biomass from forests has no impact on food security. Because Sun et al. (2017) estimated little change in water yields from thinning of forests for biomass in BT16, we do not review water availability. However, it is notable that when fuel treatments for wildfire risk reduction are undertaken in the West, water availability in streams or for vegetation may increase (Bart et al. 2020). Air quality effects and best practices are not addressed. Fuel use was the major source of ammonia and nitrogen oxides for logging residues and whole-tree biomass in BT16 (Warner et al. 2017). Sources of particulate emissions are fuel combustion and fugitive dust emissions.

Clearly, reducing fuel use would be a good practice for promoting air quality. GHG emissions from forestry are reviewed in BT16 (Canter et al. 2017). Life cycle emissions from production of forest biomass and especially residues are generally lower than for agricultural crops because of the lower quantities of diesel fuel used for site preparation and sparing use of fertilizer.

6.3.4.1 Water Quality

Water quality effects of harvesting forest biomass were roughly estimated in BT16 based on an empirical model. For example, sediment load for harvesting biomass from plantations was estimated to be less than 9 Mg/ha over 4.4 years (Rau et al. 2017), a rate much lower than that associated with agriculture, especially with BMPs (Hill 1991). Potential forest biomass estimates in this report do not reflect any constraints intended to protect water quality, though residue retention constraints, which minimize ground disturbance, are useful for that purpose.

The driver for development of most forestry BMPs is the Clean Water Act; thus, most federal BMPs were established to protect water quality by controlling nonpoint source pollution. State and nongovernment publications also recommend management practices to protect water quality. Most national forests and grasslands monitor implementation of BMPs.

Blinn and Kilgore (2001) reviewed state guidelines for managing and protecting riparian resources in forests. Most riparian guidelines include three components: width of riparian management zone, minimum quantity of trees remaining following timber harvest, and other management practices (e.g., management of forbs and grasses) (Blinn and Kilgore 2001), all of which can be implemented in biomass harvest zones (Shepard 2006). State guidelines vary, and some depend on the local or regional context (Blinn and Kilgore 2001).

BMP implementation in forests is generally high, including in a biomass harvesting context (Garren et al. 2022; Hawks et al. 2023). The overall national rate of BMP implementation in forestry was estimated in 2010 to be 89% (Ice, Schilling, and Vowell 2010). In one study, implementation of some BMPs at biomass harvest sites in Virginia was lower than for conventional harvests—these related to adequacy of streamside management zones and design and installation of stream crossings, roads, and skid trails (Barrett et al. 2016b).

6.3.4.2 Biodiversity

Woody biomass harvest, including residue treatment, can affect diversity of overstory and understory communities, potentially increasing them (Premer et al. 2016). Vertebrate biodiversity can be altered through changes in forest structure at the stand (e.g., canopy cover, residues) and landscape scales (e.g., distribution of stand ages following age-dependent harvesting) (Janowiak and Webster 2010; Donner, Wigley, and Miller 2017). Forest types, structural heterogeneity (including snags and down deadwood), and species life history traits would be some of the determinants of species diversity and related metrics. Forest harvest residues provide habitat for small mammals such as voles (Sullivan et al. 2011) and birds (Grodsky et al. 2016), and the abundance and richness of species may be dependent on the quantity of downed woody debris. However, leaving too much forest debris in place can increase the risk of wildfires, an ecosystem disservice.

Biomass can be harvested using management practices that promote forest biodiversity. For example, habitats of rare and valued species that are not already excluded from harvesting (and the biomass simulations in this report) can be avoided. However, many habitat areas suitable for specific species occur at spatial scales smaller than the county-level resolution of ForSEAM, and most do not occur in production timberlands where ForSEAM is applied. Also, the timing and spacing of harvests that maintain biodiversity metrics (e.g., suitable wildlife habitat, number of avian species present) could be applied across broader areas. The timing of harvest can be conducted so that diverse ecosystem structure is maintained across the landscape. In the specific context of salvage logging in disturbed areas, there is a concern that mechanical operations could impede recovery of native species and increase invasion by nonnative species. Stands with the highest bioenergy potential may also have the highest recruitment of new seedlings and saplings that could be damaged (Barrette, Thiffault, and Paré 2013). Species that germinate by fire could be vulnerable to post-fire salvage logging (Knapp and Ritchie 2016). Timing salvage logging to mitigate adverse impacts on biodiversity would be important (Barrette, Thiffault, and Paré 2013).

Five principles have been recommended to guide the development of BMPs for biodiversity in forests: maintaining connectivity, maintaining landscape heterogeneity, maintaining stand structural complexity, maintaining aquatic ecosystem integrity, and aligning human disturbance regimes with natural disturbance regimes (Lindenmayer, Franklin, and Fischer 2006). These principles are compatible with biomass harvesting in forests. Some BMPs designed to protect water quality may have synergistic benefits, such as streamside management zones that protect wildlife habitat (USFS 2012). Evaluating potential environmental costs of biomass harvest from forests requires site-specific analyses, as there can be a wide range of benefits for biodiversity, ecosystem function, and other services in many situations (Premer et al. 2016; Kline and Dale 2020).

Many of these BMPs could be integrated in ForSEAM. However, most BMPs are site-specific and applied only in certain contexts and at subcounty scales. Thus, the practices could be more easily applied if the model were run at finer resolution.

6.4 Concluding Thoughts

Some studies question whether sufficient land (Searchinger et al. 2023) and water (Damerau, Patt, and van Vliet 2016) are available for both food and energy crops. Other studies suggest that what is lacking is good management (Woods et al. 2015; Kline, Msangi, et al. 2017). Overall, there is significant uncertainty regarding the degree to which producers will adopt good management practices and what environmental outcomes may result from the large-scale production of biomass.

Effects of biomass supply on GHG emissions, other environmental metrics, and food depend on context (Efroymson et al. 2013) and are affected by feedstock, management practices, climatic regions, scale of deployment, reference land cover, land management, and energy systems, as well as by spatial and temporal scales (Calvin et al. 2020; DOE 2017). In this report, national biomass resource potential is quantified as a function of price, market maturity, and specified economic and environmental modeling assumptions, including constraints specifically designed to support more sustainable land management.

To test effects of deviating from sustainability constraints in the mature-market medium scenario under a reference price of $70 per ton, we relaxed sustainability constraints in models specified in Chapters 4 and 5. Results suggest:

- The simulated production of small-diameter trees from timberland is bound by economic assumptions, competing market demands, and the $70-per-ton reference price. A higher price could incentivize harvest of additional biomass from timberlands, some potentially from trees greater than 11-inch DBH. Expanding the permitted distance to road restriction also increases available forest residues.
- The simulated production of logging residues from timberland is estimated to increase from about 45% of total logging residues to 60% under the reference offered price of $70 per ton. While there is always a possibility that excessive volumes of residues are removed relative to local site requirements, this analysis suggests that about 40% of logging residues in the forest is stranded due to economic or operational accessibility. Experience suggests that for forest biomass harvesting in at least some regions, machinery designed to meet market quality requirements for low ash and contaminants also supports the sustainability constraints assumed here.
- The simulated production of agricultural residues is bound by the environmental sustainability constraints assumed in this report. Potential supply could more than double if the sustainability constraints in POLYSYS were relaxed. While deviation of future practices (e.g., harvest limits for agricultural residues) from those assumed in this report could lead to risk of overharvesting and unintended environmental consequences, market requirements for clean and sustainable biomass mitigate this risk.
- The simulated production potential of energy crop supply is determined by local profitability, competing market demands, and the $70-per-ton reference price. A higher price could drive more energy crop production. Simulation results showed energy crops established on 7% of cropland and 12% of pastureland. Modifying the model assumptions to expand energy crop production on nonagricultural land was not explored.

"Good" or "best" management practices, if employed, may contribute to sustainability and what has been termed a "social license for a growing bioeconomy" (Titus et al. 2021). Better management of productive landscapes to provide ecosystem services along with biomass products for food, feed, fiber, and fuels via integrated systems is necessary to achieve climate goals (Schulte et al. 2022; DeFries et al. 2022; Robertson et al. 2022; IEA 2021). Monitoring, outreach, incentives for ecosystem services, and regulation are options to reduce risk of undesirable sustainability outcomes. Sustainability constraints used here indicate future needs for certification or regulation to promote or enforce good practices.

Good practices that safeguard sustainability need to fit local conditions; consider practical, place-based opportunities and constraints; and incorporate knowledge of stakeholders who are informed by reliable monitoring and evaluation data to support continual improvement. This national-scale assessment does not capture opportunities that local stakeholders may identify for synergistic practices to increase both biomass potential and ecosystem services. Biomass markets that provide performance-based incentives support safeguards by promoting investment in technologies for more sustainable agricultural practices that reduce supply chain emissions and other detrimental effects.

Furthermore, biomass markets offer advantages related to sustainable development goals that were not discussed in this chapter. These include employment and reduction of wastes (Blair et al. 2021; Kline et al. 2021). The reduction of wildfire risk through fuel treatments (thinning of forests) was only touched on in this chapter and has the potential to increase biomass and benefit society.

Social acceptability is also required before the potential biomass in this report can be realized. Engaging with the public, farmers (Donnison et al. 2021), and foresters (Gruchy et al. 2012) will be important for understanding and achieving social acceptability of biomass production and harvesting. Transportation, processing, and end uses for bioenergy and bioproducts could raise additional concerns about water availability, air pollution, and distributional or environmental justice. In general, agricultural and forestry models and future resource assessments such as this could benefit from social science perspectives and applied research on human decision-making and behavior (Schrieks et al. 2021).

BT16 Volume 2 estimated the environmental impacts of harvesting about 1 billion tons of biomass. This chapter begins to evaluate the role of sustainability constraints used in U.S. national renewable carbon resource assessments in limiting potential biomass and minimizing adverse environmental effects. Monitoring and research are needed to determine whether these sustainability constraints and other good practices are being followed, and which interventions are most effective in supporting sustainable development goals.

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Chapter 07

Emerging Resources: Microalgae, Macroalgae, and Point-Source Carbon Dioxide Waste Streams

Table of Contents

7 Emerging Resources: Microalgae, Macroalgae, and Point-Source Carbon Dioxide Waste Streams

This report and supporting documentation, data, and analysis tools are available online:

- Report landing page: https://www.energy.gov/eere/bioenergy/2023-billion-ton-report-assessment-us-renewable-carbon-resources
- Data portal: https://bioenergykdf.ornl.gov/bt23-data-portal

7.1 Microalgae

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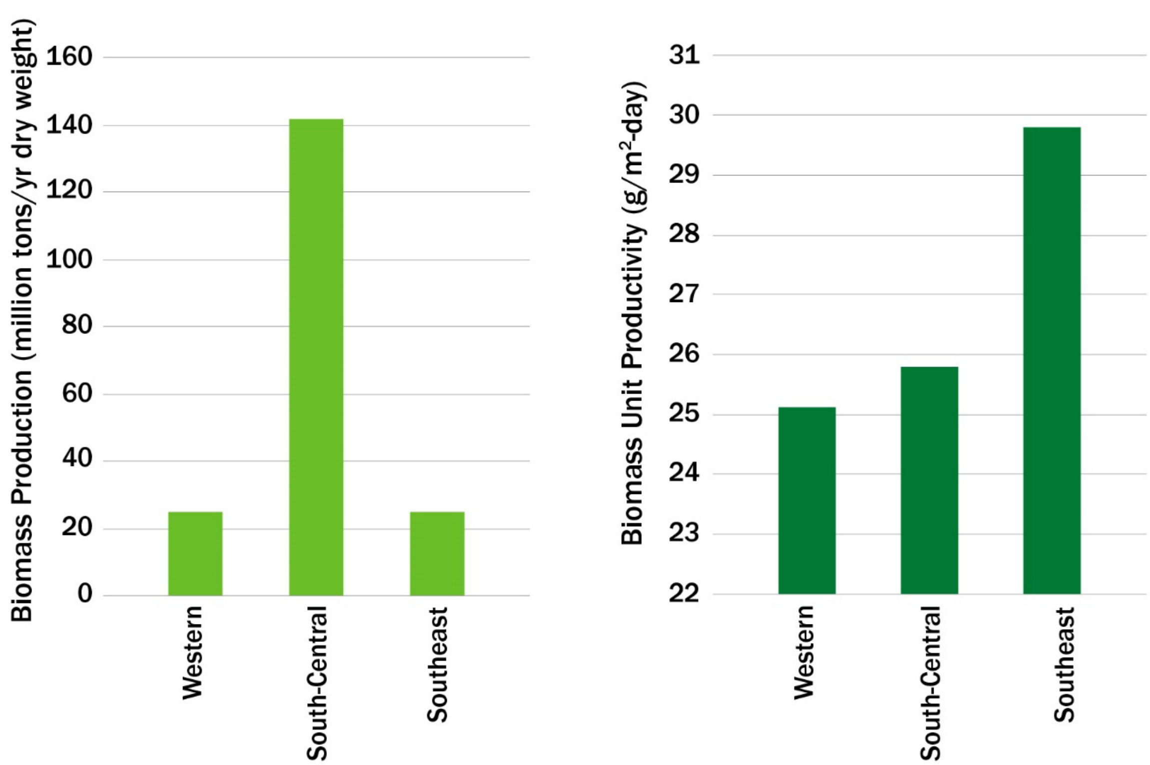

Figure 7.1. Total microalgal biomass and unit biomass productivity per region

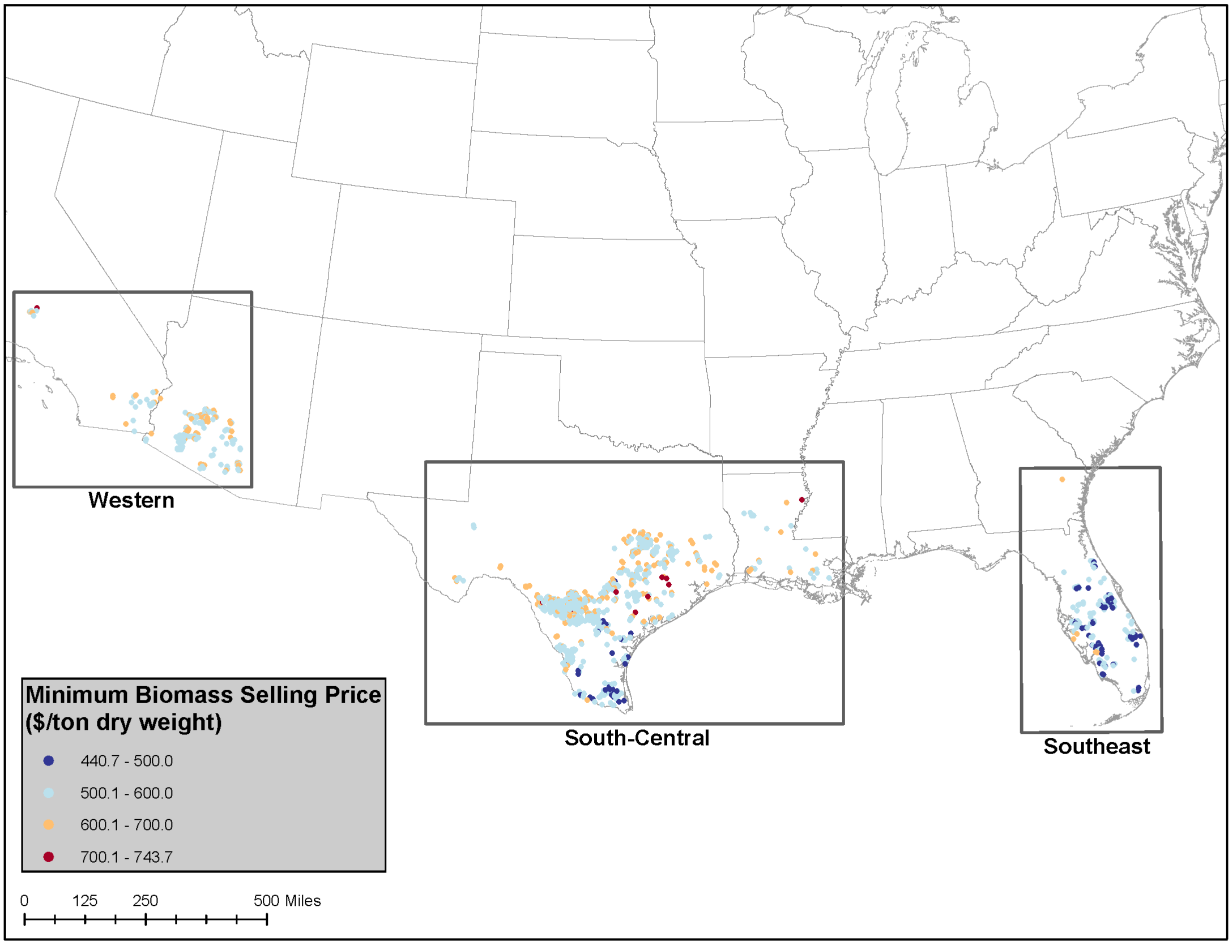

Figure 7.2. Spatial distribution of minimum biomass selling price (MBSP, 2020 dollars) by site and region

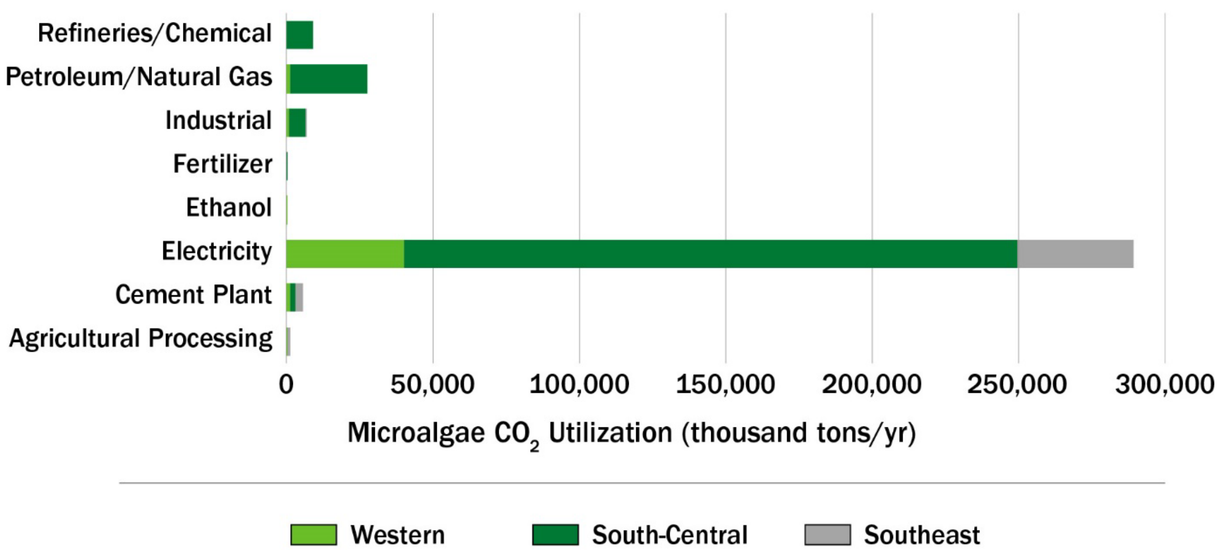

Figure 7.3. Source types and regional totals of waste CO_2 used for microalgae biomass production

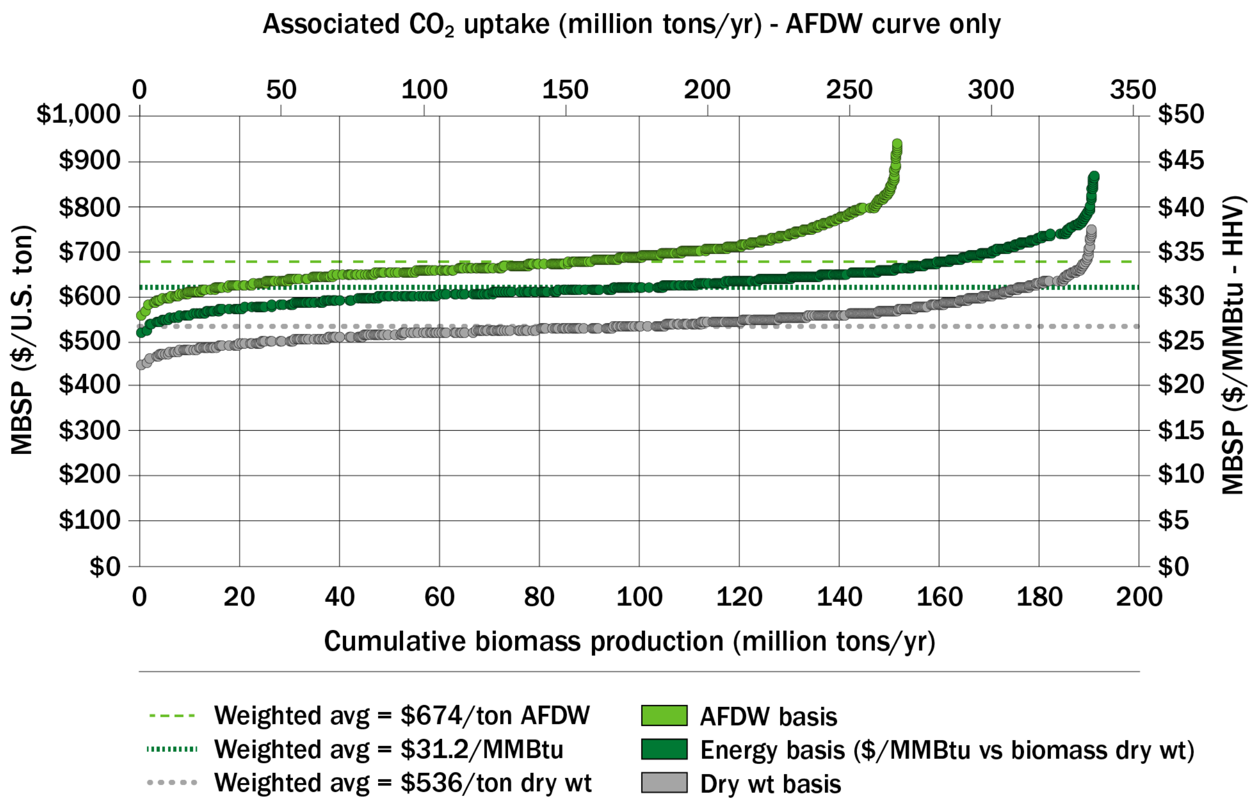

Figure 7.4. Supply curve of microalgae biomass (2020 dollars)

Summary

- Microalgae is a unique biomass resource that does not need to compete for land and water with other biomass feedstocks because it can be cultivated on low-quality unencumbered land using noncompetitive water types including saline and wastewater. It is included as a complementary resource alongside other biomass feedstocks reported in this study, albeit at higher biomass production costs reflective of more capital-intensive farming operations than typical for terrestrial biomass. Higher biomass costs can be offset by the potential to produce value-added coproducts unique to compositional constituents of microalgae.

- Relative to BT16, this chapter reflects the latest analysis from the *2022 Algae Harmonization Update*, which uses the latest parameterized and high-performing saline algal strain, second-generation carbon capture of point-source waste CO_2 and high-pressure pipeline transport resolved to specific point-source types, saline water sourcing up to 40,000 mg/L total dissolved solids for source and makeup water salinity, blowdown water treatment and recycle, and brine disposal handling.

- National-scale algal biomass availability potential was calculated at 152 million tons/yr ash-free dry weight (AFDW) (191 million tons/yr dry weight) at an average biomass productivity of 26.2 g/m^2-day AFDW (about 50 tons/acre/yr dry weight).[1] The algal biomass was cultivated on 3.9 million acres of multi-criteria screened and potentially available land for CONUS and fixed 268 million tons of waste CO_2 based on biomass uptake.

- The algae biomass can be produced at an average MBSP of $674/ton AFDW ($536/ton dry weight) in 2020 dollars,[2] corresponding to a total energy potential of 3.3 quads/yr at an average MBSP of $31.2/MMBtu (higher-heating-value [HHV] basis).

7.1.1 Background

Introduction

Microalgae represents a source of biomass with a significant longer-term potential to meaningfully contribute to renewable fuels, chemical production, bioplastics, feeds, and more at the national scale and without direct competition with terrestrial biomass resources or food and feed agricultural production (Huntley et al. 2015; Zhu et al. 2020; Davis et al. 2018). The benefits of microalgae as a complementary biomass resource are well documented in literature, including (1) the ability to utilize non-arable or otherwise unencumbered land for open-pond or closed-photobioreactor cultivation systems; (2) the ability to grow in generally noncompetitive water including brackish, saline, or other non-freshwater media such as wastewater; (3) significantly higher growth rates and associated land use efficiency (i.e., high-density biomass per unit land area) for biomass production compared to terrestrial biomass sources; (4) unique compositional characteristics of algal biomass that allow for numerous conversion options to various fuels and/or value-added products; and (5) typically high biomass carbon to energy content and associated CO_2 uptake potential (Brennan and Owende 2010; Miara et al. 2014; Huntley et al. 2015; Bleakley and Hayes 2017). Generally speaking, microalgae require a CO_2 uptake ratio of approximately 2 tons CO_2 per ton of produced biomass (Judd et al. 2015); for this analysis, high-rate production of the saline strain algae used under nutrient-replete conditions fixes about 1.76 tons CO_2 for every ton of biomass, translating to 268 million tons/yr of point-source waste CO_2 utilized. This result is based on biomass uptake alone and excludes an additional 72 million tons/yr CO_2 reflecting capture and transport efficiencies and subsequent rerelease of CO_2 through outgassing from the ponds at a 75% CO_2 utilization efficiency targeted in the analysis. Use of sparged, concentrated CO_2 (typically piped in from point-source carbon capture) is generally required to sustain high growth rates required for economic viability, although direct air capture systems are also being researched.

Owing to costs of biomass cultivation currently being roughly an order of magnitude higher than for conventional terrestrial energy crop sources, microalgae is generally viewed as a future available resource in the context of producing economically viable commodity energy products such as renewable diesel and SAF, relative to some other biomass feedstocks discussed in this report (Reed et al. 2023). Microalgae feedstocks have demonstrated flexibility in producing end-

[1] In Section 7.1, "tons" refers to U.S. tons.
[2] In Section 7.1, all costs are in 2020 dollars.

use products, including energy products (i.e., renewable diesel, naphtha, bioethanol, biokerosene and aviation fuels, biobutanol, and biomethanol), with the most straightforward and commercially practical approach to extract and upgrade algal lipids to renewable diesel and SAF through the commercial hydroprocessed esters and fatty acids (HEFA) pathway. In spite of the high cost for microalgae biomass, the high energy content of this feedstock can enable very high fuel yield potential—more than 120 gallons of gasoline equivalent (GGE) per ton of biomass—compared to terrestrial feedstocks, typically on the order of 40–80 GGE/ton (Davis et al. 2014; Jones et al. 2014). Numerous non-energy products can also be made from microalgae, including bioplastics, pigments, nutraceuticals, omega-3 fatty acids, carotenoids, biofertilizer, cooking oils and food products, and feeds for aquaculture, poultry, and livestock (Devi et al. 1981; García, De Vicente, and Galán 2017; Caporgno and Mathys 2018; Molino et al. 2018; Laurens et al. 2017).

Currently, the microalgae industry in the United States is small, at <500 acres based on dedicated algae farms (not considering algae-based remediation at wastewater treatment plants). Under current commercial operations not associated with wastewater remediation, microalgae cultivation is largely focused on very high-value, small-volume food and nutraceutical products such as omega-3 fatty acids, supplements, and carotenoids. Beyond pilot experimental operations, algae is not currently produced for fuel production at commercial scale today. Outside the United States, a larger commercial microalgae industry exists primarily for food and aquaculture products, with a total global production volume of roughly 60,000 tons/yr, concentrated primarily in Asia (Cai et al. 2021; FAO 2021). Beyond the high-value market, microalgae may hold more near-term potential in co-benefit economical fuels production via low-cost "waste" resources such as collection of harmful algal blooms in water bodies and direct utilization in municipal and industrial wastewater treatment for nitrogen, phosphorus, and heavy metal mediation (Wiatrowski et al. 2022), although this is limited to a smaller overall resource potential (likely no more than 28 million tons/yr national-scale biomass potential, compared to dedicated algae farming on the order of 150 million tons/yr, as is the focus of this chapter) (Clippinger and Davis 2021; Wiatrowski et al. 2022).

This chapter summarizes the latest microalgae analysis work conducted by DOE national laboratory partners Pacific Northwest National Laboratory, NREL, and Argonne National Laboratory, focused on a 2022 algae model harmonization analysis spanning resource assessment, techno-economic analysis (TEA), and life cycle analysis, respectively, for future microalgae production performance envisioned via dedicated high-rate, open-pond microalgae farming (Davis et al. 2024). This analysis is conducted across 980 individual locations, which by the nature of a land and resource screening analysis vary in area for an individual algal farm ranging between 1,000 and 39,000 acres (average farm size of 3,940 acres). These individual farms are modeled and then collated into an overall national-scale biomass potential spanning the full collection of identified suitable farm locations. This work builds from a prior harmonization study conducted with the same national laboratory partners in 2017 (published in 2018) that followed a similar framework spanning resource, economic, and sustainability assessment for national-scale algal systems but under a different set of assumptions and less model granularity

(Davis et al. 2018). Relative to BT16's microalgae chapter (Langholtz, Stokes, and Eaton 2016) and the subsequent 2017 harmonization study, the analysis conducted for the 2022 model harmonization update, and summarized here for BT23, reflects a number of key updates and modifications:

- Land suitability analysis was revised using latest available land use/land cover data and protected and sensitive areas, and further excludes areas with high primary productivity to avoid disturbance of natural carbon capture and storage. Relative to BT16, the updated analysis includes 115% of the land area (3.86 million acres) producing 335% of the annual biomass (191 million tons/yr dry weight). The noted increases are largely due to the use of next-generation carbon capture and transport, noted next.
- CO_2 sourcing is handled via modeling second-generation carbon capture and utilization from a variety of nearby waste CO_2 point sources. The modeled high-purity captured CO_2 is transported over high-pressure pipelines, greatly increasing the distance that CO_2 can be economically delivered to potential algae cultivation sites. This increases the total amount of biomass production potential relative to the transport of single-source-type bulk flue gas through large-diameter pipelines to collocated algae farms (as assumed in BT16).
- Variable-scale cultivation farms ranging from a minimum area of 1,000 acres to a maximum of 39,000 acres of production pond area are used to align with the total CO_2 and water resource availability in a localized area (average size of the full collection is 3,940 acres, versus fixed farm scales at 5,000 acres in the 2017 harmonization study or 1,000 acres in BT16).
- Consideration was given only for saline algae cultivation (no freshwater scenario included), utilizing a high-salinity-tolerant strain (approximately 50,000 mg/L) deployed under DOE's Development of Integrated Screening, Cultivar Optimization, and Verification Research (DISCOVR) consortium (Huesemann et al. 2023) to maximize productivity, minimize contamination, and reduce competition for freshwater resources.
- Relative to the 2017 harmonization, further granularity is now included regarding the cost and energy demand for second-generation CO_2 capture based on the specific point-source flue gas concentration, site-specific saline water sourcing, pond water blowdown management, forward osmosis treatment of pond blowdown water including freshwater recycling (utilized for washing dewatered biomass to reduce salt content, as well as recycle to the ponds), and disposal of remaining brine volume via deep-well injection.
- Cultivation and harvesting are performed under more nutrient-replete conditions, yielding biomass with higher protein and lower lipid/carbohydrate content. Although this is generally a less favorable composition for purposes of downstream conversion to fuels, it represents a more readily achievable composition to achieve cultivation productivity targets in the nearer term (slightly exceeding BETO's 25-g/m^2/day productivity target [BETO

2020] at 26.2 g/m^2/day over the full collection of sites) and may allow for coproduction of protein for food and feed markets (outside the scope of this chapter).

7.1.2 Methods Summary

The model and information flows for microalgae biomass in BT23 are depicted in Figure 7.5, focusing on the Biomass Assessment Tool (BAT) resource assessment flows and the algae farm TEA model elements to the point of ready-to-use biomass. A detailed schematic of the TEA model is presented in Figure 7.6.

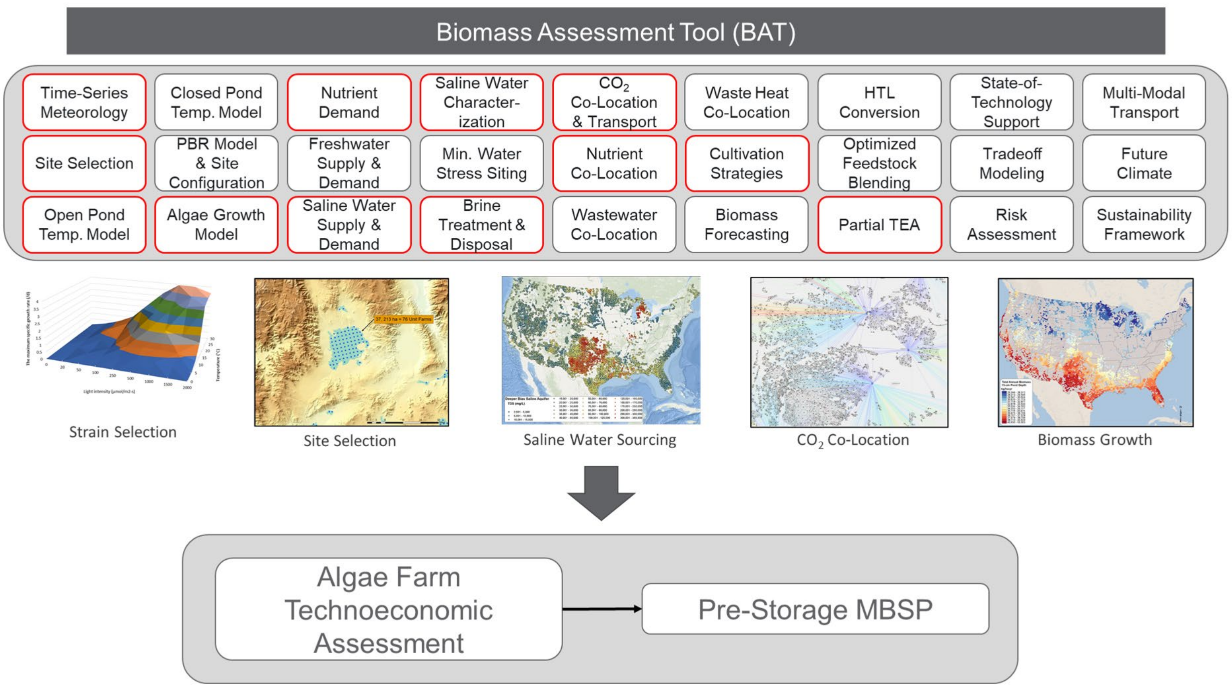

Figure 7.5. Components and workflow for microalgae resource analysis and TEA for BT23. The red highlighted boxes indicate the BAT modules used in this assessment.

Resource Analysis

BAT is a resource assessment and partial techno-economic modeling system comprising numerous modules that combine multiscale spatiotemporal modeling, biophysical modeling, and resource demand and availability using the best-available climate, water, land, and infrastructure data, along with environmental constraints, biomass growth parameterization, and more (Coleman et al. 2014; Venteris et al. 2014; Wigmosta et al. 2017; Sun et al. 2020; Xu et al. 2020; Ou et al. 2021).

A 2022 updated CONUS-wide, multi-criteria land screening model was used to identify potential open-pond algae cultivation sites in the CONUS, with exclusions of steep topography, land use restrictions, existing cultivated agriculture, forestlands, wetland, riparian areas, areas with high net primary productivity (carbon storage), and other environmentally sensitive areas (see the appendix for details).[3] We assume that a 1,000-acre contiguous land area is the minimum to be

[3] Access BT23 appendices at www.energy.gov/eere/2023-billion-ton-report.html.

included as a single farm, and the model does not enforce a maximum area threshold. The resulting contiguous land area for any given farm location is translated to the algae farm TEA model scaled to the same size, resulting in 3,255 individual sites that have variable algae farm areas from 1,000 to nearly 39,000 acres in size (averaging 3,940 acres across the full collection). The variable areas reflect how these systems could be deployed to maximize available economies of scale based on local resource availabilities and integration with downstream conversion facilities (outside the scope of discussion in this chapter).

For this analysis, potential cultivation sites are further constrained by (1) the availability of nearby, non-committed waste point-source CO_2 that can be captured and transported to the site for ≤$82.67 ton (≤$75 tonne); (2) availability of saline groundwater resources at a salinity between 2,000 and 40,000 mg/L at depths <500 m; and (3) a long-term mean daily algal biomass productivity of ≥25 g/m^2-day, resulting in 1,199 remaining sites. These sites are further downselected to 980 sites in the TEA process when limited to a $1,000/ton MBSP threshold. As a means of easily distinguishing sites based on location, the unit farms are organized into three regional groupings spanning the Western, South-Central, and Southeast CONUS regions (Figure 7.7). Note that the regional groupings are not used in the algae farm TEA models, as all biomass costs are calculated on an individual farm basis to best reflect site-specific conditions.

A high-performing saline strain investigated under the DISCOVR project was used in this assessment: *Tetraselmis striata* LANL 1001 (Huesemann et al. 2023). Using the Microalgae Growth Model within the BAT, algae biomass production was simulated for each screened site in the CONUS using 40 years of hourly meteorological data, including air temperature, relative humidity, precipitation, wind speed, atmospheric pressure, and solar radiation components. The growth rate of *Tetraselmis striata* LANL 1001 was modeled as a function of light intensity and temperature under nutrient-replete conditions. Thus, the local meteorology and long-term climatology directly impact the productivity potential. In combination with the land screening, available saline groundwater, and collocated, economically viable CO_2 location and transport, this impacts where the farm sites are located. The resulting growth model output provides a site-specific cumulative monthly time-series, total unit area biomass output (kg/ha) (Huesemann et al. 2013). No additional biomass scaling was performed here as was done in the future-looking microalgae scenarios under BT16 (Langholtz, Stokes, and Eaton 2016). Microalgae are assumed to be harvested when algae reach 0.05 wt % (0.5 g/L) concentration.

Utilizing the BAT CO_2 capture and transport module, a location-based demand and allocation spatial network model, we use the location-specific biomass productivity to establish a daily carbon demand, the 2020 reported annual point-source emissions, and the source type, subsequent CO_2 purity, and specific location. Without site-specific, time-varying operational details from the annual reported CO_2 emissions, we assume an equal daily mass availability of CO_2, and the transport pipeline calculations are established based on distance, available CO_2 mass, and the ability to hold 8 hours of additional CO_2 overnight, a process known as line packing. The model assumes that 90% of the reported emissions are captured using second-generation carbon capture and utilization, and the biomass CO_2 utilization efficiency is established at 75%, closely patterned after Huntley et al. (2015). Individual point-source CO_2 sites are able to effectively supply one to many cultivation sites, until the CO_2 supply is exhausted or exceeds the specified cost threshold, which for this study is defined as $82.67/ton ($75/tonne). Direct air capture systems were not considered here, as the cost and energetics models have not yet been built into the BAT or TEA models. Additional CO_2 modeling parameters can be found in the harmonization report (Davis et al. 2024). The BAT open-pond temperature model was established with saline operating conditions to a threshold salinity of 55,000 mg/L, reflecting the lab testing conditions in which *Tetraselmis striata* LANL 1001 was parameterized. The pond model provides a mass balance for the incoming site-specific groundwater source salinity and mass density/volume for the pond area and managed depth, and considers incoming precipitation, salinity, and temperature-based evaporative losses, as well as blowdown water volume required to maintain pond threshold salinity. The blowdown water volume is processed through a forward osmosis system, where at about 55,000 mg/L total dissolved solids, 82% of the blowdown volume is recovered as freshwater, and the remaining 12% volume is disposed of through deep-well injection. The recovered freshwater is directed first for use downstream to wash the dewatered solids to reduce salt concentrations to 15,000 mg/L, and with remaining freshwater is recycled to the ponds when available. The blowdown water volume removed from the pond is replaced with makeup water, sourced first from the forward osmosis processed water, if available, then from the saline groundwater well as required.

Algae Farm TEA

The outputs from the BAT model are run through NREL's algae farm TEA model, largely based on the set of operations and assumptions in NREL's 2016 algae farm design report (Davis et al. 2016) and the more recent 2017 harmonization report (Davis et al. 2018). Key updates were made to the published model framework for this study, including (1) incorporation of wet anaerobic storage to mitigate seasonal variabilities based on recent performance data from Idaho National Laboratory (Klein and Davis 2022) (biomass costs are tracked both before and after seasonal storage); (2) addition of a basket strainer and wash water step during dewatering to reduce exogenous ash and salt content, respectively, for downstream conversion equipment protection (using freshwater recovered from forward osmosis); and (3) inclusion of forward osmosis and updated injection well costs/power demands from the BAT models for handling saline blowdown water. In order to avoid any external freshwater usage in the algae farm/dewatering operations, if more freshwater is required for the washing step than is available from the forward osmosis unit, additional saline water is routed to the forward osmosis unit until necessary freshwater volumes are achieved (increasing costs for forward osmosis and saline injection disposal, but at the avoidance of externally sourced freshwater as an important priority for saline cultivation).

All capital and operational costing are updated to 2020 dollars, and capital expenses are designed around maximum seasonal productivities, while variable operational expenses are based on monthly resource use and throughputs. Site development and operational costs, including pond construction and circulation systems, inoculation train, groundwater source well(s), forward osmosis system, brine injection wells, CO_2 storage and delivery (following off-site capture and pipeline transport to the farm gate), nutrients, dewatering systems, and other site development costs, are included as depicted in Figure 7.6. Additional TEA modeling details can be found in the harmonization report (Davis et al. 2024) and Davis et al. (2016, 2018).

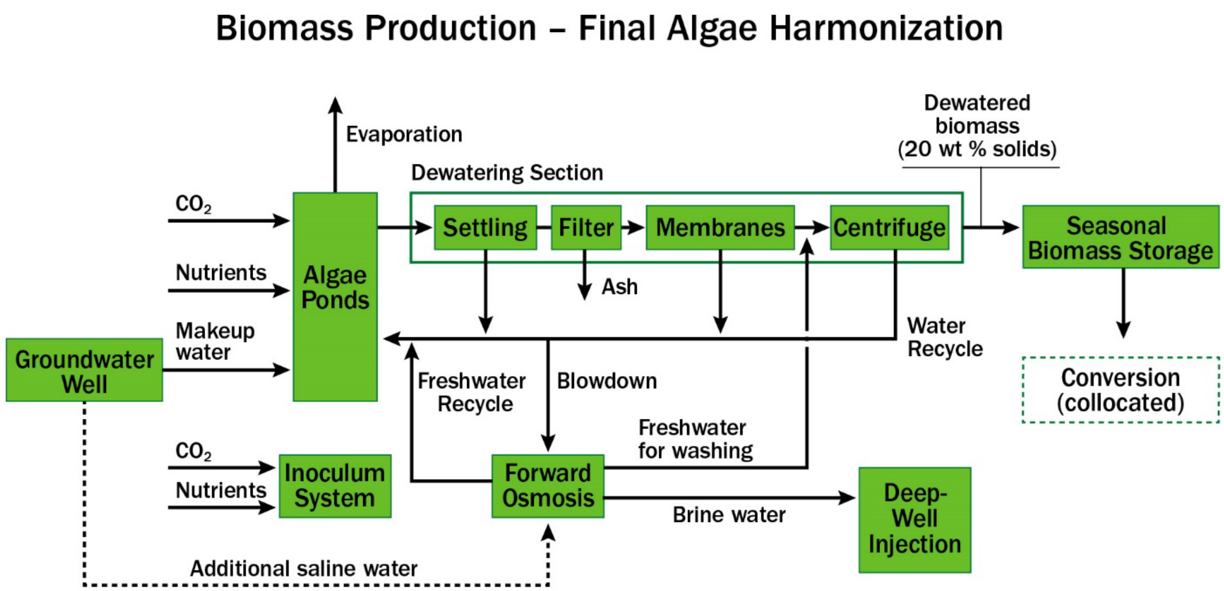

Figure 7.6. Site-level algae farm techno-economic framework used in this study, from cultivation to harvesting and seasonal biomass storage

7.1.3 Results

The location siting analysis and associated TEA analysis cutoffs ultimately identified 980 independent and contiguous potential algae cultivation sites covering a total pond area of 3,858,226 acres (1,561,368 ha). The sites dominate across five Southern-tier states, including Texas (2.85 million acres), Florida (433,000 acres), Arizona (452,000 acres), Louisiana (51,000 acres), and California (70,000 acres). The 40-year long-term daily productivity mean across all sites is 26.2 g/m^2-day (49.5 tons/acre-yr dry weight), achieving the 2030 BETO goal of 25 g/m^2-day, and summing to a total of 151.9 million tons/yr of AFDW biomass (190.9 million tons/yr dry weight) (Figure 7.9). Biomass productivities and associated costs are reported by region (Figure 7.7, Figure 7.8, and Table 7.2) and by individual farm (Figure 7.10 and Figure 7.11), with accompanying data including county-level and state-level designations so data can be evaluated in multiple ways.

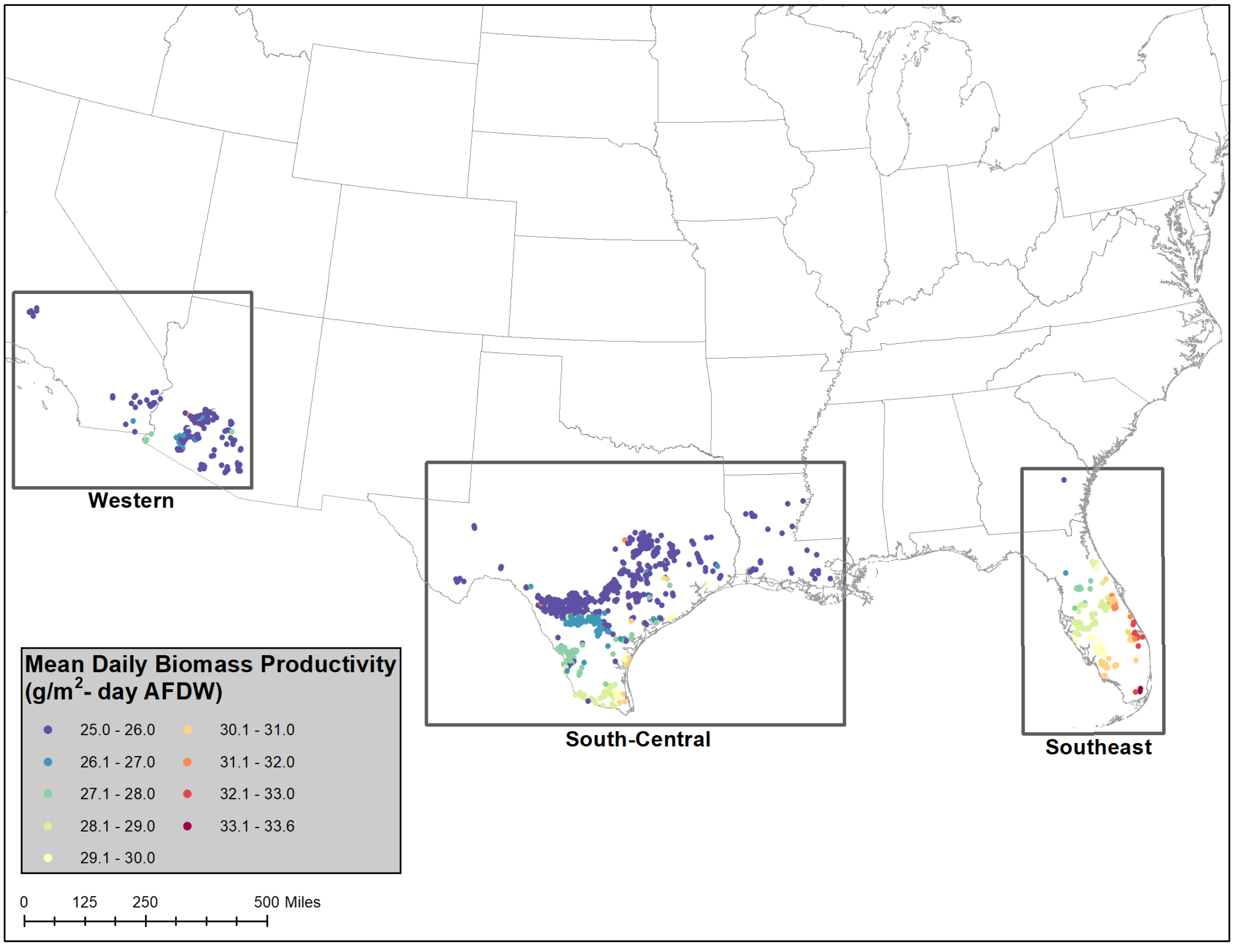

Figure 7.7. Targeted long-term mean daily biomass productivity (g/m^2-day AFDW) for potential microalgae cultivation sites. The collection of individual sites is organized into regional groupings for reporting purposes.

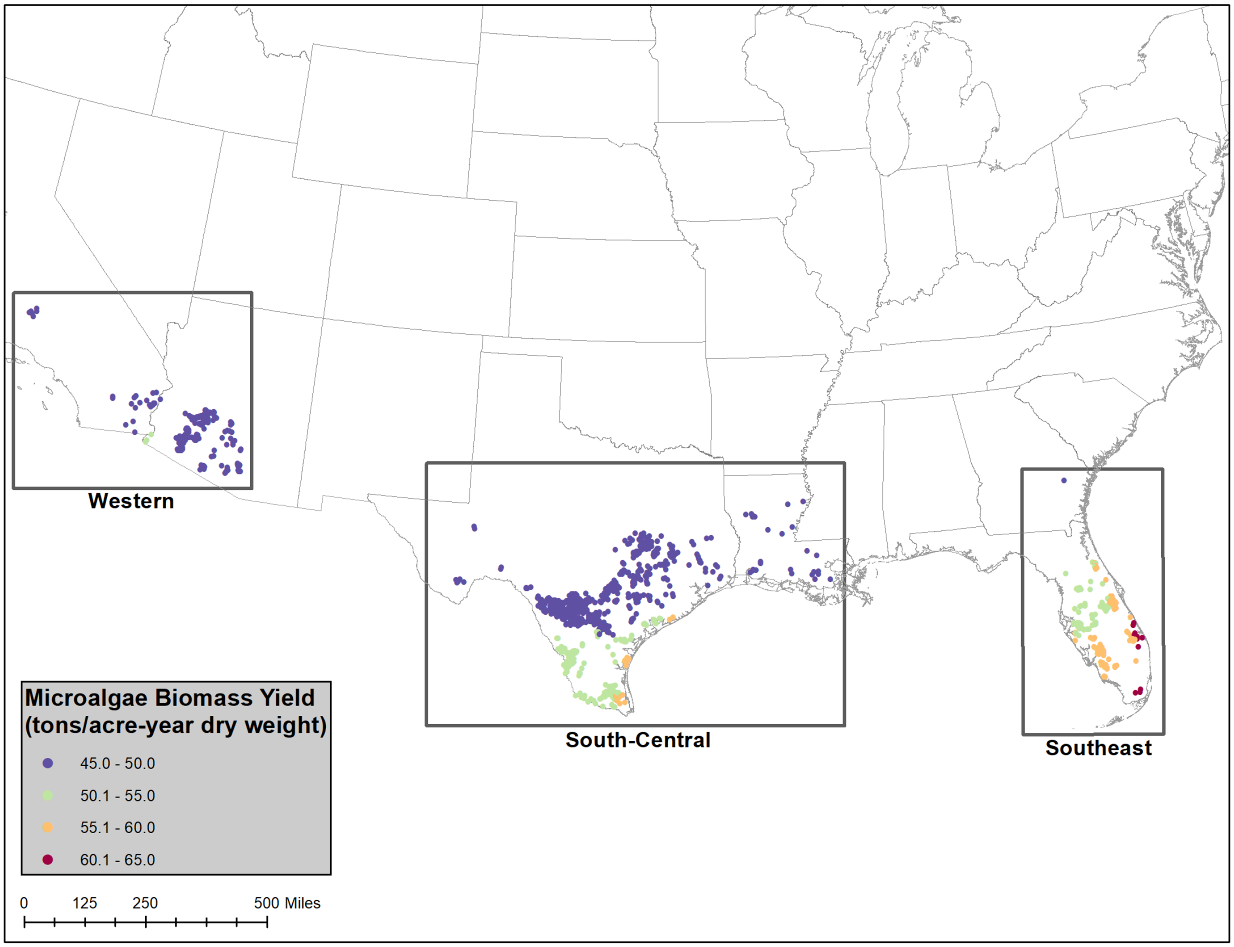

Figure 7.8. Site-scale annual microalgae biomass yield (tons/acre-year dry weight)

An important consideration in high-productivity algae cultivation is the access and utilization of CO_2, which is key for not only increasing productivity, but also meeting reduced GHG and carbon intensity targets. We assume here that 90% of 2020 reported annual CO_2 emissions (not CO_2e) are captured at the point source and transported to one or many cultivation sites, depending on the waste resource availability, total algae farm demand, and spatial proximity to economically transport CO_2 over high-pressure pipeline (Song et al. 2018). Further, we assume a 75% CO_2 uptake efficiency by the algae, with the remaining 25% delivered into the ponds, ultimately being outgassed or otherwise not used (Huntley et al. 2015). In total across all site groups, 170 point-source waste CO_2 sites are used to capture and transport 340 million tons/yr of CO_2 for algae cultivation (11.02% of CONUS total waste CO_2). On average, across all 980 potential algae cultivation sites, CO_2 is transported 23.32 miles by high-pressure pipeline. The collocated point-source waste CO_2 locations and source types are varied regionally. Table 7.1 provides a high-level assessment of CO_2 utilized for algae cultivation with respect to regional availability across the CONUS. While the algae cultivation sites are limited to Southern-tier states (Figure 7.7), to better gain a CONUS-perspective, the algae "Western" region is expanded to the 11 Western states (including and west of Montana, Wyoming, Colorado, and New

Mexico); the algae "South-Central" is expanded to "Central" and includes 13 states east of the defined Western states and those west of the Mississippi River from Wisconsin to Louisiana; and "Southeast" is expanded to "East," including the remaining 25 states east of the Mississippi River. As modeled here, approximately 15.0% of the U.S. national waste CO_2 can be beneficially utilized by microalgae processes, and approximately 9.6% of the national waste CO_2 total is fixed in the microalgae biomass. While the scope of this work was limited to current non-biogenic point-source CO_2 availabilities today, as industrial decarbonization progresses, this availability may become more limited moving into the future. Under such a scenario, to maintain (or increase) the total algal biomass potential, alternative sources of CO_2 would need to be brought in. This could include biogenic CO_2 as may be available from other terrestrial biomass processing operations if projections in the billion-ton study are realized, and/or incorporate direct air capture to decouple entirely from point-source reliance.

Table 7.1. Simulation Results for CO_2 Source Types by CONUS Region, Total CO_2 Used for Microalgae (thousand tons/yr), and the Number of Facilities Used

CO_2 Source	West		Central		East	
	Thousand tons CO_2/yr [% of regional]	# sites [% of regional]	Thousand tons CO_2/yr [% of regional]	# sites [% of regional]	Thousand tons CO_2/yr [% of regional]	# sites [% of regional]
Agricultural processing	353.8	8	0	0	401.9	5
	[7.1%]	[10.1%]	[0%]	[0%]	[5.0%]	[4.0%]
Cement plant	3,629.1	4	6,258.3	10	1,081.8	3
	[19.3%]	[9.5%]	[17.5%]	[21.3%]	[2.6%]	3.5%
Electricity generation	39,725.0	33	209,318.5	67	71,826.2	39
	[12.5%]	[11.0%]	[74.1%]	[14.8%]	[6.6%]	[5.8%]
Ethanol production	25.4	1	0	0	0	0
	[6.0%]	[12.5%]	[0%]	[0%]	[0%]	[0%]
Fertilizer production	0	0	7,883.6	3	453.2	3
	[0%]	[0%]	[37.0%]	[15%]	[6.2%]	[17.6%]
Industrial	282.2	8	1,570.1	20	215.1	2
	[3.2%]	[7.1%]	[2.6%]	[6.0%]	[0.2%]	[0.4%]
Petroleum/natural gas processing	5,046.0	20	10,109.0	103	92.4	2
	[13.3%]	[6.4%]	[19.5%]	[15.4%]	[0.6%]	[0.7%]
Refineries/ chemicals	0	0	70,214.8	53	28.8	1
	[0%]	[0%]	[33.1%]	[19.1%]	[0.1%]	[0.6%]

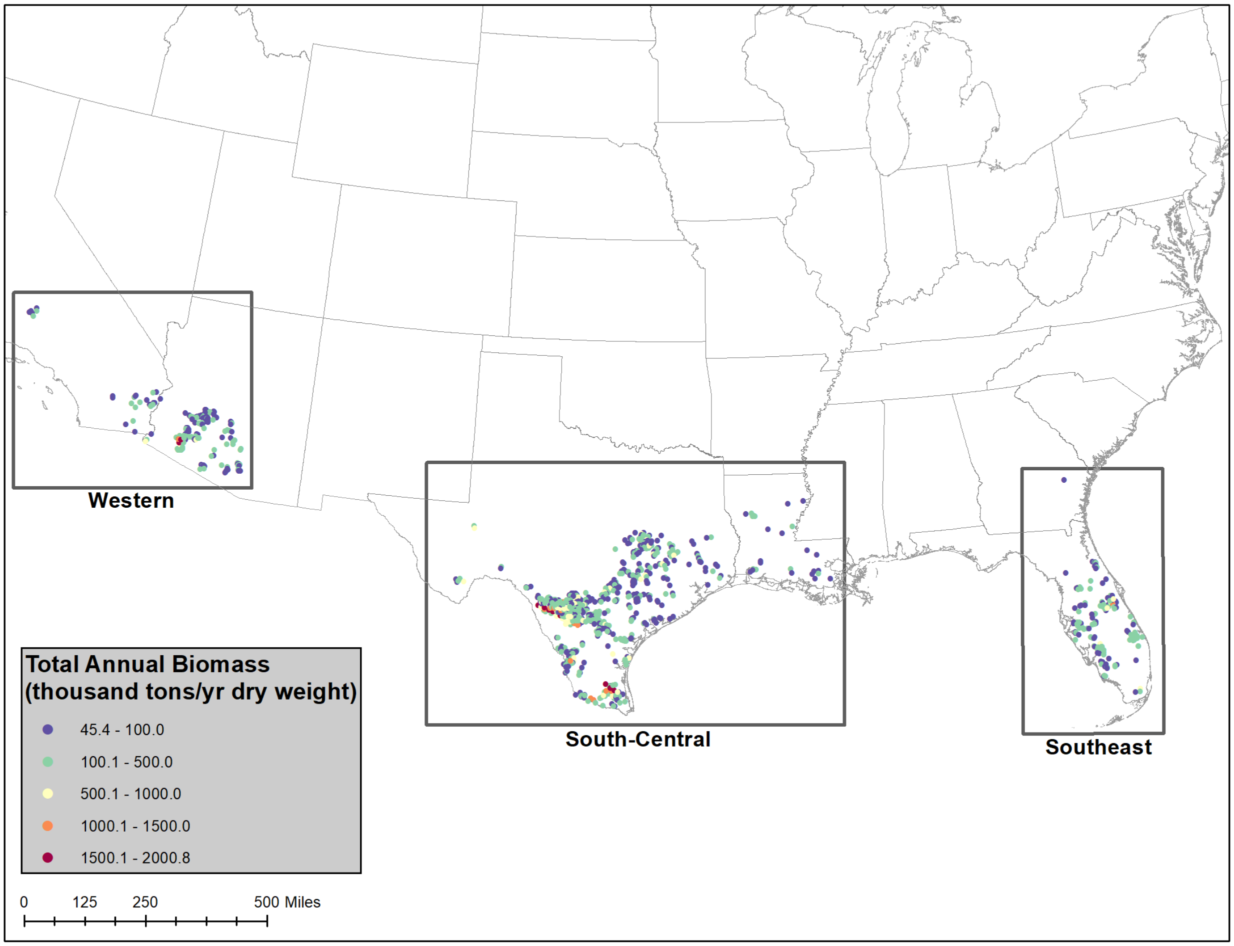

Figure 7.9. Total annual algae biomass (thousand tons/year dry weight) as modeled across identified farm sites

As documented in further detail in the 2022 microalgae model harmonization report (Davis et al. 2024), selected outputs from the BAT models were run through the algae farm TEA models, namely site-specific details for long-term monthly cultivation productivities, captured and delivered CO_2 costs, pond evaporation rates and associated saline groundwater well drilling and pumping power per volume of makeup saline water delivered at each site, forward osmosis system costs and associated power demands per volume of blowdown water processed, and brine injection disposal well development and respective pumping costs per volume of water injected (with water balances calculated in the farm models to achieve 55,000 mg/L or less salt content at harvest, followed by 15,000 mg/L or less salt content following the wash step through final dewatering for downstream delivery to conversion). The TEA models were run for each individual location, and the results presented here reflect individual location modeling granularity.

Figure 7.10 provides a summary of locations screened from the BAT models organized by regional group, overlaid with resultant MBSPs from the algae farm TEA models prior to seasonal storage. The resultant 152 million tons/yr of total algal biomass production potential

(AFDW basis) equates to 191 million tons/yr dry weight at 20% biomass ash content, as attributed to the BETO future target cultivation productivity of 25 g/m^2/day. Consistent with prior findings (Davis et al. 2016, 2018), the overall MBSP trends track closely with cultivation productivities (higher productivities translate to lower MBSPs), though with additional factors also weighing on MBSP results, particularly individual farm scale (larger farms incur economy-of-scale advantages), delivered CO_2 costs, water access, blowdown processing and disposal costs, and the degree of seasonal variability swings between peak versus minimum productivity (higher variability translates to greater seasonal storage needs/costs, as well as more total biomass subject to storage degradation losses). Table 7.2 presents a summary of key parameters organized by region, with biomass cost breakouts shown in the appendix for selected individual farms.

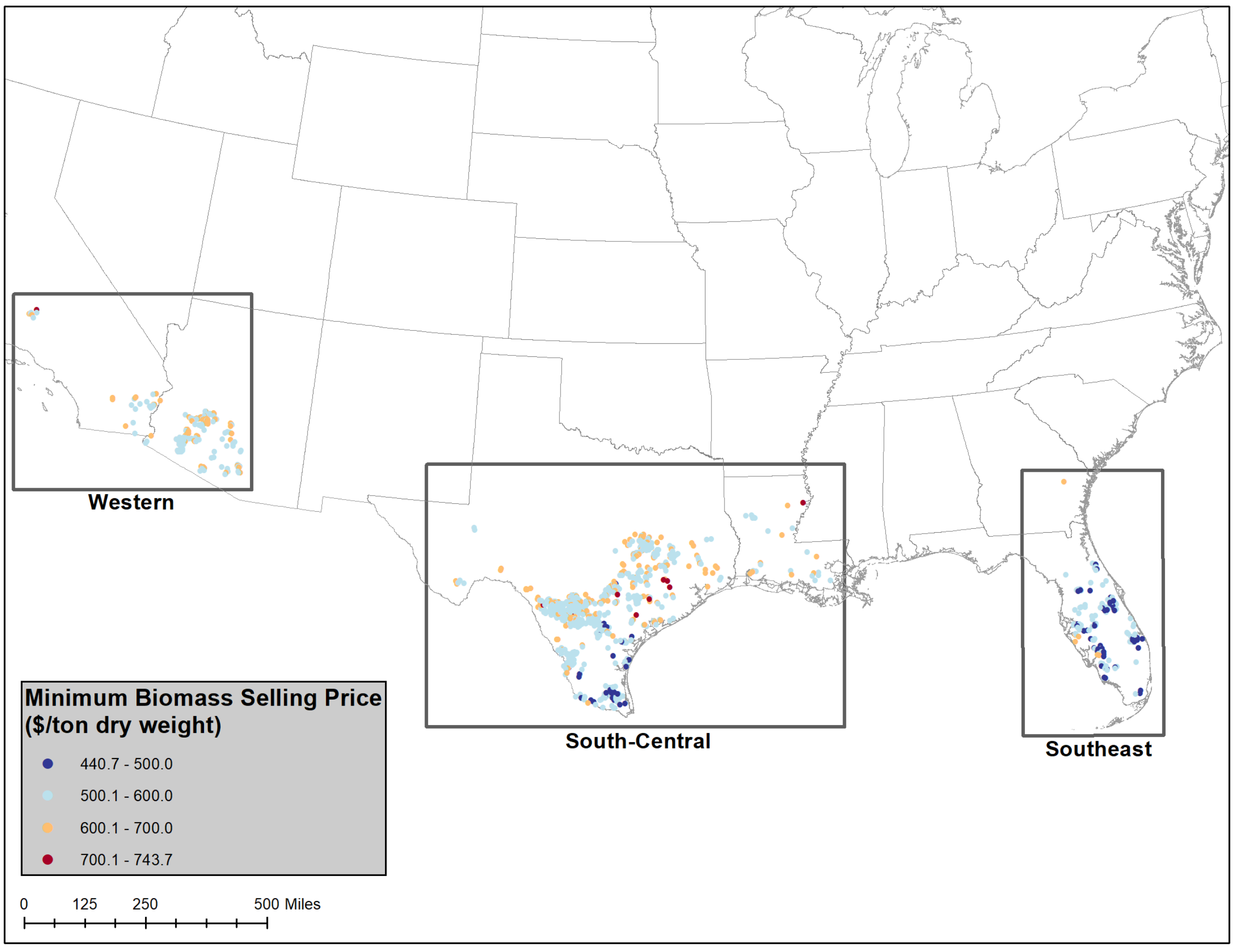

Figure 7.10. Pre-storage MBSP ($/ton dry weight) as organized by regional group

Table 7.2. Key Metrics for Algae Farm Availability and Cultivation Productivity for the Regional Groupings

Region	Number of Individual Sites	Total Cultivation Area (acres)	Total Biomass Output (million tons/year AFDW)	Annual Productivity (g/m^2/day AFDW)	Annual Yield (tons/acre-year dry weight)	Productivity Variability (max vs. min ratio)
Western	168	521,395	19.7	24.9	47.5	6.2
South-Central	675	2,903,983	112.6	25.8	48.7	5.7
Southeast	137	434,091	19.6	29.8	56.6	3.0
Total/avg.	980	3,859,469	151.9	26.2	49.5	5.4

Figure 7.11 presents curves for MBSP versus cumulative algal biomass production, both on an AFDW basis (light green curve), as is more standard in algae TEA, and a dry weight basis (gray curve), as is more comparable to other biomass feedstock types presented in this report, based on individual farm TEA modeling prior to seasonal storage. Additionally, a translation to $/MMBtu biomass energy content versus cumulative dry weight production is provided (dark green curve), recognizing the higher costs for microalgal biomass compared to other terrestrial feedstocks presented in this report, but also the higher inherent energy content, and thus fuel yield potential, than many other feedstocks. The energy content curve is based on an HHV of 20.0 MJ/kg dry weight typical for microalgae across a number of strains (Illman, Scragg, and Shales 2000; Ghayal and Pandya 2013; Shakya et al. 2017; Coimbra, Escapa, and Otero 2019). After first excluding sites in the resource assessment stage that exceed thresholds of $75/tonne delivered CO_2 and 40,000 mg/L makeup water salinity, a small number of additional sites were removed following the algae farm TEA modeling stage after applying a maximum cutoff of $1,000/ton MBSP (AFDW basis). Still, the cost curve is seen to increase more sharply beginning at roughly $800/ton AFDW, primarily reflecting sites with smaller farm scales, lower cultivation productivity, and/or higher makeup water salinity (incurring higher blowdown handling costs).

These results present an overall average pre-storage MBSP of $674/ton AFDW ($536/ton dry weight) commensurate with the cumulative production potential of 152 million tons/yr of AFDW biomass (191 million tons/yr dry weight), equating to a price of $31.2/MMBtu biomass energy content (HHV) on average. After subsequently including seasonal storage to equalize the flows sent to downstream conversion processing (outside the scope of this chapter), MBSPs increase by roughly 4% on average (average MBSP = $701/ton AFDW after seasonal storage). The results presented here translate to 268 million tons/year of CO_2 uptake potential to produce this quantity of biomass.

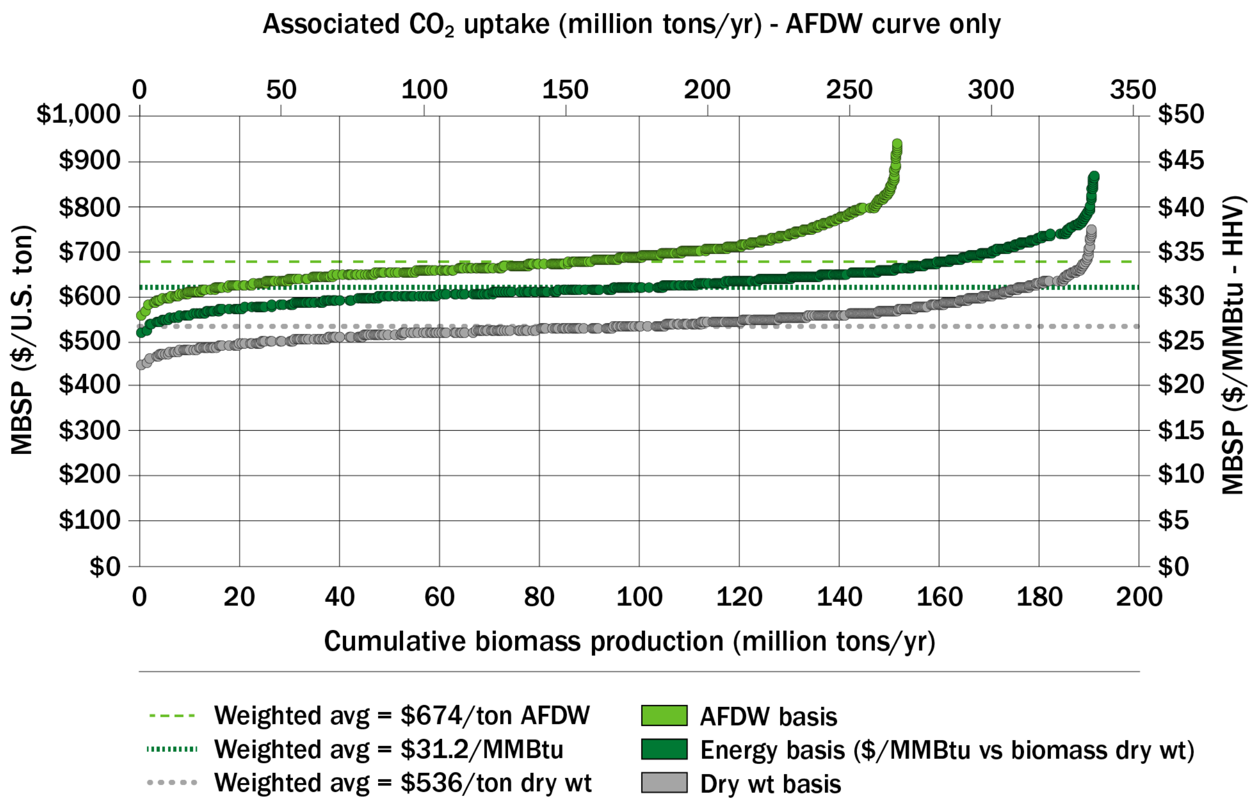

Figure 7.11. Biomass cost versus resource curves for MBSP in dollars per ton AFDW (light green curve), dollars per ton dry weight (gray curve), and dollars per MMBtu HHV energy content (dark green curve; dry weight biomass basis). Top axis for CO_2 uptake potential corresponds to the AFDW curve only.

7.1.4 Summary and Future Research

This update leverages the latest resource and techno-economic analyses for microalgal biomass as documented in the *2022 Algae Harmonization Update* study. As summarized here, that work highlights the potential to produce up to 152 million tons/yr of AFDW algal biomass across the CONUS, equating to 191 million tons/yr dry weight at roughly 20% ash content for high-salinity algal cultivation, attributed to 3.9 million acres of total available cultivation area with access to available saline groundwater water and point-source waste CO_2. This translates to an average biomass yield of 39.4 tons/acre-yr AFDW (49.5 tons/acre-yr dry weight). This material could be produced at an MBSP ranging from roughly $554 to $934 per ton AFDW, with an overall average for the identified farm sites of $674/ton AFDW (corresponding to $536/ton dry weight basis at a price of $31.2/MMBtu total HHV energy content). In turn, this resource volume reflects the ability to uptake 268 million tons/yr (9.6% of national CO_2 total) of waste flue gas captured CO_2 for subsequent upgrading to fuels and products. For context, the amount of CO_2 that can be fixed into microalgae each year is equivalent to the CO_2 output of the nation's 16 largest electricity generating stations.

Future research in this space includes opportunities to expand into lower-cost waste algae resources such as municipal wastewater treatment and collection of harmful algal blooms, as these may represent opportunities for substantially lower-cost algal biomass (albeit at more limited quantities) and thus more readily deployable systems in the near term. Additionally, longer-term opportunities exist to consider direct air capture as a means to supplement or eventually replace dependency on non-biogenic point-source CO_2 availability, as this availability may decrease over time with continued industry decarbonization. Direct air capture could further unlock higher total algal biomass given CO_2 availability, and economically viable capture and transport from the point source to the algal farm, is a key limiting factor in the current study's resource analysis screening criteria. Alternatively, if the billion-ton study's projections are realized for other terrestrial biomass feedstock availability as discussed in this report (subsequently destined for biorefinery conversion and resultant biogenic CO_2 release), more biogenic CO_2 point sources may become available for utilization in algae farming as could further supplement this resource. This presents an opportunity for future consideration.

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7.2 Macroalgae

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Summary

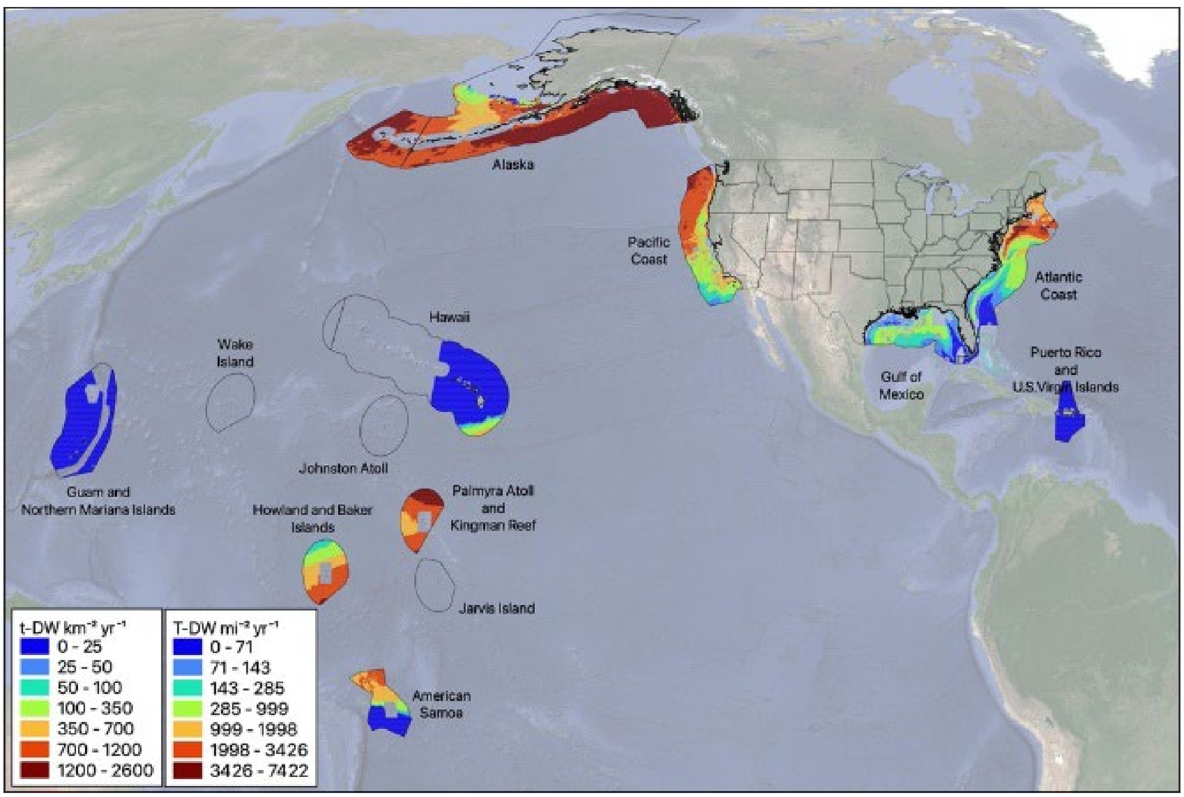

Figure 7.12. U.S. exclusive economic zone (EEZ) with screened-inclusive areas showing annual macroalgae biomass productivity estimates for the representative scenario

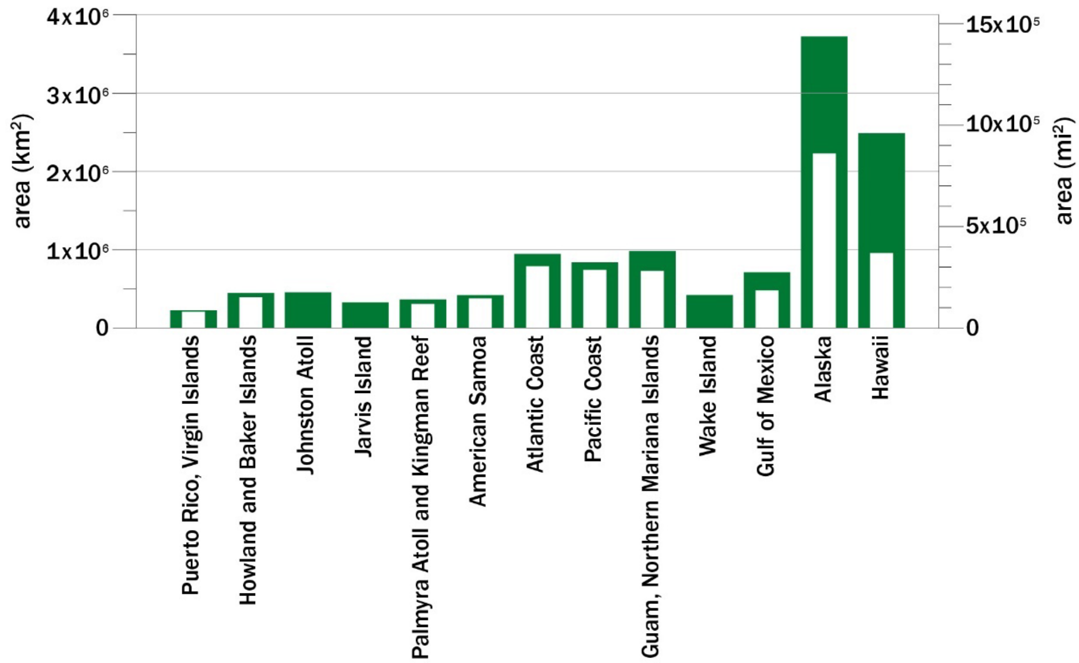

Figure 7.13. Total EEZ area by region (green bars) and remaining screened-inclusive areas (white bars) across the 13 specific regions

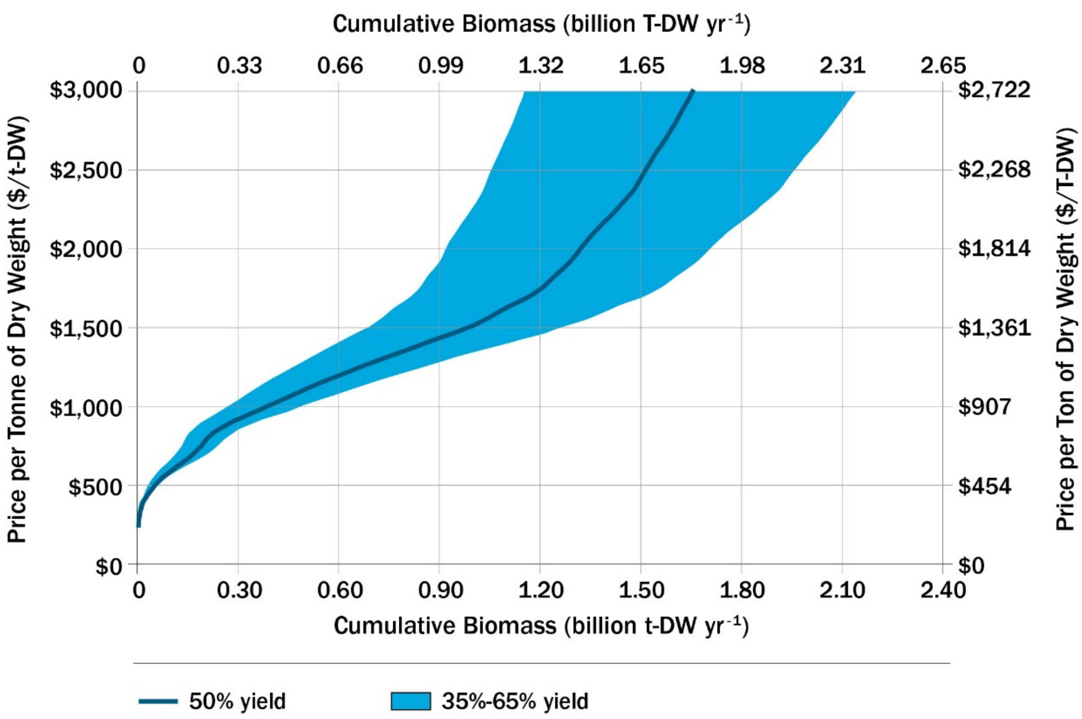

Figure 7.14. Cost-supply curve of the total U.S. EEZ for the representative scenario at 35%, 50%, and 65% area coverage

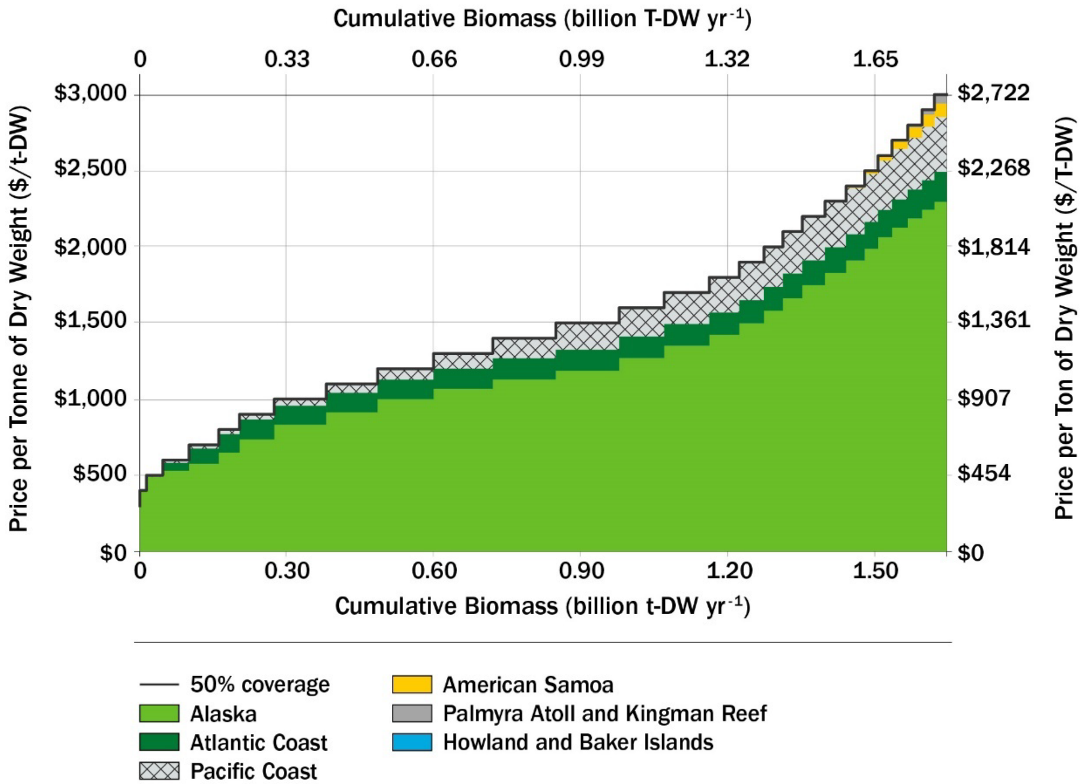

Figure 7.15. Region-specific stepwise cost-supply curve with the representative scenario and 50% area coverage. Note that unlisted regions have costs exceeding $3,000/t-DW.

This study represents the first U.S. full exclusive economic zone (EEZ) analysis for macroalgae biomass potential, inclusive of a marine area screening analysis, macroalgae biomass growth model, and associated TEA with harvest and farm gate biomass delivery.

- Of the total U.S. EEZ, 58.5% (7.1 million km^2, or 2.8 million mi^2) is potentially available for macroalgae cultivation after accounting for existing conflicting uses of marine spatial areas through a multi-criteria screening process.
- The unrestricted high-end annual biomass production over the screened marine areas estimated by the model is 3.3 billon metric tons of dry weight per year (Gt-DW/yr), or 3.6 billion short tons of dry weight per year (BT-DW/yr), which is about 34 times the mass of corn used for U.S. ethanol production and about 8 times the total U.S. corn production in 2022.[4] While this tonnage is approximately 3 times the total of the mature-market medium scenario for non-algal terrestrial sources estimated in this report, the actualizable tonnage is heavily restricted by non-mature technology and high costs.
- Utilizing a cost threshold of ≤$1,000 per metric ton of dry weight (t-DW) and a multi-criteria marine spatial area screening, a total of 293,000 km^2 in the Alaska, Pacific, and Atlantic coastal regions were identified as having the capacity to generate approximately

[4] Section 7.2 uses the following unit abbreviations: t (metric ton), T (U.S. short ton, or 200 lb.), BT (billion short tons), Gt (billion metric tons, or gigatons), and DW (dry weight).

0.38 Gt of macroalgae biomass per year (0.42 BT-DW/yr), with an estimated average farm gate cost of $739/t-DW ($670/T-DW).

7.2.1 Introduction

Macroalgae, commonly known as "seaweed," are diverse and abundant marine algae that play an important role in marine ecosystems. They not only are vital sources of food and habitat for a wide range of marine organisms, but also have significant ecological, economic, and cultural value (Neori et al. 2004). Macroalgae have been used by humans for centuries for food, medicine, and industrial applications. In the food industry, macroalgae are directly consumed; used as a source of vitamins, minerals, and dietary fiber; and used as a natural food colorant and flavor enhancer. For example, brown macroalgae, such as kelp, can contain high levels of dietary fiber, minerals (e.g., calcium, iodine, iron), and vitamins (e.g., vitamins C and K) (Holdt and Kraan 2011). The use of macroalgae (e.g., *Asparagopsis taxiformis*) as a supplement in animal feed is being investigated as a strategy for reducing methane emissions from cows and improving the nutritional quality of milk (Hristov et al. 2015; Vijn et al. 2020; Wasson et al. 2022).

Macroalgae are also used to produce a wide range of chemical products. For example, the polysaccharide alginate, which is derived from brown macroalgae, is widely used in the food, pharmaceutical, and textile industries as a thickener, stabilizer, and emulsifier (Rehm and Moradali 2018). Carrageenan, another polysaccharide derived from red macroalgae, is used as a gelling and thickening agent in food products such as ice cream, yogurt, and processed meats (Garcia-Vaquero et al. 2017). Fucoidan, a sulfated polysaccharide found in brown macroalgae, has been shown to have anti-inflammatory, anti-cancer, and antiviral properties, and is being developed as a nutraceutical and pharmaceutical ingredient (Fitton and Stringer 2019).

Macroalgae have also been identified as a potentially sustainable source of biomass and bioenergy due to their high growth rates, low lignin content, and high lipid and carbohydrate content (Godvin-Sharmila et al. 2021). An additional advantage is that macroalgae can be cultivated in marine environments, making them a potential source of renewable energy without competition for land and water resources. Studies have shown that macroalgae can be converted into bioenergy (biobutanol, bioethanol, biodiesel, biohydrogen, and biomethane) through various methods, including fermentation, hydrothermal liquefaction, anaerobic digestion, transesterification, and pyrolysis (Pourkarimi et al. 2019).

Macroalgae also have the potential to play a role in carbon sequestration and/or utilization (Krause-Jensen and Duarte 2016). As photosynthetic organisms, macroalgae absorb inorganic carbon from the surrounding water during growth. They utilize this source of carbon, along with sunlight and nutrients, to perform photosynthesis and produce biomass. It is important to note that the exact potential of macroalgae to sequester carbon depends heavily on factors such as species, carbon-to-nitrogen ratio, growth rates, cultivation methods, fate of the biomass (e.g., percent of biomass buried permanently in sediments or transformed into forms of carbon that are not easily bioavailable), ecosystem conditions, biogeochemical feedbacks (e.g., nutrient reallocation), and atmosphere-ocean CO_2 exchange (Bach et al. 2021; Hurd et al. 2022). Ongoing research in this area aims to deepen our understanding of carbon flow within both natural and cultivated seaweed systems. The objective is to assess the extent of CO_2 removal and establish reliable methods for attributing carbon sequestration to seaweeds.

Macroalgae cultivation has been practiced for centuries in countries such as China, Japan, and Korea, where it is a traditional food and a major industry (FAO 2018). However, macroalgae cultivation is a relatively new industry in the United States, with most commercial production occurring in Maine and Alaska (Kim, Stekoll, and Yarish 2019). Despite this, the global macroalgae industry has grown significantly in recent years, with the total area of farms increasing by 42% between 2011 and 2016 (FAO 2018). China is the largest producer of macroalgae, accounting for more than 60% of global production, followed by Indonesia and the Republic of Korea. In comparison, the United States accounts for less than 0.1% of global macroalgae production (FAO 2018). The low level of macroalgae cultivation in the United States is attributed to a lack of infrastructure, technical expertise, and market development. However, there is increasing interest in the potential of macroalgae cultivation in the United States, where it could provide numerous economic and environmental benefits including the creation of new jobs, the production of renewable energy, and the reduction of GHG emissions (Kim, Stekoll, and Yarish 2019).

This study is the first comprehensive analysis of macroalgae biomass potential across the full EEZ of the United States. The analysis includes (1) a dynamic macroalgae growth model (Arzeno-Soltero et al. 2023) that competes four commonly cultivated seaweed groups (red and brown temperate and red and brown tropical seaweeds) with two bounding nutrient scenarios; (2) a TEA that incorporates industry-standard farm designs, harvest practices, and farm gate biomass delivery (DeAngelo et al. 2023); and (3) a marine spatial uses dataset derived through a newly developed multi-criteria marine area screening model.

7.2.2 Methods Summary

Biophysical Model

Farmed macroalgae yields are estimated by the Global MacroAlgae Cultivation MODeling System (G-MACMODS), a dynamical biophysical model incorporating constraints from extrinsic (environmental forcing) and intrinsic factors (biological parameters such as growth rates, nitrate uptake, nitrogen exudation, and mortality, among others) (Arzeno-Soltero et al. 2023). G-MACMODS uses macroalgae biomass and nitrogen as model currencies, and globally simulates four macroalgae types, each with distinct parameterizations of temperature tolerance, nitrogen uptake, light adaptation, and crowding capacity (a form of density dependence): tropical red, tropical brown, temperate red, and temperate brown. These parameterizations combine dynamically with input environmental parameters, macroalgae health (nitrogen status), and crowding to define the macroalgae growth rate. The macroalgae type with the highest yield in each grid cell was competed and selected for further analysis. The G-MACMODS model grid resolution is 1/12º (approximately 9 km or 5.6 mi at the equator) and uses a daily time step for growth and harvest calculations.

The model uses inputs of surface nitrate concentration (Long and Saenz 2023), sea surface temperature, surface chlorophyll-*a* concentration, downward shortwave irradiance (Behrenfeld and Falkowski 1997; Ocean Productivity 2022), current speed (Global Ocean Forecasting System 2022), and significant wave height and period (European Centre for Medium-Range Weather Forecasts 2022). To gauge potential yield, seeding/out-planting timing and harvest were optimized across 17 years (2003–2019) of model inputs; non-optimized harvest schedules are also available (based on current farming practices). A limited-nutrient scenario is also available, where nitrate available for macroalgae growth is limited to an estimate of natural renewal from vertical ocean transport processes (upwelling and mixing), and which is more representative of restricted nutrient availability under intensive seaweed cultivation practices. G-MACMODS simulations analyzed here assume no artificial macronutrient amendments and do not include riverine nitrate (runoff). Final yield calculations were made using inputs from 2017, the most recent year with available data that is identified with having a neutral El Niño–Southern Oscillation index.

Macroalgae Techno-Economic Model

The macroalgae techno-economic model is based on the methodology detailed in DeAngelo et al. (2023) and modified to represent the cost of end-use-agnostic macroalgae biomass delivered to shore. The cost of harvested macroalgae biomass is estimated using all costs related to the macroalgae farming process, up to and including the point of harvest at the farm location, as well as costs related to the transportation of harvested biomass to the nearest port. Calculations were made using metric units, and the final results are also reported in imperial units. A high-level representation of the techno-economic model is presented in Figure 7.16.

Spatially explicit costs of macroalgae production are calculated based on annual macroalgae biomass productivity (t-DW/km^2) of the highest-yielding macroalgae type in each grid cell, cultivation line spacing, and harvest interval (species-dependent) from the G-MACMODS biophysical growth model, as well as ranges of capital costs (\$/km^2), operating costs (including labor, \$/km^2), harvest costs (\$/km^2), and transport costs (\$/t/km) from the ARPA-E Macroalgae Research Inspiring Novel Energy Resources (MARINER) farm partners and the scientific literature (Table 7.3; appendix; ARPA-E 2023). The “distance to the nearest port (km)” (Global Fishing Watch 2020) is used to calculate the cost of transporting the harvested macroalgae biomass (wet weight) to the “farm gate,” defined here as delivery to shore. This is analogous to terrestrial energy crop availability after harvest and delivery to roadside. Datasets of ocean depth (m) (General Bathymetric Chart of the Oceans 2022) and significant wave height (m) (European Centre for Medium-Range Weather Forecasts 2022) are used to estimate spatially explicit increases in capital costs due to increased anchoring depth and the impact of rough seas on equipment lifetime, respectively.

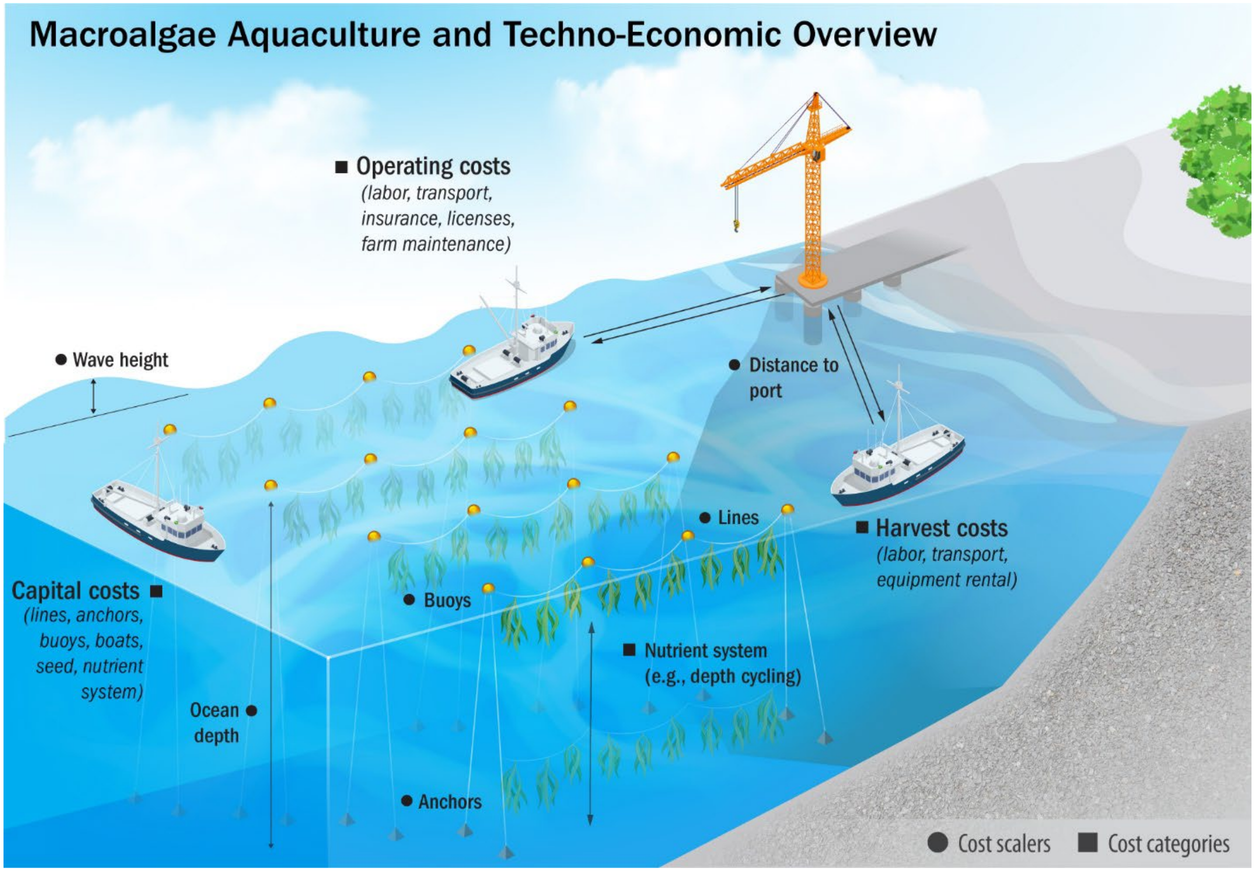

Figure 7.16. High-level overview of the major components influencing macroalgae productivity and capital and operational expenses, all of which comprise the techno-economic model

To assess uncertainty in our estimates that arise from both widely varying farm cost data and uncertainty in the G-MACMODS biomass output, three techno-economic scenarios are assessed: (1) a low-yield, low-cost scenario; (2) a medium-yield, low-cost scenario; and (3) a high-yield, high-cost scenario (Table 7.3). The medium-yield, low-cost scenario is highlighted throughout this chapter as the representative scenario for cost results and is reflective of a scenario where the biomass yield is based on ambient nutrients, but harvesting and seeding schedules are based on current practices. See Section 7.2.2: Methods Summary for more information. Scenario 2 is contrasted with Scenario 3, where potential future technology allows for highly optimized harvest and seeding timing, which would likely require substantial cost increases. Results from the “low-yield, low-cost” and “high-yield, high-cost” scenarios, as well as a detailed scenario of cost inputs, are detailed in the appendices.

Table 7.3. The Framework for Three Techno-Economic Macroalgae Cultivation Scenarios

	Scenario 1 (Low Yield, Low Cost)	Scenario 2 (Representative Scenario) (Medium Yield, Low Cost)	Scenario 3 (High Yield, High Cost)
Biophysical Model			
Nutrient case	Limited nutrients	Ambient nutrients	Ambient nutrients
Seeding and harvesting condition	Standard practices (non-optimized)	Standard practices (non-optimized)	Optimized practices
Techno-Economic Model			
Summary	Costs reflect limited nutrient yield using standard practices (low input costs and no nutrient replenishment system)	Costs reflect ambient nutrient yield using standard practices (low input costs, but nutrient replenishment system required)	Costs reflect fully optimized ambient nutrient yield (high input costs for optimization and nutrient system required)
Cost framework	Minimum of MARINER costs (scaled to model farm footprint)	Minimum of MARINER costs (scaled to model farm footprint) plus nutrient system cost	75th percentile of MARINER costs (scaled to model farm footprint) plus nutrient system cost

Further techno-economic modeling assumptions are provided in the following appendices:

- Production Cost Calculation Overview
- Capital Cost Inputs and Calculations
- Operating and Maintenance Cost Inputs and Calculations
- Harvest Cost Inputs and Calculations
- Transport Cost Inputs and Calculations
- Cost Model Parameter Input Values
- Low-Yield, Low-Cost Scenario Results
- High-Yield, High-Cost Scenario Results.

Marine Spatial Planning

Marine spatial planning is a relatively new process, mostly developed over the last two decades, and focuses on balancing ecological, economic, and social needs (Ehler 2021). Initial efforts were at the state level, with Oregon adopting the Oregon Territorial Sea Plan in 1994, followed by Massachusetts, Rhode Island, and New York—partially driven by offshore wind farm proposals (Portman et al. 2009; Ehler 2021). Federally, the National Oceanic and Atmospheric Administration (NOAA) National Centers for Coastal Ocean Science (NCCOS) provide ecological and socioeconomic data and scientific support for coastal and offshore managers (NCCOS 2023). NOAA and the Bureau of Ocean Energy Management maintain MarineCadastre.gov (marinecadastre.gov/), a source for authoritative ocean data and tools, and NCCOS provides coastal planning and siting products and services to support aquaculture. The marine environment is dynamic, with potentially harsh and varying physical conditions and complex laws and regulations (Roesijadi et al. 2011; Silverman-Roati, Webb, and Gerrard 2021).

Unlike other analyses in this report that are limited to the CONUS, this analysis is based on a resource that is only available outside the CONUS and thus includes a different spatial extent. Specifically, to assess the macroalgae productivity and techno-economic potential, the entire U.S. EEZ was used, inclusive of the coastal waters around the CONUS, Alaska, Hawaii, and the 14 U.S. territories (Figure 7.17). The surface area of the U.S. EEZ is vast, encompassing 24% more surface area (12.2 million km^2, or 4.7 million mi^2) than the total U.S. onshore area (9.9 million km^2, or 3.8 million mi^2). To date, NOAA has performed the most intensive analysis of marine areas for aquaculture opportunity, though for limited regions. For example, the Southern California Bight (Morris et al. 2021) and Gulf of Mexico (Riley et al. 2021) NOAA Aquaculture Opportunity Area atlases document 395 stakeholder engagement sessions that were held with a total of 1,848 participants (NOAA 2021).

This analysis utilizes the methods developed in NOAA's Aquaculture Opportunity Analysis atlases to identify the most conflicting areas. These conflicting areas are defined as uses or features that NOAA considers as constraints, or areas excluded for aquaculture purposes. The associated geospatial data encompass the broader categories of natural and cultural resources, national security, industry, navigation, transportation, and fishing and aquaculture, with most data sourced from NOAA (Figure 7.18; appendix). Any area that intersects the conflicting areas was masked out (screened) before considering the results from the biophysical and techno-economic models. The screening analysis is performed at a 200-m grid resolution, and features like submarine cables, ferry routes, wrecks, and obstructions had a minimum linear width of 1 km (Figure 7.19). This high-resolution screening layer was resampled to 1/12° spatial resolution to match the G-MACMODS biophysical and techno-economic models by taking the majority (screened/not screened) within each model grid cell. The resampling process reduced some of the detail of the screening, no longer capturing areas with a few cables or ferry lines (relatively small areas) but retaining larger features like unexploded ordinance areas. The result is that any grid cell that is not screened contains mostly nonconflicting use, and the uncertainty in the exact value can be reflected with farm area coverage scenarios. This screened-inclusive model layer was then used to calculate representative yield and cost.

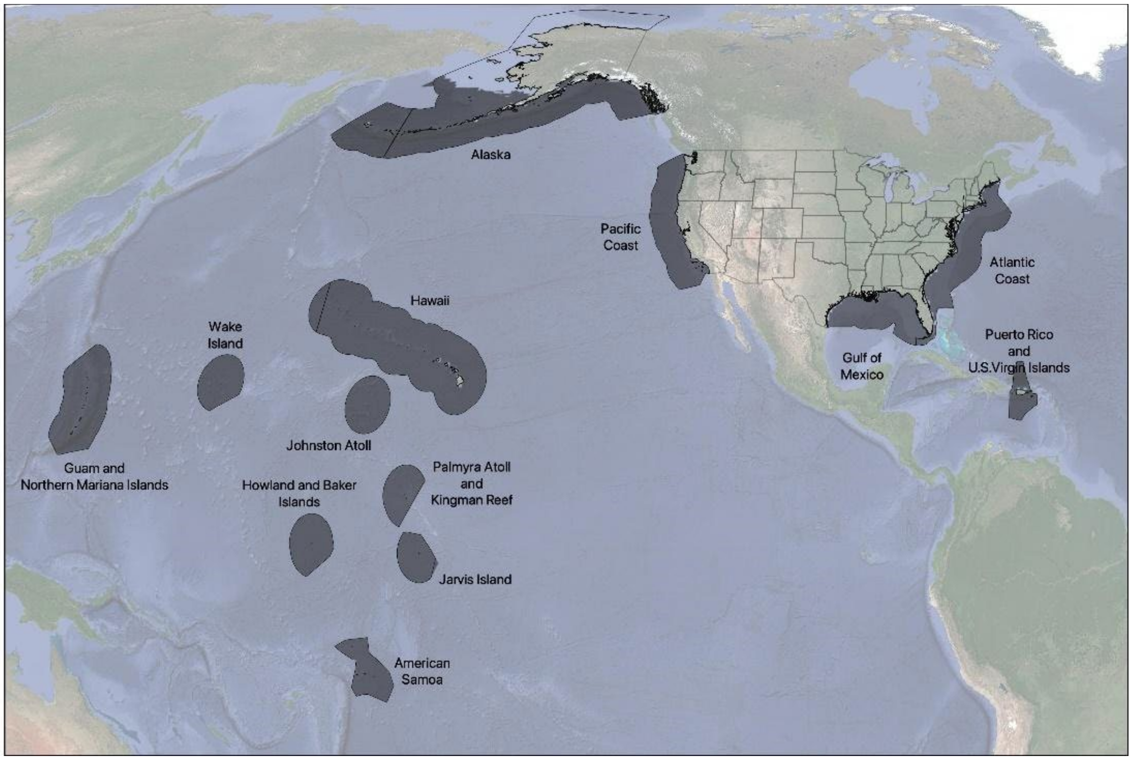

Figure 7.17. The U.S. EEZ considered in this analysis (gray polygons) has an area of 12.2 million km^2 (4.7 million mi^2).

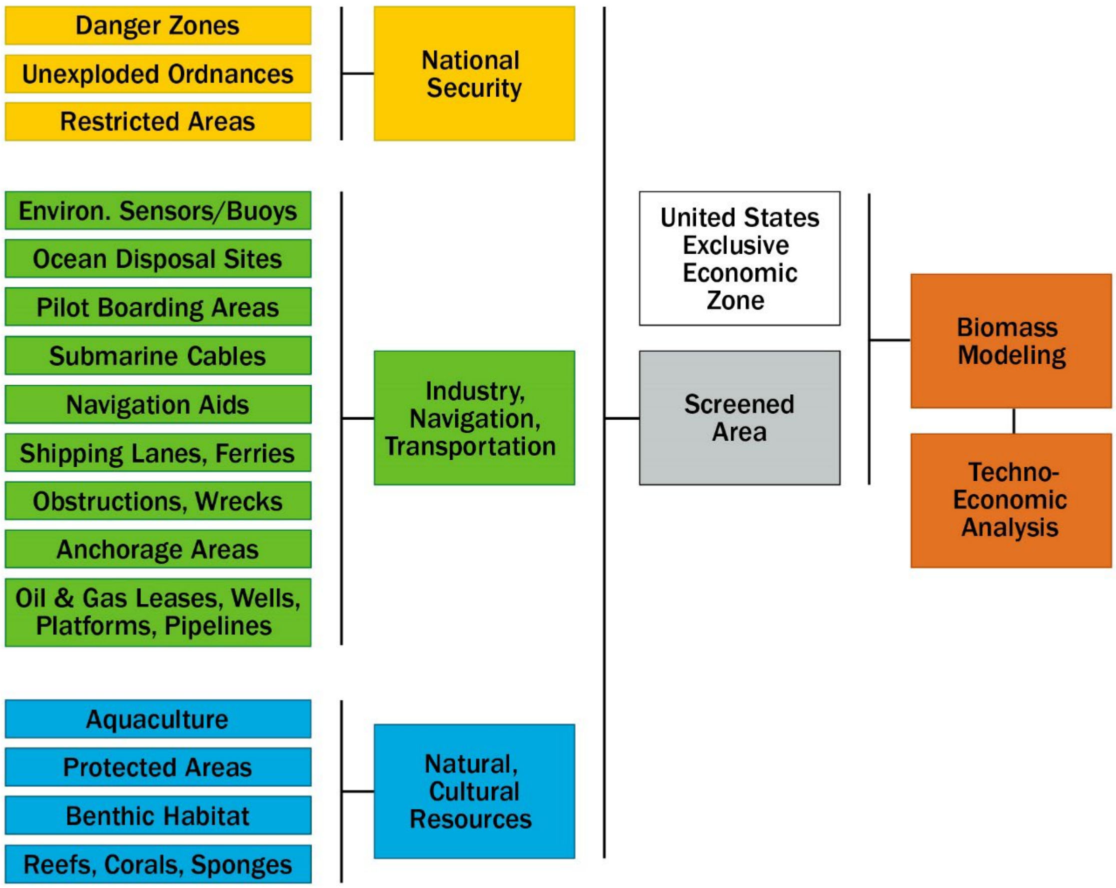

Figure 7.18. General marine area screening methodology based on NOAA's Aquaculture Opportunity Area workflow. Screened areas are merged with G-MACMODS biomass productivity and TEAs.

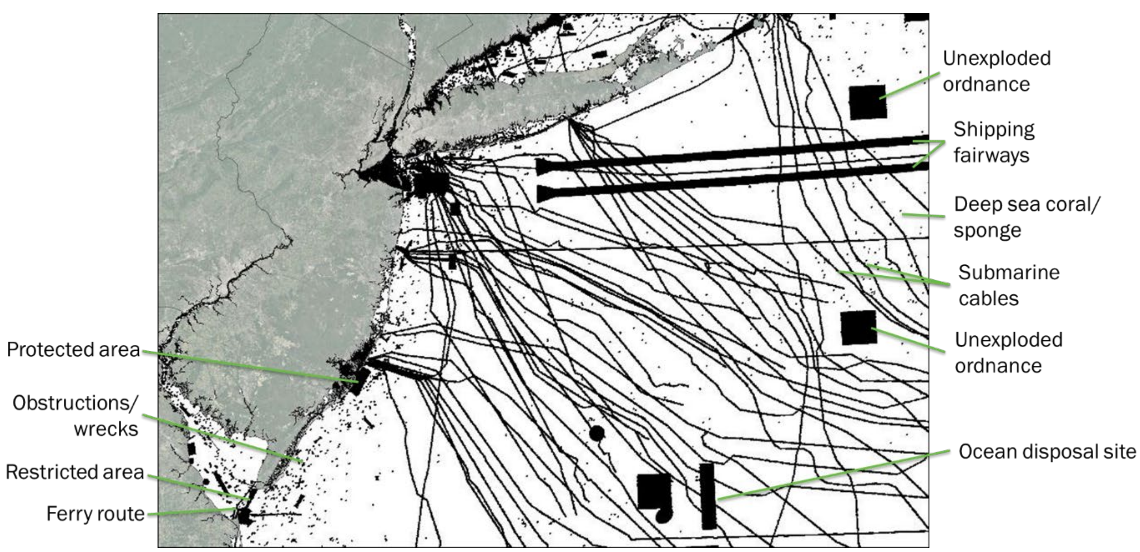

Figure 7.19. Example marine screening inclusion/exclusion analysis. The base spatial resolution of this analysis is 200 m. The black areas represent conflicting areas because of an existing use, and thus not appropriate for macroalgae cultivation.

Using the representative scenario, cost-supply curves were generated for each region to determine the possible yield at four cost thresholds: \$500/t-DW, \$1,000/t-DW, \$2,000/t-DW, and \$3,000/t-DW (\$453/T-DW, \$907/T-DW, \$1,814/T-DW, and \$2,722/T-DW, respectively). The cost thresholds are easily adapted to evaluate additional scenarios. The cost-supply curves utilize the lowest-cost areas first to generate the cumulative sum of annual biomass yield. As modeled, the yield estimates assume full utilization. In other words, outside of required line spacings within a given farm, all screened-inclusive areas are used. To better account for individual farm spacing, infrastructure/access channels within and between farms, coastline and outcrop features, conflicting use areas, and ecological sensitivities, three area yield utilization scenarios are considered: 65%, 50%, and 35% area coverage (see Figure 7.20 for general area coverage reference). The 50% area coverage provides a middle-ground scenario, while the 65% and 35% yield scenarios represent more and less optimistic estimates, respectively.

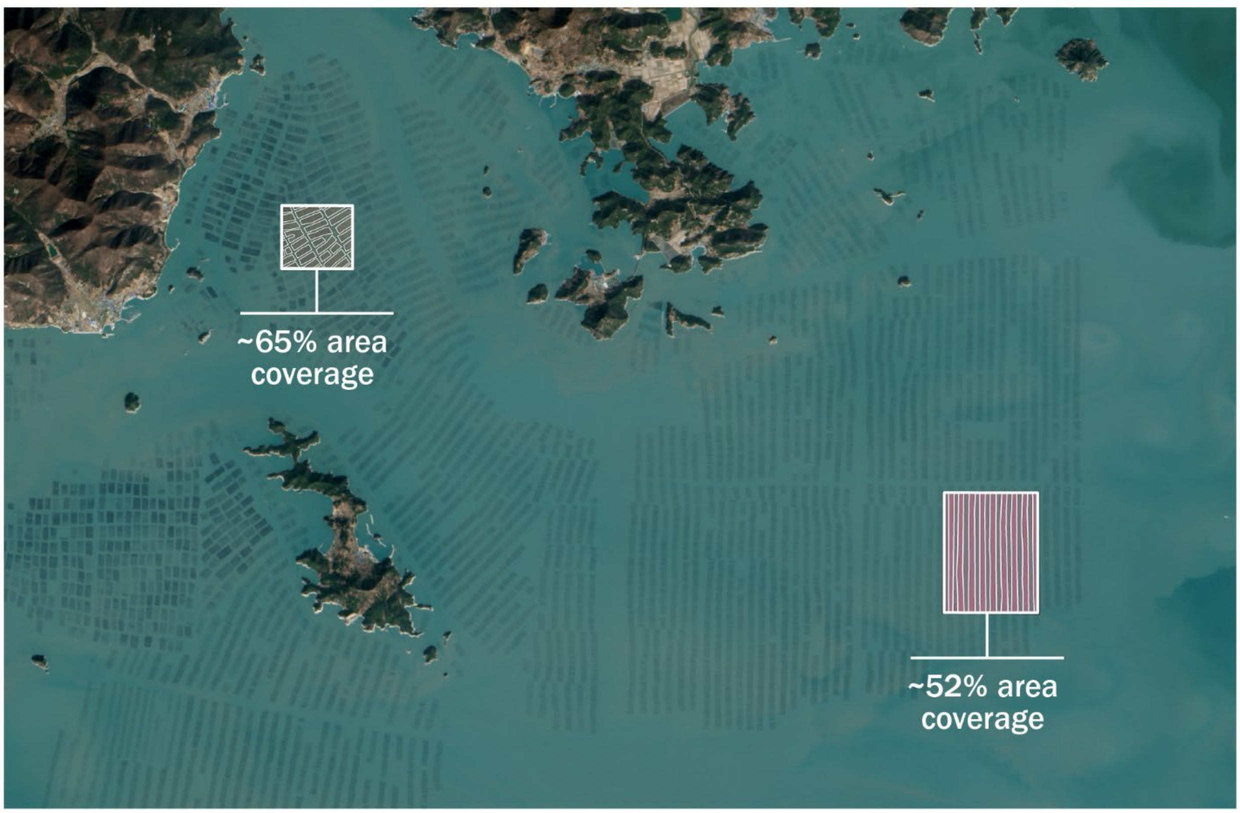

Figure 7.20. Examples of area coverage at existing macroalgae farm sites in the Republic of Korea.

Source: NASA 2015

7.2.3 Results

Screening for conflicting areas leaves 7.1 million km^2 (2.8 million mi^2) for possible macroalgae cultivation, which equates to 58.5% of the total 12.2 million km^2 (4.7 million mi^2) in the U.S. EEZ area. For reference, this equates to 72.3% of the U.S. onshore area (CONUS, Alaska, Hawaii, U.S. territories, and inland water bodies included). Different regions yield different levels of screening depending on environmental and safety protections, existing use, and other defined constraints, with a summary shown in Figure 7.21. Detailed screened-inclusive area values are available in the appendix.

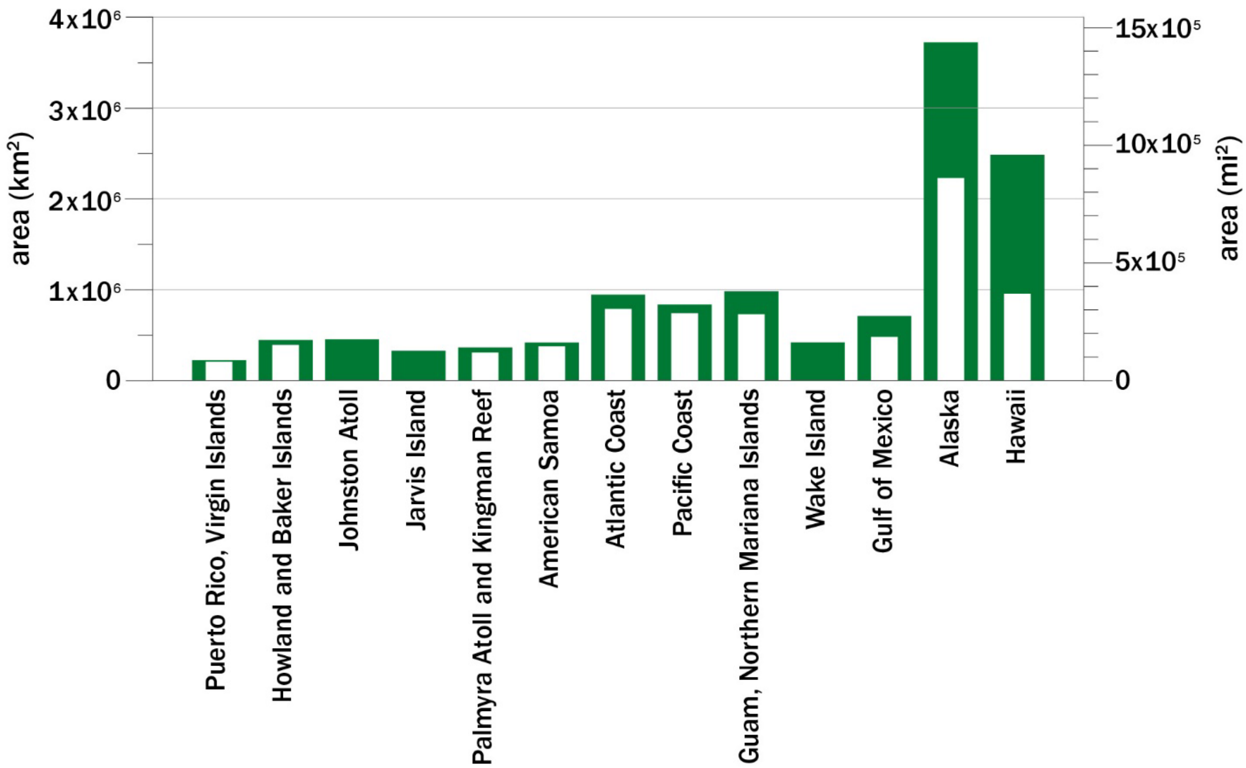

Figure 7.21. Total EEZ area by region (green bars) and remaining screened-inclusive areas (white bars) across the 13 specific regions

Areas of the highest macroalgae biomass productivity for the representative scenario are shown along the coastal and/or offshore areas of the northern Atlantic/New England; the U.S. West Coast (central to northern Pacific); southeastern Alaska and westward through the Aleutian Peninsula and islands; the South Pacific including Palmyra Atoll, Kingman Reef, Howland and Baker islands; and the northerly portion of American Samoa (Figure 7.22). At the U.S. EEZ scale, it is evident that expansive areas were excluded, and this is largely due to existing protected areas (e.g., western Hawaiian island chain, Wake Island, Johnston Atoll, and Jarvis Island). Generally, the areas showing lower macroalgae biomass productivity (e.g., Puerto Rico, U.S. Virgin Islands, Hawaii, Guam) are associated with low concentration of nutrients in the surface ocean. Areas with lower costs tend to be closer to shore and have higher biomass productivity and/or require fewer harvests for the same amount of biomass, since each additional harvest in the biophysical model has associated costs reflected in the techno-economic model (Figure 7.23). The model results for the Gulf of Mexico predict relatively low productivity due to low surface nutrient concentrations in model inputs. This result may be due to insufficient model resolution and freshwater input in this highly riverine-influenced region, and this is discussed as a limitation of the study in Section 7.2.5. The region-specific biomass productivity and techno-economic mapping results provide more detail and are presented in the appendix, where pockets of higher productivity are shown (e.g., Southern California—San Diego and Catalina islands). Figure 7.24 shows the range of productivity and costs per region.

Evaluating the U.S. EEZ as a whole, considering the 65%, 50%, and 35% coverage areas within the screened-inclusive areas and cost thresholds of $500, $1,000, $2,000, and $3,000 per t-DW ($454, $907, $1,814, and $2,722 per T-DW), productivities range from 0.03 to 2.14 Gt-DW/yr (0.03 to 2.36 BT-DW/yr), and associated average costs range from $419 to $1,470 per t-DW ($380 to $1,333 per T-DW) (Table 7.4). To detail this further, a regional analysis by cost threshold is presented with $500/t-DW ($454/T-DW) (Table 7.5), $1,000/t-DW ($907/T-DW) (Table 7.6), $2,000/t-DW ($1,814/T-DW) (Table 7.7), and $3,000/t-DW ($2,722/T-DW) (Table 7.8). Note that there are 13 regions evaluated across the U.S. EEZ (Figure 7.17); if a specific region is not shown, it indicates it was excluded due to the aforementioned cost thresholds. The U.S. EEZ cost-supply curve for the representative scenario and different area coverage scenarios is presented in Figure 7.25. A region-specific stepwise cost-supply curve using the representative scenario and 50% area coverage is presented in Figure 7.26.

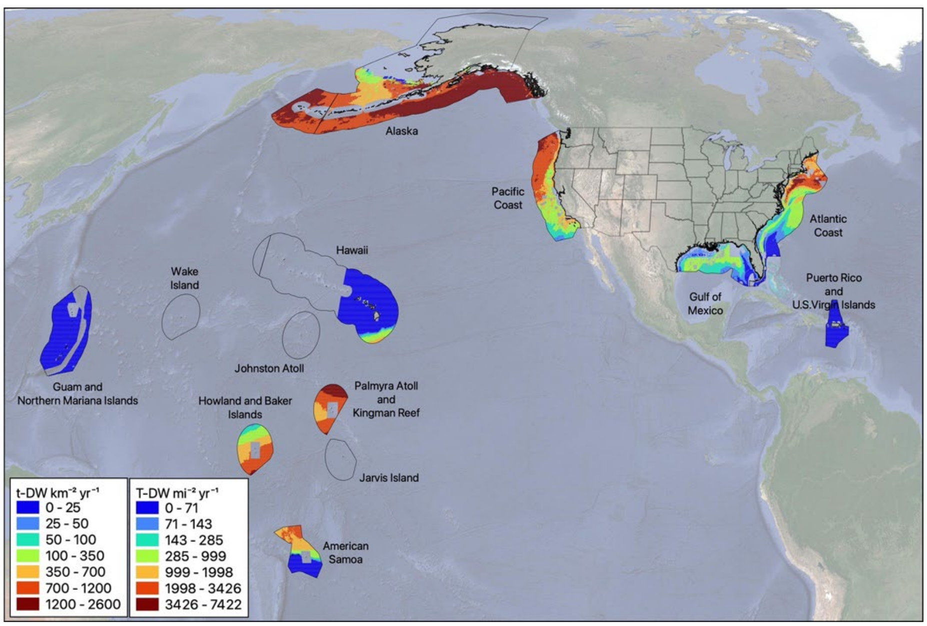

Figure 7.22. U.S. EEZ with screened-inclusive areas showing annual macroalgae biomass productivity estimates for the representative scenario

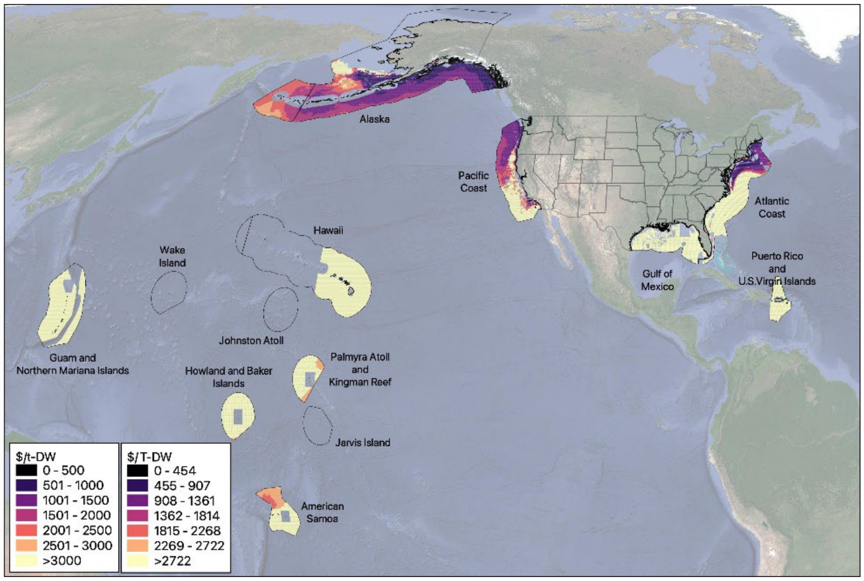

Figure 7.23. U.S. EEZ with screened-inclusive areas and techno-economic results for macroalgae biomass for the representative scenario, with areas >$3,000/t-DW (>$2,722/T-DW) being grouped into a common class

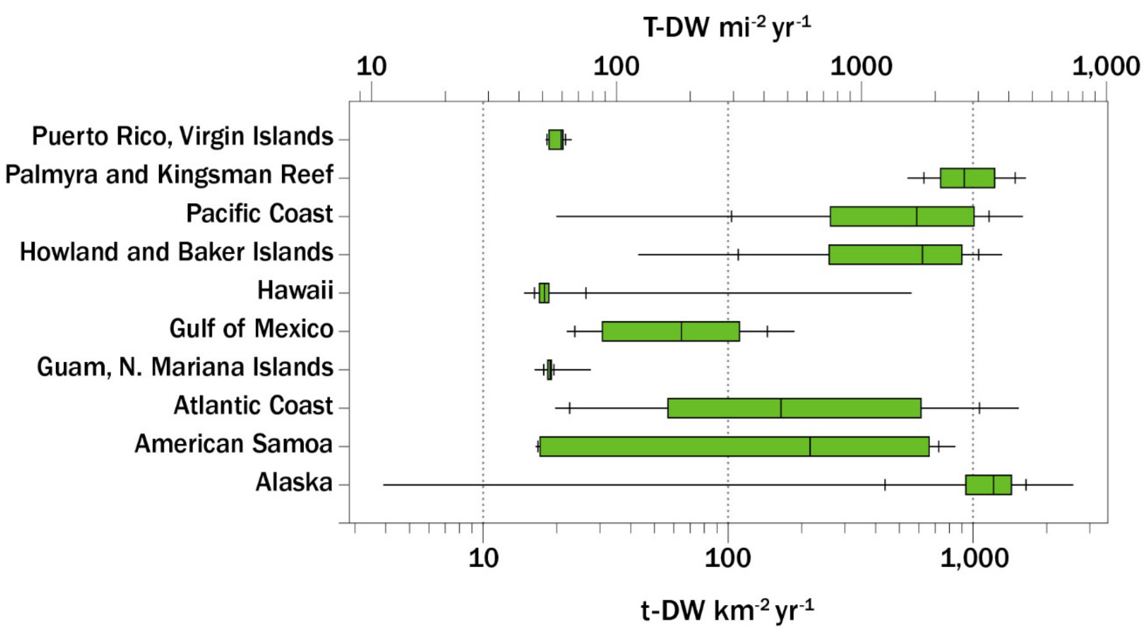

Figure 7.24. Full (100%) area productivity (top) and costs (bottom) of the representative scenario for each region. Each line extends from the minimum to the maximum value, with hashes shown at the 10th and 90th percentiles, boxes covering the 25th to 75th percentiles, and a 50th percentile line in the middle. Note that Wake Island, Johnston Atoll, and Jarvis Island are not included in the plots, as these areas were fully excluded during the marine area screening

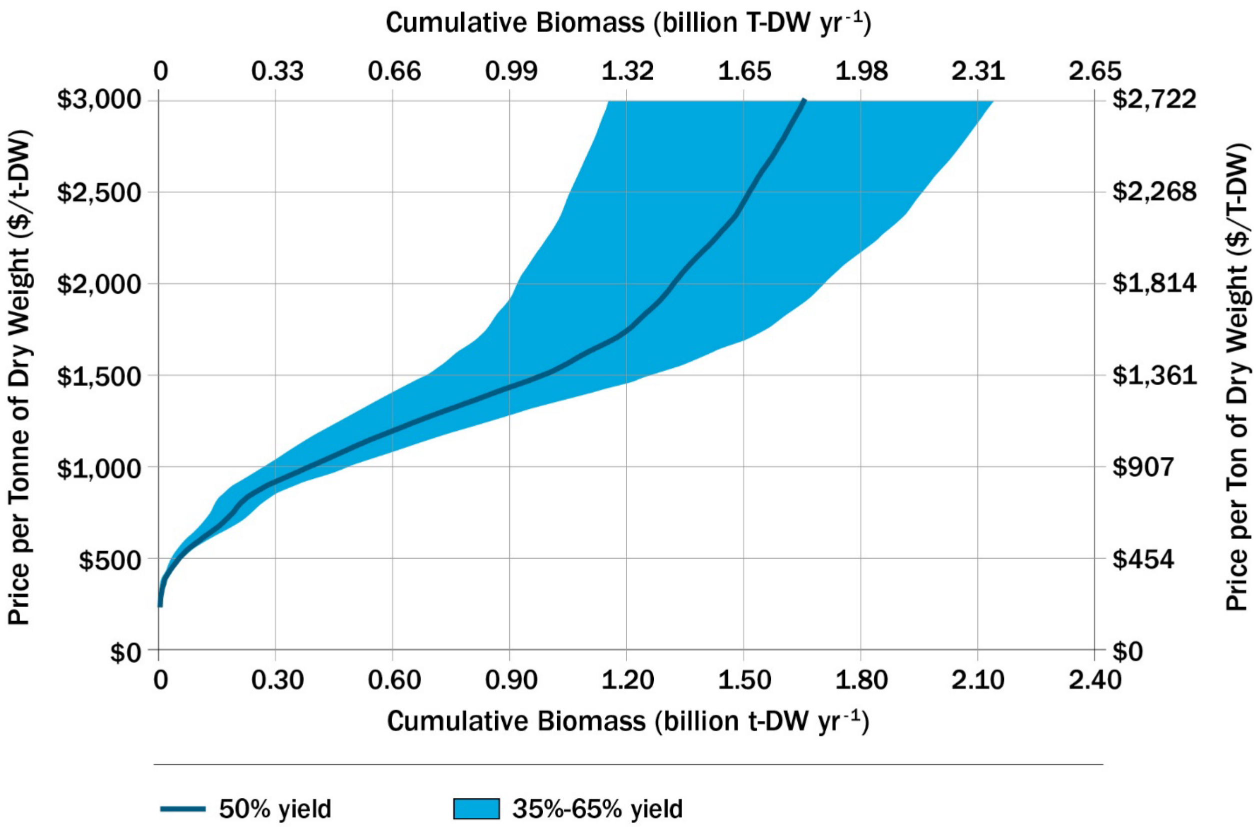

Figure 7.25. Cost-supply curve of the total U.S. EEZ for the representative scenario (Scenario 2) at 35%, 50%, and 65% area coverage

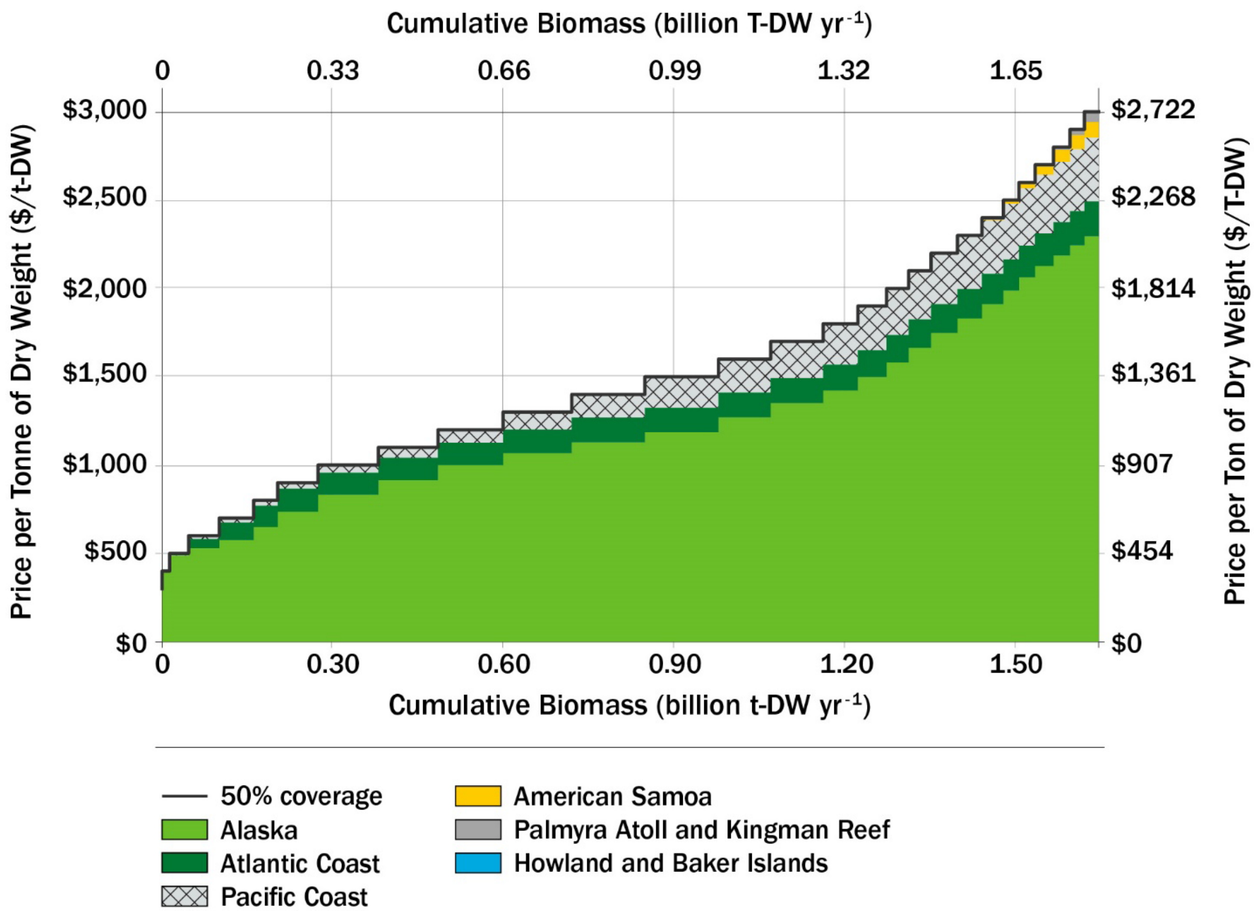

Figure 7.26. Region-specific stepwise cost-supply curve with the representative scenario and 50% area coverage. Note that unlisted regions have costs exceeding $3,000/t-DW.

Table 7.4. Summary of Total Annual U.S. EEZ Biomass Potential for the Representative Scenario at 65%, 50%, and 35% Coverage Areas and Cost Thresholds of $500, $1,000, $2,000, and $3,000 per t-DW ($454, $907, $1,814, and $2,722 per T-DW, Respectively)

Cost Cap ($/t-DW) [$/T-DW]	Area (km^2) [mi^2]	65% Coverage Area (Gt-DW/yr) [BT-DW/yr]	50% Coverage Area (Gt-DW/yr) [BT-DW/yr]	35% Coverage Area (Gt-DW/yr) [BT-DW/yr]	Average Cost ($/t-DW) [$/T-DW]
500 [454]	57,000 [22,008]	0.06 [0.07]	0.05 [0.05]	0.03 [0.04]	419 [380]
1,000 [907]	585,000 [225,869]	0.50 [0.55]	0.38 [0.42]	0.27 [0.29]	739 [670]
2,000 [1,814]	2,207,000 [852,124]	1.71 [1.88]	1.31 [1.45]	0.92 [1.01]	1,222 [1,108]
3,000 [2,722]	3,006,000 [1,160,618]	2.14 [2.36]	1.65 [1.82]	1.15 [1.27]	1,470 [1,333]

Table 7.5. Region-Specific Cost Threshold of $500/t-DW ($454/T-DW) at 65%, 50%, and 35% Coverage Area for the Representative Scenario

Region	Area (km²) [mi²]	65% Coverage Area (Gt-DW/yr) [BT-DW/yr]	50% Coverage Area (Gt-DW/yr) [BT-DW/yr]	35% Coverage Area (Gt-DW/yr) [BT-DW/yr]	Average Cost ($/t-DW) [$/T-DW]
Alaska	55,000 [21,236]	0.062 [0.068]	0.048 [0.052]	0.033 [0.037]	418 [380]
Pacific Coast	2,000 [772]	0.002 [0.002]	0.001 [0.001]	0.001 [0.001]	450 [408]

Table 7.6. Region-Specific Cost Threshold of $1,000/t-DW ($907/T-DW) at 65%, 50%, and 35% Coverage Area for the Representative Scenario

Region	Area (km²) [mi²]	65% Coverage Area (Gt-DW/yr) [BT-DW/yr]	50% Coverage Area (Gt-DW/yr) [BT-DW/yr]	35% Coverage Area (Gt-DW/yr) [BT-DW/yr]	Average Cost ($/t-DW) [$/T-DW]
Alaska	458,000 [176,834]	0.41 [0.46]	0.32 [0.35]	0.22 [0.24]	737 [669]
Atlantic Coast	93,000 [35,907]	0.06 [0.07]	0.05 [0.05]	0.03 [0.04]	733 [665]
Pacific Coast	34,000 [13,127]	0.02 [0.02]	0.02 [0.02]	0.01 [0.01]	788 [715]

Table 7.7. Region-Specific Cost Threshold of $2,000/t-DW ($1,814/T-DW) at 65%, 50%, and 35% Coverage Area for the Representative Scenario

Region	Area (km²) [mi²]	65% Coverage Area (Gt-DW/yr) [BT-DW/yr]	50% Coverage Area (Gt-DW/yr) [BT-DW/yr]	35% Coverage Area (Gt-DW/yr) [BT-DW/yr]	Average Cost ($/t-DW) [$/T-DW]
Alaska	1,621,000 [625,869]	1.35 [1.49]	1.04 [1.14]	0.73 [0.80]	1,208 [1,096]
Atlantic Coast	233,000 [89,961]	0.13 [0.15]	0.10 [0.11]	0.07 [0.08]	1,062 [964]
Pacific Coast	353,000 [136,293]	0.23 [0.25]	0.17 [0.19]	0.12 [0.13]	1,399 [1,269]

Table 7.8. Region-Specific Cost Threshold of $3,000/t-DW ($2,722/T-DW) at 65%, 50%, and 35% Coverage Area for the Representative Scenario

Region	Area (km^2) [mi^2]	65% Coverage Area (Gt-DW/yr) [BT-DW/yr]	50% Coverage Area (Gt-DW/yr) [BT-DW/yr]	35% Coverage Area (Gt-DW/yr) [BT-DW/yr]	Average Cost ($/t-DW) [$/T-DW]
Alaska	2,092,000 [807,722]	1.64 [1.81]	1.26 [1.39]	0.88 [0.97]	1,410 [1,279]
Atlantic Coast	258,000 [99,614]	0.14 [0.15]	0.11 [0.12]	0.08 [0.08]	1,132 [1,027]
Pacific Coast	461,000 [177,992]	0.26 [0.29]	0.20 [0.22]	0.14 [0.15]	1,527 [1,385]
American Samoa	142,000 [54,826]	0.06 [0.07]	0.05 [0.05]	0.03 [0.04]	2,626 [2,382]
Howland and Baker islands	4,000 [1,544]	0.003 [0.003]	0.002 [0.002]	0.002 [0.002]	2,943 [2,670]
Palmyra Atoll and Kingman Reef	49,000 [18,919]	0.04 [0.04]	0.03 [0.03]	0.02 [0.02]	2,859 [2,594]

7.2.4 Summary and Future Research

To our knowledge, this is the first U.S. EEZ-wide analysis for macroalgae biomass potential, inclusive of a marine area screening analysis, macroalgae biomass growth model, and associated TEA to the farm gate, defined as wet biomass delivery at the nearest port (Global Fishing Watch 2020). Using a cost cap of $1,000/t-DW ($907/T-DW) and 585,000 km^2 of marine area over portions of the Alaska, Atlantic, and Pacific coasts, 0.38 Gt-DW/yr (0.42 BT-DW/yr) could be produced assuming 50% of the marine area is productive, with an average cost of $739/t-DW ($670/T-DW). If the cost cap were lifted to $3,000/t-DW ($2,722/T-DW), production could expand across 3,006,000 km^2 of marine area. This would add portions of American Samoa, Howland and Baker islands, Palmyra Atoll, and Kingman Reef, producing 1.65 Gt-DW/yr (1.82 BT-DW/yr) under a 50% productive marine area, and at an average cost of $1,470 t-DW ($1,333/T-DW). High capital and operational costs of deep-water farm locations can make farming even in some high-yield regions cost prohibitive. For example, the EEZ water surrounding American Samoa and the Palmyra Atoll show high yields (Figure 7.22) due to the high nitrate conditions from equatorial upwelling in this region. However, the cost per tonne of seaweed yield is also very high (Figure 7.23), primarily due to high farming costs in deep waters. Transport cost is also a factor at the Palmyra Atoll (where no port exists), but still constitutes less than 10% of the total cost. It is, however, important to note that yields and costs presented here are reflective of the medium-yield, low-cost scenario, more representative of current, small-scale farm efforts. For high-intensity farming over large areas, the low-yield scenario is most relevant, as it considers nutrient competition between farms (see appendix).

Macroalgae as a biomass feedstock has significant potential, but production in the United States has yet to be realized, with relatively high costs associated with a new industry. This feedstock is unique compared to other biomass sources, as it would be situated over near-coastal and offshore waters, which, screening for conflicting uses, equates to 7.1 million km^2 of potential area. These conflicting uses include protected areas, military restrictions, and existing industry like oil and gas. While developing macroalgae resources remains a complex endeavor, aquaculture generally does not conflict with other biomass sources or land-based agriculture, meaning it is a complementary feedstock source that fits well within many of BETO's 2023 Multi-Year Program Plan objectives.

Given this massive area, the $1,000/t-DW ($907/T-DW) cost cap potential macroalgae production (under the 50% coverage area) of 0.38 Gt-DW (0.42 BT-DW) is about one-third of the total mature-market medium scenario for terrestrial feedstocks. The results reported here provide a representative medium-yield, low-cost scenario, where ambient nutrient sources are modeled and standard farm practices are implemented. While the costs may be considered optimistic, as they reflect minimum costs reported through the ARPA-E MARINER program for cutting-edge aquaculture technology (ARPA-E 2023), production costs will undoubtedly change with development and scaling of macroalgae farming in U.S. waters.

The biophysical modeling used in this work provides a dynamic model of potential macroalgae growth across four macroalgae types (tropical red, tropical brown, temperate red, and temperate brown) and does so on a large scale (U.S. EEZ) at reasonable spatial and temporal resolutions (1/12º, daily). The biophysical macroalgae biomass growth model includes environmental (e.g., downward shortwave irradiance, water temperature, ocean currents, wave heights, nutrient availability), biological (e.g., growth rate, crowding/shading) and farm configuration (e.g., line spacing, harvest time) factors, plus the selection of the best macroalgae type for an area. The techno-economic model represents the cost of macroalgae biomass cultivation and delivery to port, considering farm dynamics (line spacing and harvest interval), growth from the biophysical model, and capital costs (operating, harvest, and transport).

7.2.5 Present Assumptions, Limitations, and Future Work

G-MACMODS is a dynamic macroalgae growth model that estimates farm yield as constrained by environmental variables and farming practices. Several assumptions were made in the simulations reviewed above, which are described here briefly and in more detail in Arzeno-Soltero et al. (2023):

- G-MACMODS predictions assume that nitrogen is the limiting macronutrient for the growth of all seaweed groups and, further, that micronutrient supplementation (such as iron embedded within grow lines) will be deployed in areas deficient in trace minerals.
- The techno-economic model assumes that macroalgae is grown and harvested from an anchored floating array.

- Farming costs are modeled assuming longline (tropical brown, tropical red, temperate brown) or net (temperate red) arrays.
- The harvest and transport scheme assumes that macroalgae farming boats would travel the shortest sea-route distance between farms and the nearest port.

Modeled yields may vary (higher or lower) than actual yields due to model limitations:

- Biomass yields for locations near coastal rivers and/or sources of anthropogenic nutrient enhancement may be underestimated. Riverine and anthropogenic nitrate sources are not included in this version of the model.
- Wave erosion of macroalgae biomass is parameterized in G-MACMODS (Arzeno-Soltero et al. 2023), but the inherent variability in large storms and wave events for the many regions modeled results in uncertainty in this form of biomass loss.
- Pests, including grazers and epiphytes, as well as disease, are currently a large source of loss to macroalgae operations worldwide; episodic outbreaks are not simulated by G-MACMODS.

G-MACMODS is global-level model. Regional modeling products that can resolve local riverine nutrient inputs and mesoscale oceanographic features are recommended to guide exploration and investment in farm sites. The current marine area screening focuses on hard constraints, or areas where we are confident an existing use would conflict with macroalgae cultivation. However, there may be areas that were not screened that, in a more localized analysis, may still not be considered viable. Future marine spatial planning analysis could include social or cultural data (nearshore), species distributions, sensitive habitat, potential environmental impacts to the ecosystem, and impacts to shipping and navigation outside of designated shipping lanes (Farmer et al. 2022). The spatial analysis would also benefit from including collocation potential with existing infrastructure such as offshore wind or other future complementary marine energy projects, which could potentially reduce cost and minimize environmental and social impacts. A full suitability analysis, where a favorability score is produced, would help in selecting the best sites for macroalgae cultivation. Additional marine area screening limitations are documented in the appendix.

Separate from the technical considerations of the simulations, this analysis of yield and cost potential does not include the social, cultural, or environmental impacts from large-scale cultivation of macroalgae. Future macroalgae aquaculture marine spatial planning efforts and development projections will be improved by considering such impacts. Best efforts were made to include sustainability constraints in this analysis that account for limitations around environmental concerns. For example, exclusion areas and a reduction factor (35%, 50%, or 65%) were applied to account for constraints that are unknown, including ecological sensitivities. As a theoretical scoping analysis of an evolving resource, it is expected that more sustainability constraints could be added in the future, which could reduce potential supplies. Additionally, sensitivity and uncertainty analyses should be incorporated to reflect the dynamic nature of meteorology, extreme events, and climate change, including projected changes in ocean conditions that can stress growing seaweeds such as rising sea surface temperature, increases in the frequency and severity of storms, and decreases in surface nitrate concentrations due to increases in stratification.

Lastly, the cases presented in this report do not incorporate a projected future learning curve. However, as the seaweed cultivation industry matures, it is expected that farmers will develop more efficient techniques and tools, leading to higher yields per cultivation area. This improved efficiency can result in reduced production costs as operational processes become optimized.

Case Study: Ocean Rainforest

Kate Champion and Eliza Harrison

Ocean Rainforest is among the leading pioneers of macroalgae-based aquaculture in the Western Hemisphere. In 2018, ARPA-E's MARINER program provided an opportunity for Ocean Rainforest and their partners to develop new technologies that would propel the macroalgae cultivation industry forward. The team proposed a pilot farm to demonstrate the feasibility of growing *Macrocystis* for commercial use. *Macrocystis* is native to the U.S. West Coast and is among the fastest-growing organisms on the planet.

Despite many obstacles, the team has successfully put lines in the water to begin cultivation. Now in their second year of production, they have managed yields of 25 kg wet weight per meter of line, well within range of model predictions. Over the course of the project, they have performed dozens of experiments to optimize yield, develop hatchery protocols with near 100% induction success, and refine their seeding methodology. Of note, aquaculture permitting in the United States is complex and split across local, state, and federal control, resulting in conflicting requirements that present time and resource challenges to aquaculture farmers.

Ocean Rainforest is moving forward under a limited permit to install the first deep-water offshore farm for macroalgae cultivation in the United States. This new site sits in 75–80 m of water approximately 5 miles from the Santa Barbara Harbor in the central California coastal area. Working in deep, open ocean waters (>50 m) is rare, even for major macroalgae-producing countries like South Korea. The deep-water site will also enable continued optimization of macroalgae cultivation strategies while continuing technical advancements and market development. Testing remote-operated vehicles with the capacity to install screw anchors could, for example, reduce farm footprint and associated mooring costs. Similarly, unmanned underwater vehicles equipped with cameras and sonar could drive down labor and monitoring costs associated with maintaining the farm. Data generated from the site will also help validate models that predict yield—helping to demonstrate the economic, social, and environmental benefits of macroalgae farming.

The planning is oriented toward the development of a 1,000-ha commercial site that would yield 10,000 t-DW/yr (11,023 T-DW/yr) based on modeling assessments. Such an operation would allow for a private industry operation to deliver a meaningful supply of regenerative biomass for the bioenergy, biofuel, and agricultural industries.

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7.3 CO_2 Emissions from Stationary Sources

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7.3.1 Introduction

According to the EPA, the United States emitted about 5,547 million U.S. tons of direct CO_2 in 2022, resulting from stationary[5] and small mobile sources across economic sectors such as transportation, industry, and power generation (EPA 2022b). Stationary sources, defined as "any building, structure, facility, or installation that emits or may emit any regulated air pollutant or any pollutant listed under section 112(b) of the Clean Air Act" (Code of Federal Regulations 2016), represent a large portion (49%) of total CO_2 emissions. Most of these stationary sources currently emit CO_2 and other pollutants into the atmosphere, contributing to local air pollution and climate change (Zamuda et al. 2018). Capture of CO_2 emissions from these facilities for conversion into valuable products (including organic chemicals and transportation fuels) is an emerging opportunity that could support decarbonization across multiple sectors (Badgett, Feise, and Star 2022).

CO_2 emissions can be divided into biogenic and non-biogenic. Biogenic CO_2 emissions are defined by the EPA as those "related to the natural carbon cycle, as well as those resulting from the harvest, combustion, digestion, fermentation, decomposition, or processing of biologically based materials" (EPA 2017). In other words, biogenic CO_2 represents CO_2 that was previously sequestered from the atmosphere via plant growth. According to BETO, CO_2 emissions from ethanol plants, food and beverage operations, pulp and paper mills, dedicated biomass power plants, landfills, wastewater treatment plants, and manure management processes are considered biogenic CO_2 emissions, while non-biogenic CO_2 emissions are those resulting from the combustion of fossil fuels and other non-combustion processes (BETO 2017). For example, coal and natural gas power plants, cement manufacturing, oil and gas extraction, and many other industries emit non-biogenic CO_2. BETO is required to focus on CO_2 emissions acted on by some biological process; therefore, non-biogenic sources of CO_2 must go through a biological conversion process to be of interest to BETO (BETO 2017). The same condition does not apply

[5] Large sources of CO_2 can be referred to as "point" or "stationary" sources. In this section we distinguish between these labels at a facility level, where "stationary source" refers to a single location that emits CO_2 and "point source" refers to a specific stream of CO_2 at a stationary source, of which there can be multiple. For example, at an ethanol production facility there could be one point source of CO_2 from fermentation processes with additional on-site point sources from other processes such as natural gas combustion for process heat. Please see the appendix for further discussion.

to biogenic sources—they can go through either biological or thermochemical conversion and still be of interest to BETO (BETO 2017).

The intent for this section is to provide a high-level assessment of the potential for CO_2 captured from stationary sources to serve as a feedstock for biological-mediated processes that create carbon-based products. This section provides a CO_2 supply curve that illustrates the estimated cost of capture ($/ton) across a wide range of stationary-source categories along with county-level mapped inventories of annual (2022) CO_2 emissions for CONUS drawn from publicly available datasets. Some industries (e.g., ethanol and ammonia production) have process exhaust streams that are nearly pure in terms of CO_2 purity, and estimated cost of capture is more economically feasible than lower-purity sources. Given the comparatively lower cost, capture from sources that exhaust high-purity CO_2 is considered to be an opportunity of interest to BETO, and this section includes a closer look at the quantities and costs for this category. Non-CO_2 GHGs emitted from stationary sources such as methane, oxides, or fluorinated GHGs are not considered here.

7.3.2 CO_2 from Stationary Sources

Stationary sources of CO_2 arise from a wide range of industrial and commercial activities, and their characteristics can vary between facilities in terms of CO_2 purity, the type and percentage of any trace contaminants, and the temperature and pressure of emissions (EPA 2022a). Based on EPA's Greenhouse Gas Reporting Program (GHGRP) data, it is estimated that 2,724 million tons of CO_2 were emitted by stationary sources in 2022 (EPA 2022b). About 95% (2,584 million tons) comes from non-biogenic sources, and the remaining 5% (141 million tons) is from biogenic sources. Figure 7.27 illustrates the geographic distribution of total (biogenic and non-biogenic) CO_2 emissions from stationary sources by county.

The availability and cost of CO_2 captured from a stationary source is highly dependent on the nature of the process generating the CO_2, the scale of the source, the CO_2 capture technology, and the required properties (e.g., pressure, temperature, purity) of the CO_2 at the plant gate. Figure 7.28 shows an estimated supply curve for a range of CO_2 stationary sources and estimated cost of CO_2 capture based on datasets from the Office of Fossil Energy and Carbon Management's National Energy Technology Laboratory (NETL). Capture cost estimates provided here are based on capture technologies considered commercial or near-commercial for the specific applications. CO_2 capture systems for high-purity processes rely primarily on compression and dehydration of the already nearly pure CO_2 exhaust stream. CO_2 capture systems for low-purity streams rely primarily on solvent-based post-combustion capture technology followed by compression and dehydration of the captured CO_2 stream. Industrial facilities can vary in complexity, with some facilities limited to a single, large stationary source, while others can have multiple point sources of varying size and exhaust stream properties including total CO_2 purity and different ranges of impurities.

The estimated cost of capture reported here assumes supercritical CO_2 delivered at the fence line with a design purity suitable for pipeline transport. Examples of design considerations that could lead to higher or lower costs are provided here but are outside the scope of this analysis. The pipeline purity specifications assumed for the costs presented here have limited consideration for trace constituents and may exclude impurities of concern for biological conversion processes.

Additional purification may be required to make the CO_2 stream a suitable feedstock for biological conversion processes. Any additional purification will likely result in increased cost of the CO_2 feedstock. The estimated capture costs also exclude transport beyond the fence line, which may be a reasonable assumption if the conversion process is located on-site. Any transport and storage needs will also lead to additional costs. Cost savings may be realized through reduction in capital and operating costs if the CO_2 can be delivered at the fence line at lower pressure than the baseline assumption.

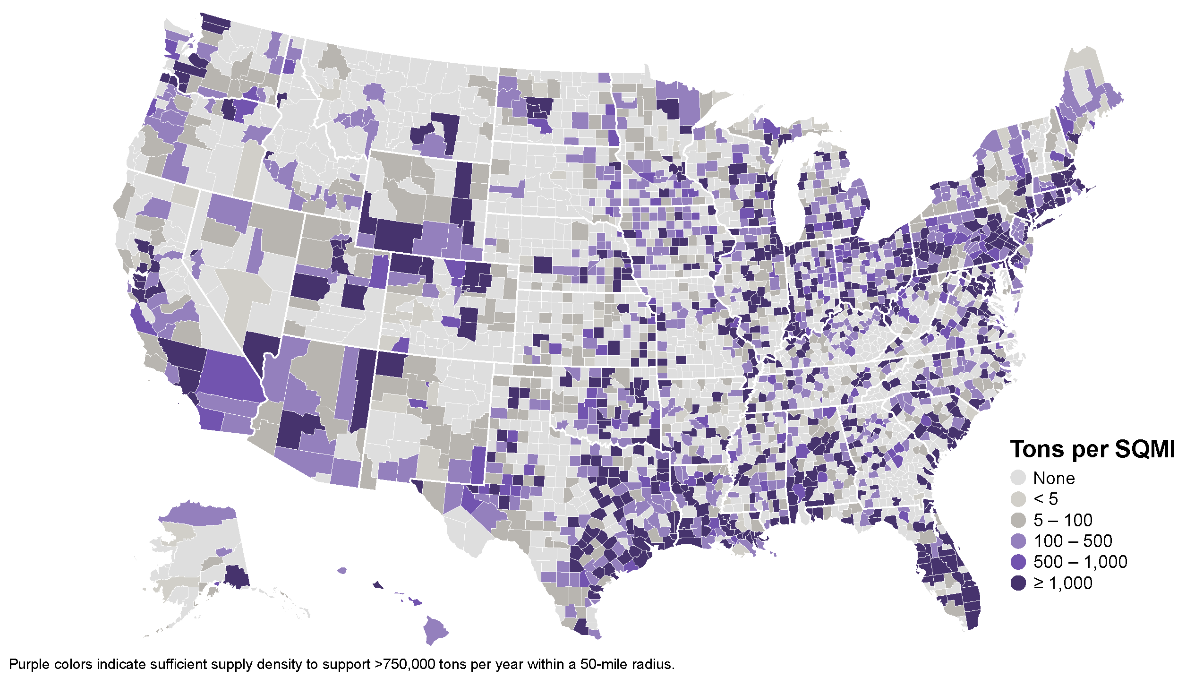

Figure 7.27. Total CO_2 emissions from stationary sources aggregated to the county level. Data adapted from the EPA's GHGRP (EPA 2022a). Please see the appendix for further discussion on how this dataset was created.

The greatest amounts of CO_2 are emitted in the Mountain West, Gulf Coast, and East Coast (Figure 7.27). The largest stationary sources of CO_2 considered here are from combustion-based processes such as coal- and natural-gas-fired power plants and large-scale steel manufacturing (Figure 7.28). While these facilities emit the largest amounts of CO_2, the CO_2 purity in flue gas emissions is low (<30%) and can have impurities that make capture and purification more costly (Hughes and Zoelle 2023; Schmitt et al. 2022) (Figure 7.28). Because the largest single sources of CO_2 tend to be from combustion-based processes, CO_2 captured from these sources might not be available at the lowest costs. Moreover, emitting facilities are often spatially dispersed and may not be in close proximity to demand for CO_2-based products. Cost associated with transport from the point of capture to end use, as well as additional purification (if needed), are not included in the cost estimates provided here and would be adders to the final "delivered price." How and where CO_2 utilization systems are deployed will depend on the particular product being manufactured, potential additive costs for transporting either CO_2 or CO_2-based products, and other market factors that are beyond the scope of this work.

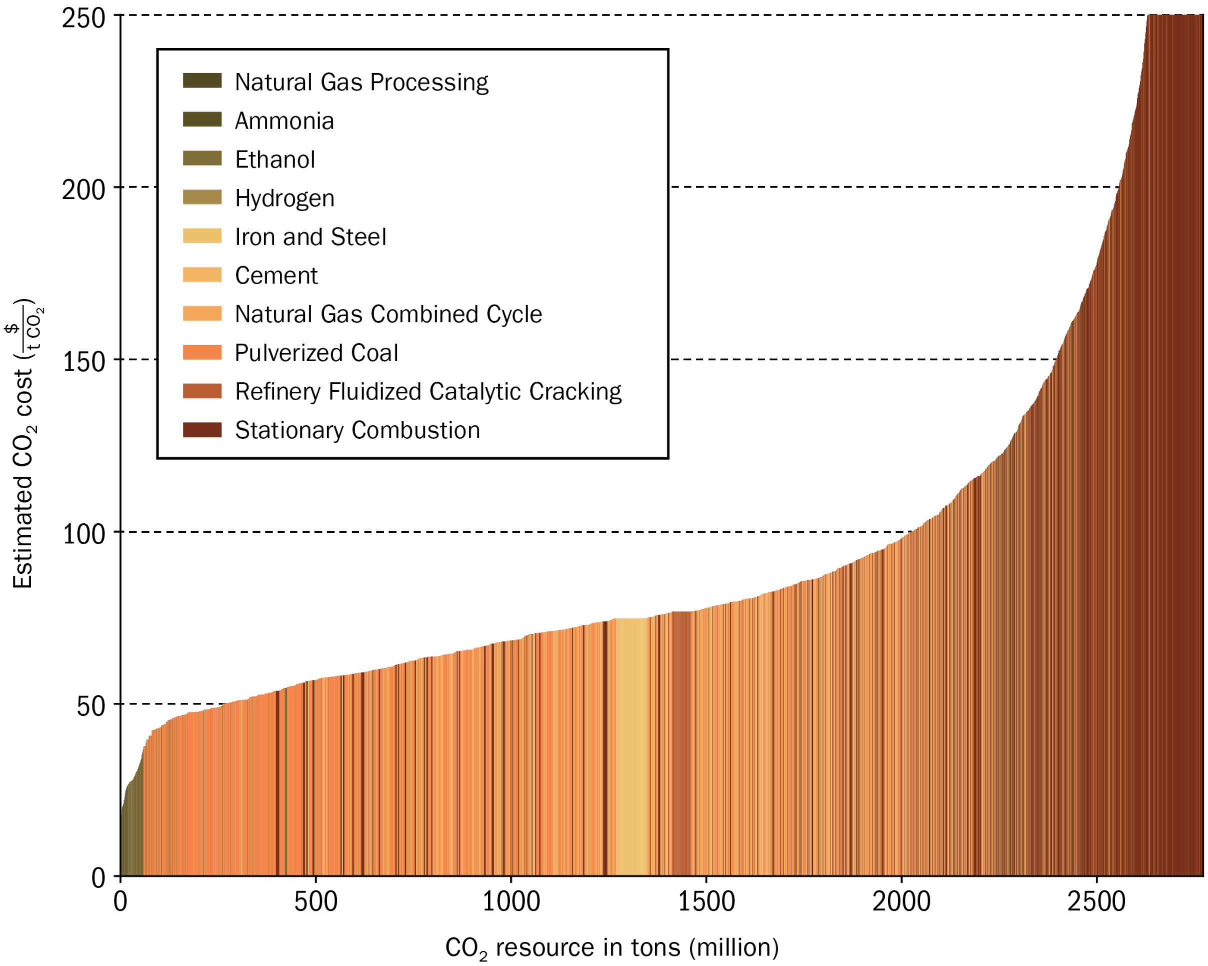

Figure 7.28. Subset of total CO_2 resource by facility category for stationary source and estimated cost of CO_2 capture and purification. Figure using data from NETL and the Office of Fossil Energy and Carbon Management (NETL 2023; Fahs et al. 2023; Schmitt et al. 2023). Please see the appendix for further information.

Variability also exists in total resource estimates between datasets and by year. Total CO_2 emitted from stationary sources (Figure 7.27) uses EPA datasets from 2022, while data shown in Figures 7.28, 7.29, and 7.30 are based on 2021 datasets. While the year-by-year variations in CO_2 streams likely influence the total amounts in these datasets slightly, explicitly quantifying and comparing these differences is beyond the scope of the nationwide resource analysis discussed in this section. Annual changes in total potential CO_2 supply can result from facility-level changes (e.g., operation, equipment improvements and process design, feedstock input changes) as well as demand for end-use products (i.e., decrease in reliance on electricity generated from fossil fuels would decrease sector emissions, while increase in demand for domestically produced steel or cement would increase associated sector emissions). For example, in 2019 the National Petroleum Council estimated approximately 2,866 million tons of CO_2 from stationary sources (National Petroleum Council 2019), while this 2022 analysis estimates about 2,724 million tons of CO_2. While fossil-fueled (coal and natural gas) power plants compose the largest single stationary source categories of CO_2 currently and may be required to consider CO_2 capture under proposed regulations (EPA 2023), ongoing efforts to decarbonize the electric power sector may result in the closure of high-emitting facilities and would likely reduce the respective total amount of CO_2 available for capture, conversion, and use. How large-scale CO_2 markets might respond to such supply dynamics is uncertain and will depend on factors like demand profiles for CO_2-based products, competing technology pathways, and other market forces.

7.3.3 Opportunities and Market Outlook

Stationary sources from processes that produce high-purity CO_2 exhaust streams (e.g., ethanol and ammonia production plants) are less expensive to capture and purify compared to exhaust gases with low CO_2 purity, making them more attractive feedstocks. These sources and existing applications for high-purity CO_2 streams are discussed in detail in this section. High-purity CO_2 stationary sources are generally associated with agriculture, and are therefore predominantly sited in the central United States (Figure 7.29), and are the primary driving force for the lower CO_2 capture costs shown in these areas (Figure 7.30). This analysis does not focus on capture and purification technologies beyond the high-level discussion and data provided in this section and its appendix, but readers should note that the cost of capture and purification of CO_2 depends on the state of these technologies. Advances in process efficiency, novel capture technologies, and integrated capture and conversion systems could shift these costs and therefore CO_2 market development.

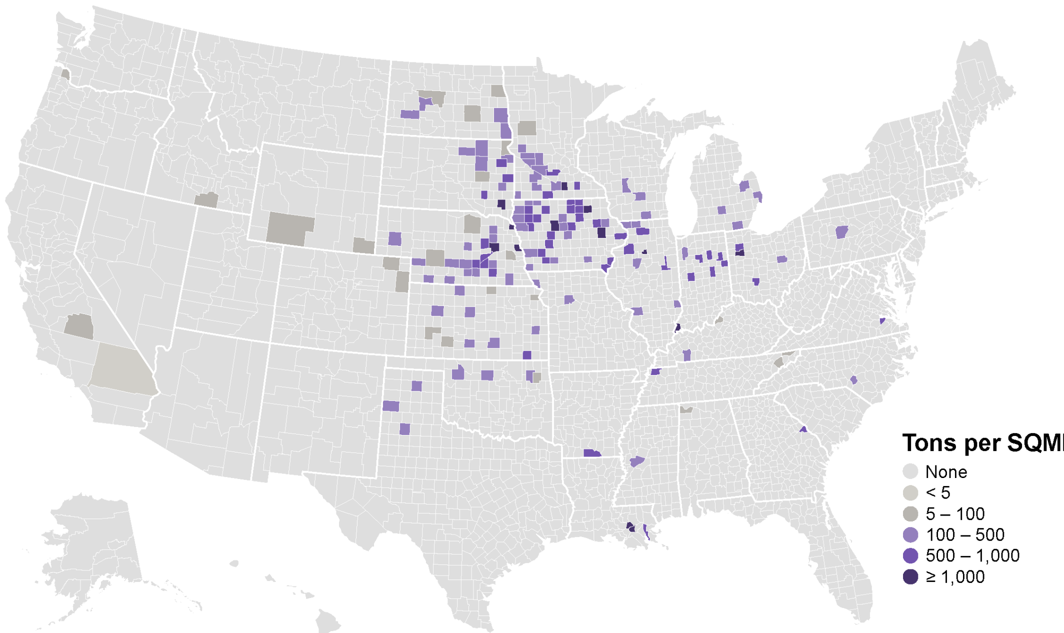

Figure 7.29. Estimated supply of high-purity CO_2 for ethanol and ammonia production facilities. These supply estimates exclude high-purity CO_2 already captured at operating facilities. See the appendix for additional detail.

Use of high-purity streams of CO_2 from ethanol and ammonia stationary sources is viewed as the most amenable for near-term deployment of biologically mediated CO_2 conversion processes. As discussed further in the appendix, some of these facilities are already capturing the high-purity CO_2 and utilizing it on-site (ammonia conversion to urea) or selling into the merchant market. However, these high-purity sources represent only a portion of total CO_2 emitted from stationary sources annually (the selected resources provided here represent about 47.2 million tons, or 2% of total stationary-source CO_2 emissions reported by the EPA). If demand from large-scale CO_2 utilization technologies exceeds the available high-purity resources, capture from additional stationary sources will likely be from processes producing lower-purity CO_2 streams and higher costs of capture.

When assessing the feasibility of capturing CO_2 from stationary sources, it is important to evaluate the site-specific aspects of CO_2 availability and process-level design of the facility. Total amounts of CO_2 reported to the EPA from a single facility can encompass streams from multiple different processes and unit operations, with potential variation in the feasibility of capturing each stream. For example, ethanol and ammonia production facilities emit high-purity streams of CO_2 from specific processes but are also likely to emit lower-purity CO_2 streams from other unit operations such as natural gas combustion for process heat, among others. Moreover, configuration of the capture process can influence both the amount and purity of the product CO_2. Additional CO_2 may be produced if carbon-based fuels (fossil or biomass) are used to satisfy thermal energy requirements of the capture system. Additionally, CO_2 product purity can vary depending on the degree and nature of treated stream impurities, as well as the characteristics of the CO_2 capture process. Lastly, purity requirements of CO_2 as a feedstock can impact the feasibility of the conversion process. Understanding the nature of the CO_2 resource at the facility level (e.g., specific proportions of high- and low-purity CO_2 streams, types and quantities of non-CO_2 impurities) and requirements of the conversion technology of interest is crucial to designing and optimizing integration of CO_2 sources with on-site conversion technologies.

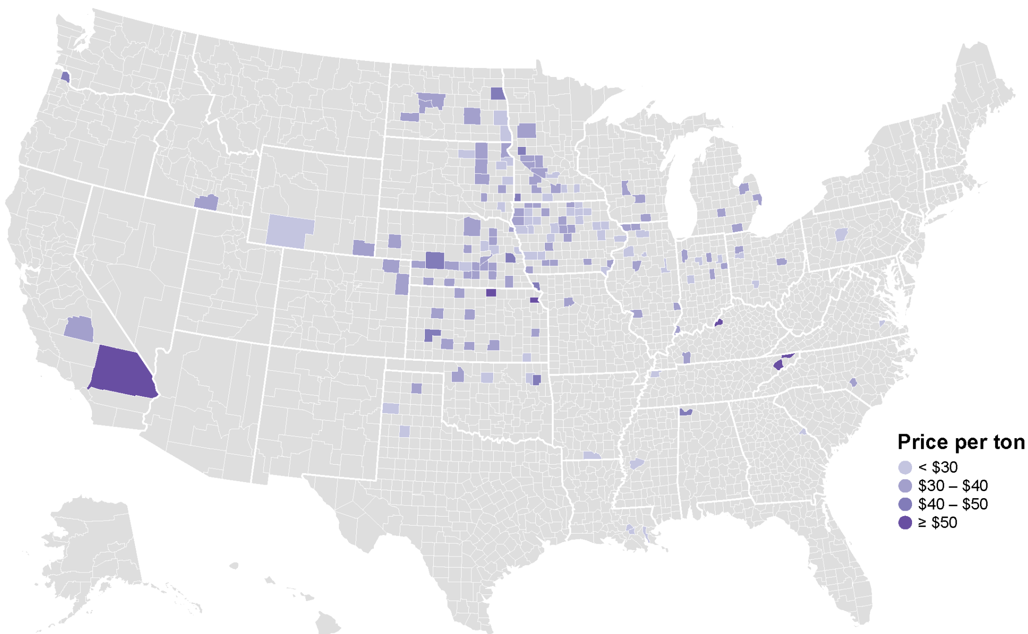

Figure 7.30. Average estimated cost of high-purity CO_2 captured from ethanol and ammonia production facilities

Markets for CO_2 are present in the United States today and consume CO_2 from existing sources at a small scale relative to total annual emissions (EPA 2022c). The total amount of CO_2 captured from industrial sources and produced from natural sources (excluding CO_2 captured and utilized on-site, such as production of urea at integrated ammonia facilities) in the United States was 52.5 million tons in 2022 (EPA 2022c). This amount represents about 1.9% of total supply from the stationary sources considered in this analysis. The majority of CO_2 emissions from stationary sources (98.1%) is released to the atmosphere and is not currently captured in a form available for utilization. As of 2022, the majority of CO_2 captured and utilized was used for enhanced oil recovery (40 million tons, or about 78%), with other consumers including food and beverage (5.5 million tons, or about 10%), pulp and paper manufacturing, and other industries (EPA 2022c). Almost 40% of this utilized CO_2 comes from the capture of emissions from industrial facilities, including ethanol plants, natural gas processing facilities, and ammonia plants, again demonstrating the favorability of leveraging the lower cost of capturing CO_2 from process streams that have high (near-pure) CO_2 purities. While the current amount of CO_2

captured and utilized is small, it is clear that the majority of this CO_2 comes from economically favorable, high-purity, stationary-source emissions (e.g., ethanol and ammonia plants).

Decarbonization efforts in industry and the power sector will also influence CO_2 availability, and a number of current incentives may act favorably for the deployment of respective capture technologies and non-carbon alternatives, such as greater reliance on renewable resources for power generation and hydrogen produced as a replacement for fossil-fuel-intensive industries (e.g., steel manufacturing). Over the long term, structural changes of energy-intensive industries as a means to transition to net-zero technologies may lead to significant reduction and possibly elimination of existing industries considered as potential CO_2 resources. Recent analysis (Zhou et al. 2023) suggests that existing CO_2 stationary sources could reduce in the future as fossil-fuel-based power generation and industrial processes shift and move toward decarbonization, and other stationary sources such as cement, ethanol, and ammonia production continue to operate and might represent a larger share of CO_2 supply. However, other stationary sources of CO_2 could emerge from bioenergy processes in the future, again shifting the supply of CO_2 available and likely impacting prices for this stream.

Precedent for shifts in these future markets can be seen in the development of RNG from organic sources, valorizing these emissions and impacting the value of gases that might otherwise be viewed as wastes. It is important to note that this trajectory is just one possibility in a future that could change depending on numerous technical, economic, and regulatory uncertainties. Depending on the future market demand for CO_2-based fuels and products and the current state of direct air capture technologies, direct air capture could also provide atmospheric CO_2. Understanding the dynamics between CO_2 stationary sources, decarbonization efforts, and opportunities to deploy CO_2 removal technologies such as direct air capture is crucial for processes aiming to produce CO_2-based fuels and products.

It is reasonable to expect that as markets for CO_2 emissions develop, demand will increase and technology advances could impact supply dynamics and resource prices in ways that cannot be easily projected and are not contemplated in this analysis. As such, future potential end uses could compete with bioenergy-specific CO_2 utilization pathways and should be considered in subsequent resource and market analyses. Using modeling capabilities developed for the microalgae portion of this report, we considered potential competitive use estimates for CO_2 emissions in the case that microalgae pathways utilize stationary-source emissions. Under deployment scenarios for microalgae pathways, we estimate that a range of 5%–10% of total CO_2 emissions from stationary sources could be used for conversion. For further information and discussion on microalgae utilization and modeling, please refer to Section 7.1.

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Chapter 08 Looking Forward and Next Steps

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8 Looking Forward and Next Steps

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- Report landing page: https://www.energy.gov/eere/bioenergy/2023-billion-ton-report-assessment-us-renewable-carbon-resources
- Data portal: https://bioenergykdf.ornl.gov/bt23-data-portal

Summary

Bioenergy remains one of our nation's oldest, largest, and most versatile forms of renewable energy. Fully 5% of our nation's energy needs are provided through biomass and waste resources. Biomass is a source of renewable carbon, which can make an essential and substantial contribution in meeting our national net carbon emissions reduction goals (commonly referred to as "decarbonization"). The purpose of this document is to quantify the future availability of biomass under suitable market conditions, geospatially and with estimated costs of production. Qualitatively, this report finds that under mature-market conditions, the United States could grow its biomass resources by a factor of 3. In the longer term, assuming emerging resources can be economically brought to the market, another 1 or 2 billion tons could be available. Yet we find that no one single feedstock can supply all the biomass; different regions tend to produce different feedstocks, which collectively can be used to help address our nation's decarbonization goals. The limiting factor becomes the cost and long-term social and environmental consequences of producing these vast quantities of biomass. One of the key benefits of a robust bioeconomy is that a large swath of the country can participate. Rural economies across the nation can produce a wide variety of feedstocks identified in this report, while urban areas can harness and utilize waste-based resources rather than simply disposing of them.

The analysis upon which this report is based includes several constraints designed to model long-term environmental sustainability. In this analysis, we relax the sustainability constraints to explore the economic incentives for producing biomass from the agricultural and forestry sectors, beyond what could be considered a sustainable level. We address the topic of direct and indirect LUC, as well as unintended deforestation, including limits to modeling in this report (e.g., the assumption that timberland does not convert to agricultural land). The primary sustainability constraints are also discussed. We find that existing management practices can serve as guides to avoid unintended consequences of biomass production, though it is unclear how widely these practices would be adopted in the future based on existing economic

incentives. Clearly more work needs to be done in these areas, but our hope is that this document continues meaningful dialogue.

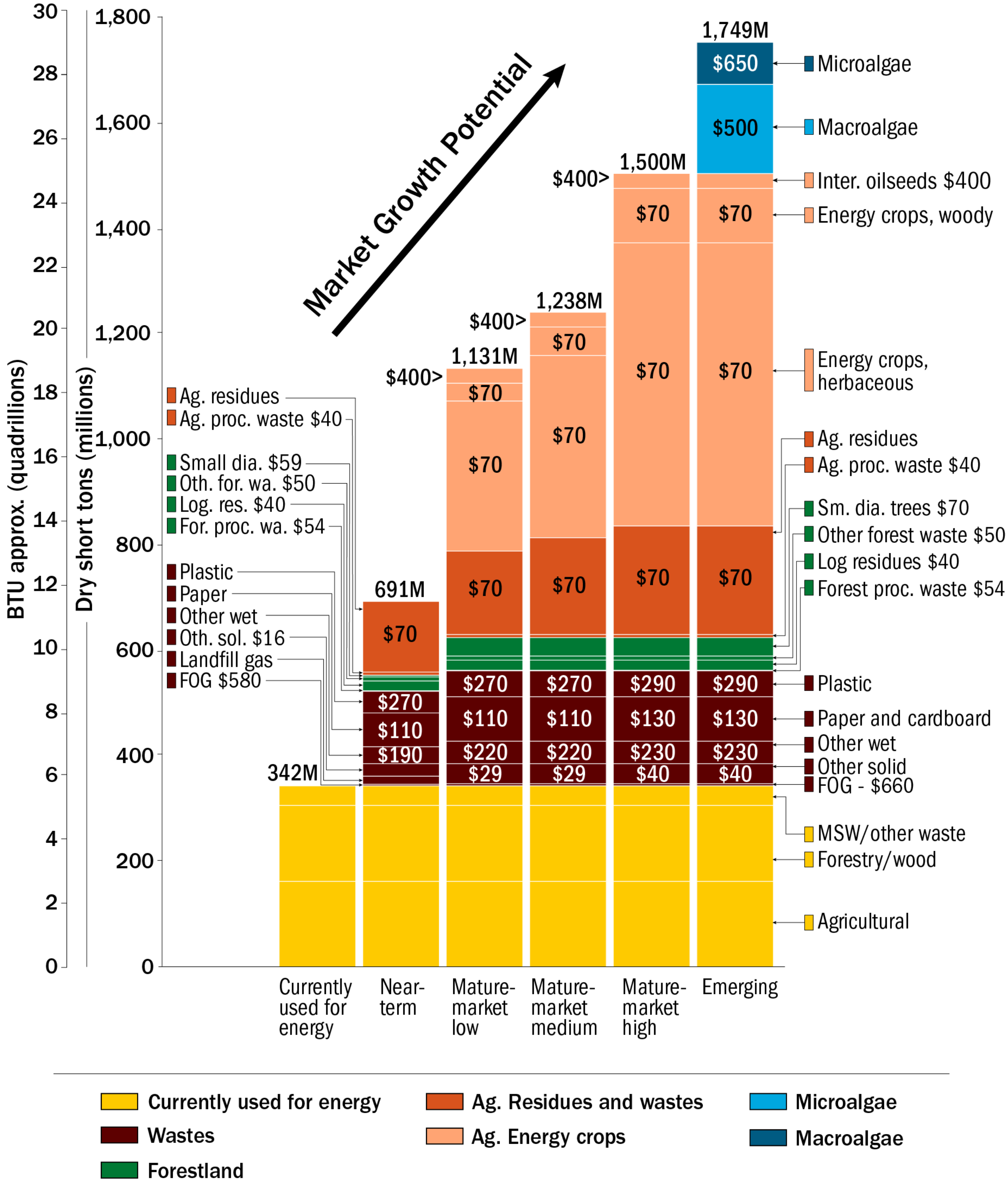

Figure 8.1. Summary of biomass resources by scenario

8.1 Looking Forward and Next Steps

As with other sources of renewable energy, a combination of supply push and market pull is needed to advance commercialization. Supply push can come in the form of technologies or practices that increase biomass supply, add value, or decrease cost. Waste resources are being used commercially today, and this trend is likely to continue. Market pull includes innovations or market changes that increase demand or willingness to pay. Supply-side innovations that provide supply push include:

- Increases in purpose-grown energy crop yield.
- Reductions in supply chain costs, uncertainty, and risk.
- Improved attributes in terms of quality and consistency.

Research needs identified in the development in this report to address supply-side limitations include:

- Alternative futures of biomass resource potential based on different demand scenarios (e.g., starch-, lipid-, terpene-, or cellulosic-specific pathways).
- Range of climate change impacts and uncertainties on agriculture, forest landscape, and biomass resource production.
- Likelihood of deviating from sustainability constraints assumed in this report and associated environmental risks, including land use pressures.
- Further analyses of potential impacts of biomass crop production on conventional markets.
- Potential for a shift to biogenic CO_2 for carbon capture and storage and/or algae fertilization if the mature-market conditions in this report are realized.

This report is not exhaustive of all biomass resources in the United States. Notable biomass resources that could increase quantities in this report include:

- Forest biomass from realization of USFS Wildfire Crisis Strategy forest fuel reductions (addressed in case studies in chapter 4, but not in national totals).
- Herbaceous intermediate crops (e.g., winter rye, alfalfa) (addressed in chapter 5, but not in national totals).
- Removal of invasive species such as melaleuca (*Melaleuca quinquenervia*), Chinese privet (*Ligustrum sinense*), and black locust (*Robinia pseudoacacia*).
- Purpose-grown energy crops produced on mined lands, reclaimed lands, brownfields, and other nonagricultural lands.
- Episodic woody biomass sources such as salvage from hurricane and storm debris, beetle kill, and wildfires.

Examples of uncertainty in this national assessment include:

- Product-specific market demands, which will incentivize a mix of energy crops different from those reported here.
- Adoption premiums, which will cause prices to vary over time and by region.
- Short-stature corn, as an agronomic innovation with unknown impacts on residue availability.
- Progress in waste reduction.
- Changes in future energy profiles, which will change point sources of CO_2 emissions, but could cause point sources of biogenic CO_2 emissions to increase.

This report is intentionally agnostic to end use, and other than describing their current uses, does not recommend the possible or optimum uses of these biomass resources. The versatility of biomass to support a variety of uses such as heat, fuel, chemicals, or durable materials is one of its strengths. Feedstock-specific quality attributes make different feedstocks more or less suited to different end use applications. Similarly, different conversion processes are more or less able to optimally process these feedstocks. Advances in conversion pathways and the willingness to develop these options will play a large part in the specific pathways brought to market. While beyond the scope of this report, it would be instructive to better explore the various uses of biomass across the transportation, industrial, and electrical sectors.

The analysis within this report assumes a robust mature market able to incentivize the conversion of near-term feedstocks such as waste, forest, and agricultural residues and the production of longer-term feedstocks such as purpose-grown energy crops and emerging resources. This report, however, does not address any of the various policy actions that might be necessary to realize that mature market. Multiple policy actions will likely be needed and helpful in stimulating this market, and the impacts of these policies both nationally and regionally need to be articulated. Similarly, policy interventions to ensure sustainability are not directly addressed, although modeling constraints have been used to assess their potential need. These costs of future policies need to be weighed against the positive impact of using biomass for different decarbonization pathways. More work needs to be done to understand the positive and negative impacts of growing a robust bioeconomy on the lives of nearby communities, especially underserved communities. But the goal of a mature market for biomass cannot be realized without growth in the bioeconomy sector. Certainly, progress has been made, but more needs to be done to begin to realize these aspirational goals. It is our hope that this report moves us in that direction.

8.1.1 Biomass Potentials in Decarbonization Studies

Many U.S. and global decarbonization scenarios feature expanded use of biomass as a renewable carbon feedstock for producing liquid fuels for hard-to-electrify sectors, or as a means of carbon removal (Butnar et al. 2020; Field et al. 2020; Langholtz et al. 2020; U.S. Department of State 2021; Hawkins et al. 2023). However, second-generation biofuels have been slow to develop.

The RFS established by the 2007 Energy Independence and Security Act (110th Congress of the United States 2007) was anticipated to drive new cellulosic biomass production on the order of 250 million tons per year to support the production of 16 billion gasoline-equivalent gallons of cellulosic ethanol annually by 2022. The Biomass Crop Assistance Program established under the 2008 Farm Bill provided supplemental payments to farmers delivering biomass to approved conversion facilities, and covered some of the costs of establishing novel dedicated energy crops (Miao and Khanna 2017). These supportive policies led to the construction of an initial cohort of commercial-scale cellulosic ethanol biorefineries about a decade ago (Peplow 2014). Those biorefineries were all shut down in the intervening years due to technical challenges and unfavorable market conditions (Lynd 2017; Dale 2018).

Because the timing of demand growth is unknown, this report presents an assessment of biomass potential—rather than a specific forecast of future production—contingent on increasing industrial demand to provide market pull and support supply chain development. The current report also deemphasizes time relative to previous ones (see Table 1.1). BT23 modeling considers some practical limitations on deployment rates and sector dynamics (e.g., stover harvest equipment adoption) but lacks other potentially important effects such as germplasm scale-up and how rates of adoption of novel energy crops might be limited by landowner risk preference and information diffusion. For example, surveys suggest that only a fraction of farmers are currently interested in producing novel energy crops, and many would only do so if the energy crops offered a substantial net revenue premium over current practices (Fewell, Bergtold, and Williams 2011; Skevas et al. 2016; Swinton et al. 2017), though these adoption dynamics are not accounted for in the current POLYSYS modeling. Future assessment efforts could attempt to incorporate some of these limitations and produce deployment projections, potentially drawing from or harmonizing with systems dynamics models such as the Biomass Scenario Model (Vimmerstedt et al. 2023).

8.1.2 Modeling Energy Crops on Marginal Land

Because dedicated energy crops make up such a large fraction of the total biomass resource, it is important to examine where within existing agricultural landscapes they might most realistically and beneficially be grown. This report models such production in competition with conventional agriculture (both row crops and grazing lands) at the county scale. The underlying PRISM-EM dataset of energy crop yields is responsive to broad environmental gradients based on climate and soil properties (Lee et al. 2018). This assessment finds that most energy crop production will likely occur outside of intensive row cropping areas such as the Corn Belt, and instead in areas of less favorable climate for conventional crops such as the southern Great Plains (Figure ES-4). In contrast, other assessment studies restrict energy crop production to areas of marginal, degraded, or abandoned land within existing agricultural landscapes, for sustainability concerns (Khanna et al. 2021; Field et al. 2023). DOE has funded large research efforts to assess and improve the performance of energy crops on such marginal lands (Gelfand et al. 2013; Peters 2018). This is complicated by multiple competing definitions for marginal land, resulting in different regional patterns (Khanna et al. 2021) and uncertain yield performance on these lands (Searle and Malins 2014).

Future billion-ton assessment efforts could consider extending POLYSYS for subcounty-scale modeling that competes energy crops with conventional crops across both prime and marginal land within existing agricultural landscapes—e.g., representing integrated landscape management (Nair et al. 2017). A variety of remote sensing studies have identified significant subfield areas that frequently lose money under conventional crops and tend to have disproportionately poor nutrient use efficiency (Brandes et al. 2018; Brandes, Plastina, and Heaton 2018). Such modeling would need to quantify sensitivity of both conventional and energy crop yields to land quality, possibly using data from the National Commodity Crop Productivity Index (Wightman et al. 2015) or remote sensing (Basso et al. 2019).

8.1.3 Biomass Production in a Changing Climate

Climate change will affect the productivity of dedicated energy crops, thus introducing a feedback where the timing of bioenergy deployment might influence its efficacy (Wagner and Schlenker 2022). BT16 Volume 2 explored how shifts in annual average temperature ranges and precipitation totals might affect energy crop yields using PRISM-EM (DOE 2017). It identified potential regionally important shifts in energy crop ranges, but only modest effects on total biomass productivity at national scale. Energy crop yields are also affected by sub-annual extreme temperature and precipitation anomalies and increased CO_2 concentrations (Jagermeyr et al. 2021), and the latter might lead to significant yield benefits for energy crops utilizing the C3 photosynthetic pathway (Gernaat et al. 2021). Perhaps even more significantly, future climate change is likely to affect conventional crop yields and ranges, which in turn influences the amount of land available for energy crops. There is already evidence that climate change is reducing the rate of yield increases (Ortiz-Bobea et al. 2021) and shifting optimal crop cultivation ranges globally (Sloat et al. 2020), creating both challenges and opportunities for bioenergy and other land-based mitigation measures (Thornton et al. 2023).

Future feedstock modeling efforts should ideally attempt to capture climate effects on agricultural land use, bioenergy crop yields, and alternative land-based mitigation measures in a self-consistent manner. The Agricultural Model Intercomparison Project has assembled an ensemble of process-based crop models driven by downscaled climate projections to robustly simulate conventional crop performance under future temperature and precipitation extremes and CO_2 levels (Jagermeyr et al. 2021). Such data could be leveraged to explore the range of possible land use futures for conventional crops, and how that affects land availability for energy cropping. Alternately, Earth system models can provide a more holistic representation of land–climate interactions, including soil carbon storage and other GHG emissions for both croplands and natural land cover, thus better capturing LUC impacts and potential trade-offs between bioenergy and natural climate solutions (Field et al. 2020; Melnikova et al. 2023). Earth system models have typically featured only limited differentiation of food and energy crops (e.g., Melnikova et al. 2021, 2023), though there are now methods available to better capture the climatic ranges of individual important crops (Xu et al. 2022). An ideal approach would seek to combine the granular approach to crop–environment modeling in the existing billion-ton workflow with these state-of-the-art agricultural and Earth system modeling tools.

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Glossary of Key Terms

***2005 Billion-Ton Study* (BTS)** – *Biomass as a Feedstock for Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion Ton Annual Supply* is the first of the billion-ton reports; a national-level, strategic assessment of the potential biophysical availability of biomass. It identified more than 1 billion tons of biomass resources in the United States from agricultural land and forestland.

2011 *U.S. Billion-Ton Update* (BT2) – *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry* is the second of the billion-ton reports. It expanded and updated analyses of the *2005 Billion-Ton Study* to provide a more comprehensive assessment of U.S. biomass resources and evaluated the potential economic availability of biomass feedstocks under a range of offered prices and yield scenarios between 2012 and 2030.

***2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy* (BT16)** – The third of the billion-ton reports, providing the most recent estimates before the present report of potential biomass that could be available for biorefining. Volume 1 focuses on biomass potentially available at specified prices, and Volume 2 on changes in environmental sustainability indicators associated with select production scenarios in Volume 1.

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.

agricultural land – Cropland and pastureland as specified by the USDA National Agricultural Statistics Service.

agricultural residues – Unharvested portion of crops.

AgSTAR – A collaborative program sponsored by the EPA and USDA to promote biogas recovery systems to reduce methane emissions from livestock waste.

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.

animal fats – Tallow, choice white grease, and poultry fat.

bio-based product – As defined by the Farm Security and Rural Investment Act of 2002, 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, 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.

bioenergy – A form of renewable energy that is derived from biomass.

bioenergy equivalent – Conversion estimate for the quantity of raw biomass to an energy product, assuming a particular heating content and thermal conversion efficiency.

Bioenergy Knowledge Discovery Framework (Bioenergy KDF) – Online collection of bioenergy-related research, datasets, applications, and maps for bioenergy researchers, policymakers, and industry, including the billion-ton report interactive data and visualizations.

biofuel – Fuel made from biomass resources or their processing and conversion derivatives. Biofuels include ethanol, biodiesel, and methanol.

biogas – Gas generated from the decomposition of organic material, which is composed of approximately 50% methane and 50% carbon dioxide.

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 Assessment Tool (BAT) – A resource assessment and partial techno-economic modeling system comprising numerous modules that combine multiscale spatiotemporal modeling, biophysical modeling, and resource demand and availability using the best available climate, water, land, and infrastructure data, along with environmental constraints, biomass growth parameterization, and more.

biomass resource analysis – The quantification of a supply of biomass that can be used to generate biofuel or biopower under specified conditions (e.g., availability of land, water, and fertilizer; spatial resolution and extent; time frame).

biopower – The use of biomass feedstock to produce electric power or heat through direct combustion of the feedstock, gasification and then combustion of the resultant gas, or 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, intermediates). The biorefinery concept is analogous to a petroleum refinery, which produces a slate of multiple fuels, intermediates, and products from a petroleum feedstock.

Bioregional Inventory Originated Simulation Under Management (BioSum) – Provides simulation-based analytical tools that leverage data from FIA—the nation's forest census—to predict and statistically summarize the consequences of forest management strategies over multimillion-acre forested landscapes. Management strategies can be multiobjective, vary among owner groups, evolve over time, and be contingent on targeted sets of specific site and vegetation attributes.

black liquor – Solution of lignin residue and the pulping chemicals used to extract lignin during the manufacture of paper.

British thermal unit (Btu) – 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°F to 40°F.

construction and demolition (C&D) 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.

chip-n-saw – Similar to fuelwood trees, but these trees are converted to two products by one machine: the outside of the log is chipped, and the rest is sawn into lumber. Chip-n-saw trees are the smallest or lowest-quality conifer sawtimber trees. Logs harvested as chip-n-saw must produce lumber or timbers, but a significant proportion of the volume is chipped for pulp production.

Class 1 timber – Timber greater than 11-inch DBH.

Class 2 timber – Timber 5–11-inch DBH.

Class 3 timber – Timber less than 5-inch DBH.

Component Ratio Method – A method introduced in 2009 used to estimate non-merchantable volumes from merchantable trees by the USFS using species-specific volume and biomass estimation equations.

Composite Resistance Score – Composed of four subscores (0–3) to get a score of 0–12 (with lower scores being better) of crown base height, crown bulk density, predicted volumetric tree mortality under a 6–8-foot flame length surface fire, and proportion of fire-resistant species comprising the stand basal area.

Conservation Reserve Program (CRP) – A land conservation program administered by the Farm Service Agency 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.

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.

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.

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."

current bioenergy, agriculture – The portion of current U.S. bioenergy derived from agricultural lands (e.g., corn to ethanol, soybeans to biodiesel).

current bioenergy, forestry – The portion of current U.S. bioenergy derived from timberlands (e.g., timber processing wastes to power, forest residues to pellets).

current bioenergy, waste – The portion of current U.S. bioenergy derived from wastes (e.g., landfill gas).

delivered cost – An estimate of all costs—including production, harvest, storage, handling, preprocessing, and transportation—to deliver biomass feedstocks to the reactor throat.

dried distillers grains – A byproduct of the corn ethanol industry typically used as a protein-rich animal feed. For local markets, distillers grains are sold in wet form. For longer distances, they are dried to about 10% moisture to reduce weight.

dry ton – Material weight without moisture

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.

feedstock – A product used as the basis for manufacture of another product.

fiber products – Products derived from fibers of herbaceous and woody plant materials. Examples include pulp, composition board products, and wood chips for export.

Forest Inventory and Analysis (FIA) – A congressionally mandated program that delivers current, consistent, and credible information about the status of forests and forest resources within the United States by continually collecting and analyzing data about these forests and the values they provide.

Forest Resource Outlook Model (FOROM) – A global recursive dynamic partial equilibrium model of the forest sector that recognizes RPA assessment regions as separate producing, consuming, and trading market regions within a complete global market.

Forest Sustainable and Economic Analysis Model (ForSEAM) – A linear program that solves for county-level woody biomass availability from timberland. It accounts for county-level timber stand age class distribution, growth and yield, stumpage prices, and harvest costs. The model includes sustainability constraints according to stand type, slope, and proximity to roads.

Forest Vegetation Simulator (FVS) – A distant independent, individual tree growth and yield model designed to project forest stands through time under management, with the capacity to simulate the effects of very detailed silvicultural prescriptions on future stand conditions and outputs of harvested wood.

forestland – Defined by the USDA as 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. Includes timberland.

Fuel Reduction Cost Simulator (FRCS) – A forest harvesting costing model utilized in this report to estimate the cost of harvesting small-diameter trees for biomass. **fuelwood –** Wood harvested for energy production for industrial or domestic applications and that is often sourced from small-diameter roundwood, branches, or residues and from wood of any size sourced from lower-value or lower-quality species.

Global MacroAlgae Cultivation MODeling System (G-MACMODS) – Integrates a tested regional ocean model (with an integrated biogeochemical model) with a fine-scale hydrodynamic model, capable of resolving turbulent fluxes at sub-meter resolution, and a macroalgal growth model that includes the influence of hydrodynamics in the uptake of nutrients.

glycerin – Also known as glycerol, a nontoxic, colorless, and odorless liquid used in a wide variety of applications (e.g., food, pharmaceuticals, cosmetics). Glycerin is a byproduct of soap and biodiesel production, with the latter being most common today.

greenhouse gas (GHG) – 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 GHGs in the Earth's atmosphere.

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-inch DBH and larger.

hardwood species – A category of tree species (angiosperm) that have broad leaves and true flowers with the seed being enclosed.

harvest index – For conventional crops, the ratio of residue to grain.

high scenario (agriculture)– Mature market (simulated as 18 years after 2023), 3% per year dedicated biomass yield improvements, conventional crop yields improve 1.5 times the USDA trend, harvest technology improves from 50% to 90% efficiency. See scenario specifications in Table 1.2.

higher heating value (HHV) – The amount of heat released from a material that is heated from 25°C to vaporization and returned to 25°C. This includes the latent heat of vaporization of water.

idle land – A land class defined as cropland used for cover crops or soil improvement, but not harvested, pastured, or grazed.

industrial wood – All commercial roundwood products except fuelwood.

intermediate crops – Any crop that is planted and harvested between two main crops.

irrigated pasture – Any pastureland that falls under the "irrigated land" land class defined by the USDA.

land use change (LUC) – Any change in land use, defined by the Intergovernmental Panel on Climate Change as "the total of arrangements, activities and inputs applied to a parcel of land."

logging residues – The unused portions of growing-stock and non-growing-stock trees cut or killed by logging and left in the woods.

low scenario (agriculture) – Mature market (simulated as 18 years after 2023), no dedicated biomass crop yield improvements, conventional crop yield improvements assume the USDA baseline, no harvest technology improvements. See scenario specifications in Table 1.2.

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).

marginal lands – Use of this term varies with context. Resource analysis in this report does not target marginal land per se, but rather simulates optimal allocation based on inputs such as yield, which is a component of defining marginal lands. Can be generally defined as lands that are less than optimal from a production perspective (see Csikós, Nándor, and Gergely Tóth. 2023. "Concepts of agricultural marginal lands and their utilisation: A review." *Agricultural Systems* 204: 103560. doi.org/10.1016/j.agsy.2022.103560).

mature-market scenario – Simulated future market scenarios as specified in Table 1.2.

medium scenario (agriculture) – Mature market (simulated as 18 years after 2023), 1% per year dedicated biomass yield improvements, conventional crop yield improvements assume USDA baseline, harvest technology improves from 50% to 90% efficiency. See scenario specifications in Table 1.2.

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.

municipal solid waste (MSW) – Wastes (garbage) collected from municipalities consisting mainly of yard trimmings and paper products.

near-term scenario (agriculture) – 7 years after 2023, only crop residues. See scenario specifications in Table 1.2.

non-forestland – Land that has never supported forests and lands formerly forested where use of timber management is precluded by development for other uses. Non-forestland includes areas 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 U.S. Census Bureau as land. If intermingled in forest areas, unimproved roads and non-forest strips must be more than 120 feet wide, and clearings, must be more than 1 acre in area to qualify as non-forestland.

oilseed crops – Crops primarily produced for lipid production (e.g., pennycress).

other forestland – Forestland other than timberland and reserved forestland. It includes available forestland that 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, silvicultural operations such as precommercial thinnings, or 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 forestland.

other solid waste – Mixed MSW other than paper or plastic waste.

other wet waste – Wet wastes (e.g., sludge and manures) other than FOG.

pastureland – Land that is primarily used for livestock production.

perennial – A plant that lives for more than 1 year.

permanent pastureland, 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."

plastic waste – Any discarded plastic (organic, or synthetic, material derived from polymers, resins, or cellulose) generated by any industrial process, or by consumers (source: United Nations Environmental Programme)**.**

Policy Analysis System Model (POLYSYS) – A linear program partial equilibrium model that simulates the U.S. agriculture sector. With national inputs on projected demands for food, feed, fiber, and exports, and county-level inputs on starting cropland acres, pastureland acres, potential crop yields, and crop production budgets, the model solves for the most profitable allocation of land from the landowners' perspective.

primary agricultural resources – Resources included within this category include energy crops (annual energy crops, coppice and non-coppice woody crops, and perennial grasses), crop residues (barley straw, corn stover, oat straw, sorghum stubble, and wheat straw), and conventional crops (barley, corn, cotton, hay, oats, rice, sorghum, soybeans, and wheat).

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.

pulpwood – Trees that are harvested specifically for pulp production (e.g., for paper).

purpose-grown energy crops – In the context of this report, any crop produced for the primary purpose of energy (fuels or power) and coproducts: switchgrass, miscanthus, biomass sorghum, energy case, willow, poplar, pine, microalgae, or macroalgae.

renewable identification numbers (RINs)-gallon – The back-calculated volume of fuel that generated the document RINs.

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 that the generation of renewable fuels can also produce valuable biomass-based products or chemicals.

Renewable Fuel Standard (RFS) – 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 (sometimes referred to as RFS1) was expanded upon (RFS2) by the Energy Independence and Security Act of 2007 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 GHG requirements (less than fossil fuels they replace) for renewable fuels.

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.

resource class (resource analysis class) – One of the resource analysis classes as presented in this report (i.e., currently used for energy and byproducts): forestland/timberland resources; agricultural land resources; and microalgae, macroalgae, and CO_2.

resource subclass (resource analysis subclass) – One of the groupings of biomass resources within the resource analysis classes (e.g., subclasses of agricultural residues, woody energy crops, herbaceous energy crops, and agricultural processing wastes within the agricultural land resources analysis class).

Resources Planning Act (RPA) – 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.

Revised Universal Soil Loss Equation (RUSLE2) – A computer program that estimates erosion and sediment delivery for conservation planning in crop production.

roundwood products – Logs and other round timber generated from harvesting trees for industrial or consumer use.

sawtimber – Trees of a larger size and higher quality from commercial species, with at least one 12-foot saw log or two noncontiguous saw logs, each at least 8 feet long.

shadow price – An estimated monetary value for biomass that is not typically bought or sold in a marketplace.

small-diameter trees – In the context of this report, a tree less than 11" DBH.

softwood species – Conifers and gymnosperms, meaning they are evergreen trees that do not shed their leaves.

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 (i.e., price for the right to harvest).

Subregional Timber Supply (SRTS) – An empirical bioeconomic model of timber supply based on detailed FIA data. From these data, we can extract forest inventory, removals, and biological factors for custom subregions that are important to a model client. The flexibility of regional scope makes SRTS applicable to analyzing a variety of problems, from broader policy and sustainability questions to analysis of a small timber basin. The maximum regional extent of the model is the Southern U.S. region.

sustainability – An aspirational concept denoting the capacity to meet current needs while maintaining options for future generations to meet their needs.

thinnings (other forestland treatment thinnings) – The practice of reducing the number of plants in an area or 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 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.

Timber Product Output (TPO) – 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 RPA Assessment. This set of national TPO data consists of 11 data variables that describe for each county the roundwood products harvested, logging residues left behind, timber otherwise removed, and wood and bark residues generated by its primary wood-using mills.

timberland – Forestland that is producing or 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.

urban wood wastes – Wastes coming from MSW and 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.

waste grease – Used cooking oil and trap grease.

wet ton – No moisture removed from the material.

yield – The volume of feedstock on a designated land unit at a specific point in time.

Terrestrial Energy Crop Species Modeled

biomass sorghum – *Sorghum bicolor* (L.) Moench

camelina – *Camelina sativa*

carinata – *Brassica carinata*

energy cane – *Saccharum* spp.

eucalyptus – *Eucalyptus* spp.

miscanthus – *Miscanthus × giganteus*

pennycress – *Thlapsi arvense* L.

pine – *Pinus* spp., typically *Pinus taeda* or *Pinus echinata*

poplar – *Populus* spp.

switchgrass – *Panicum virgatum*

willow – *Salix* spp.

Classes, Subclasses, and Resources in the 2023 Billion-Ton Report

Table 1. Analysis classes, subclasses, and resources.

Class	Subclass	Chapter	Resource
Currently Used for Energy	Agricultural	2	Current - Agricultural
	Forestry/Wood	2	Current - Forestry/Wood
	Municipal solid waste/other wastes	2	Current - MSW/Other Wastes
Wastes	Fats, oils, and greases	3	FOG, animal fats
	Fats, oils, and greases	3	FOG, brown grease
	Fats, oils, and greases	3	FOG, yellow grease
	Gaseous resources	3	Landfill gas
	Other solid waste	3	Rubber and leather
	Other solid waste	3	Textiles
	Other solid waste	3	Urban wood, clean
	Other solid waste	3	Yard waste
	Other wet waste	3	Food waste, nonresidential
	Other wet waste	3	Food waste, residential
	Other wet waste	3	Manure, beef
	Other wet waste	3	Manure, dairy
	Other wet waste	3	Manure, swine
	Other wet waste	3	Sludge
	Paper	3	Paper and paperboard
	Plastic	3	Plastics
Forestland	Forest processing waste	4	Hardwood processing residues
	Forest processing waste	4	Softwood processing residues
	Logging residues	4	Hardwood lowland logging residues
	Logging residues	4	Hardwood upland logging residues
	Logging residues	4	Mixed wood logging residues
	Logging residues	4	Softwood natural logging residues
	Logging residues	4	Softwood planted logging residues
	Other forest waste	4	Forest waste human generated
	Small-diameter trees	4	Hardwood lowland small-diameter trees
	Small-diameter trees	4	Hardwood upland small-diameter trees

Class	Subclass	Chapter	Resource
	Small-diameter trees	4	Mixed wood small-diameter trees
	Small-diameter trees	4	Softwood natural small-diameter trees
	Small-diameter trees	4	Softwood planted small-diameter trees
Agriculture	Agricultural processing waste	5	Pruning residues, citrus
	Agricultural processing waste	5	Pruning residues, non-citrus
	Agricultural processing waste	5	Pruning residues, tree nuts
	Agricultural residues	5	Barley straw
	Agricultural residues	5	Corn stover
	Agricultural residues	5	Cotton field residues
	Agricultural residues	5	Oats straw
	Agricultural residues	5	Rice straw
	Agricultural residues	5	Sorghum stubble
	Agricultural residues	5	Wheat straw
Agriculture	Energy crops, herbaceous	5	Biomass sorghum
	Energy crops, herbaceous	5	Energy cane
	Energy crops, herbaceous	5	Miscanthus
	Energy crops, herbaceous	5	Switchgrass
	Energy crops, woody	5	Eucalyptus
	Energy crops, woody	5	Pine
	Energy crops, woody	5	Poplar
	Energy crops, woody	5	Willow
	Intermediate oilseeds	5	Camelina
	Intermediate oilseeds	5	Carinata
	Intermediate oilseeds	5	Pennycress
Microalgae	Microalgae	7	Microalgae
Macroalgae	Macroalgae	7	Macroalgae
Carbon Dioxide	Carbon Dioxide	7	Carbon dioxide, total point-source emissions
Carbon Dioxide	Carbon Dioxide	7	Carbon dioxide, high-purity point-source emissions

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BIOENERGY TECHNOLOGIES OFFICE

For more information, visit: energy.gov/eere/2023-billion-ton-report

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