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

Chapter 01 | Background and Introduction

Table of Contents

1 Background and Introduction

Matthew H. Langholtz

Oak Ridge National Laboratory

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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.

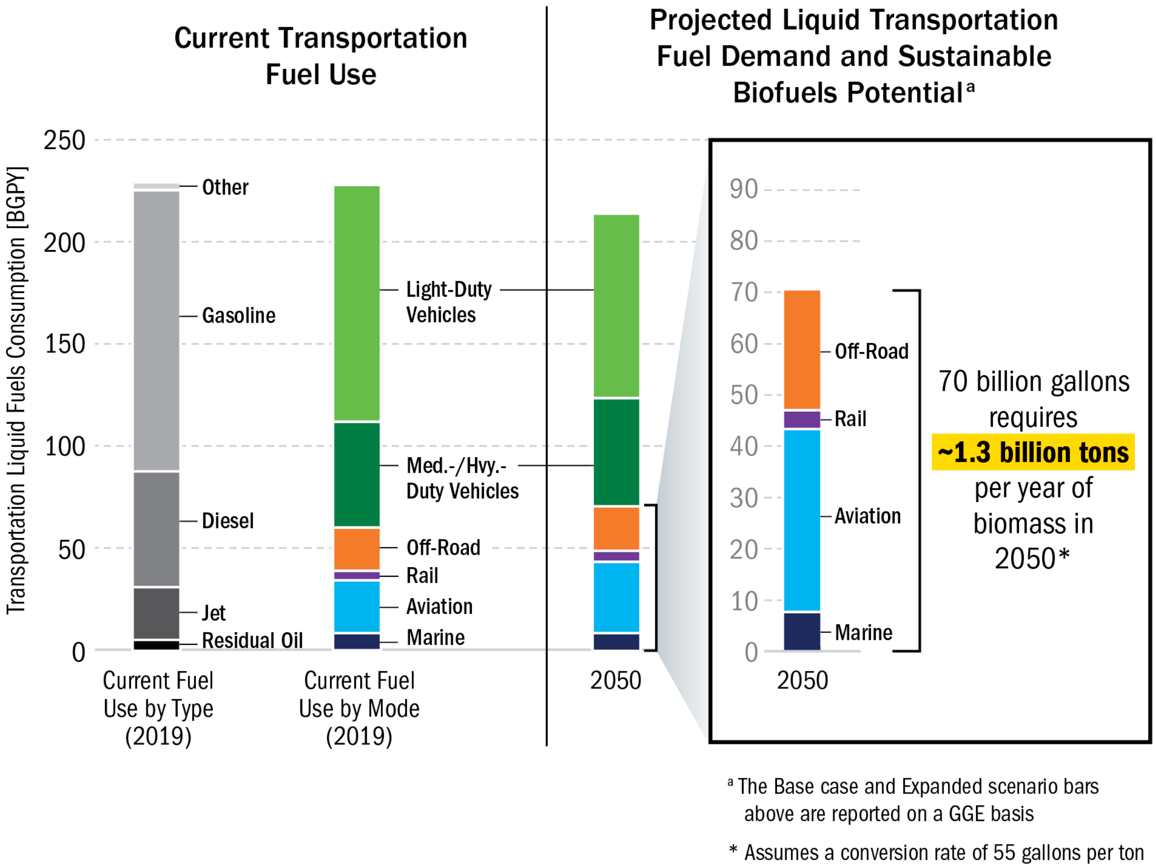

Figure 1.1. Current and projected liquid transportation fuel demand and sustainable biofuel supply.

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.

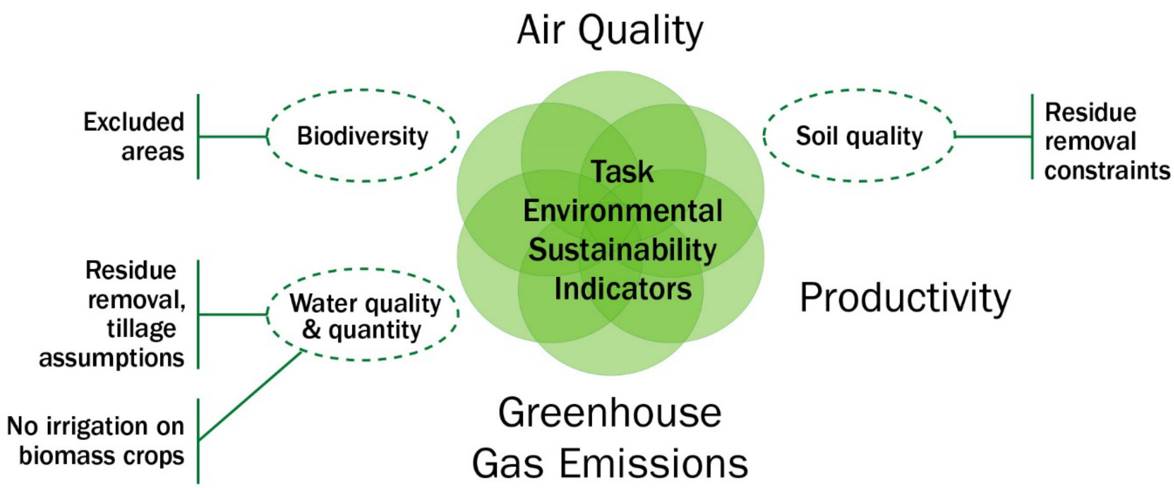

Figure 1.2. Sustainability constraints and sustainability indicator categories (green dashed circles) implemented in this report

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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