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

Chapter 04 | Biomass from the Forested Land Base

Table of Contents

4 Biomass from the Forested Land Base

Maggie Davis,[1] Lixia Lambert,[2] Ryan Jacobson,[1] David Rossi,[3] Consuelo Brandeis,[4] Jeremy Fried,[4] Burton English,[5] Robert Abt,[3] Karen Abt,[4] Prakash Nepal,[4] Claire O'Dea,[4] Jeffrey Prestemon,[4] and Matthew Langholtz[1]

[1] Oak Ridge National Laboratory

[2] Oklahoma State University

[3] North Carolina State University

[4] United States Department of Agriculture Forest Service (USDA-FS)

[5] University of Tennessee (retired)

Suggested citation: Davis, M., L. Lambert, R. Jacobson, D. Rossi, C. Brandeis, J. Fried, B. English, et al. 2024. "Chapter 4: Biomass from the Forested Land Base." In *2023 Billion-Ton Report.* M. H. Langholtz (Lead). Oak Ridge, TN: Oak Ridge National Laboratory. doi: 10.23720/BT2023/2316170.

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

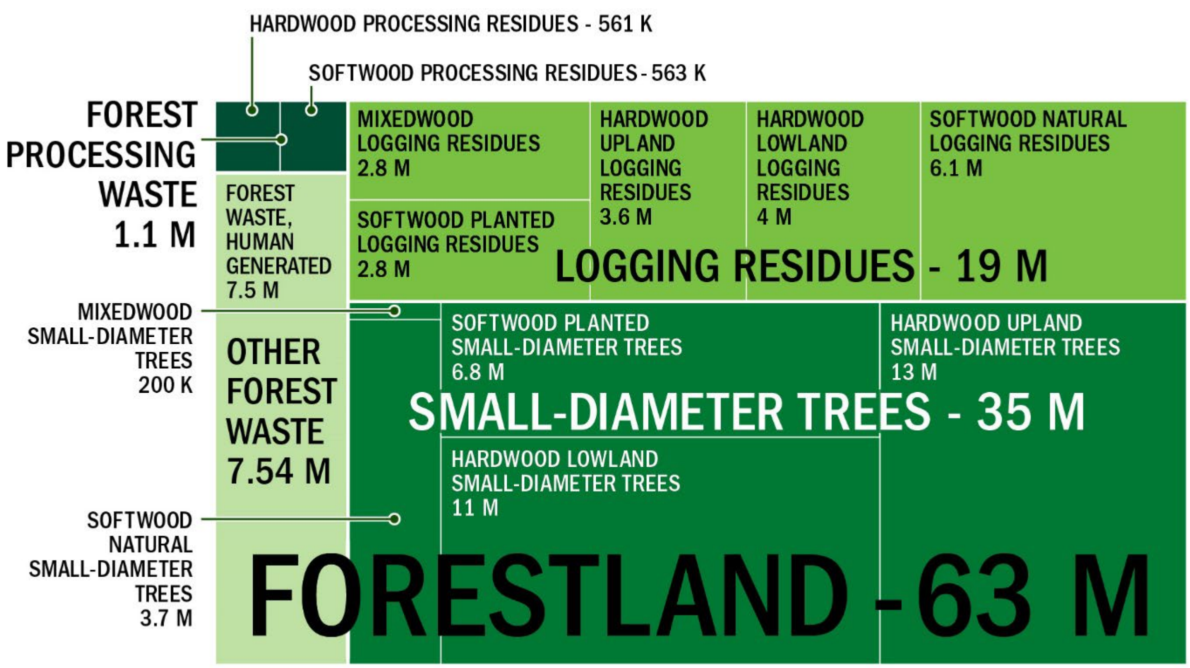

Figure 4.1. National resources from forested lands, mature-market medium scenario at a shadow price of up to $40 per dry ton for logging residues and up to $70.1 per dry ton for small-diameter trees

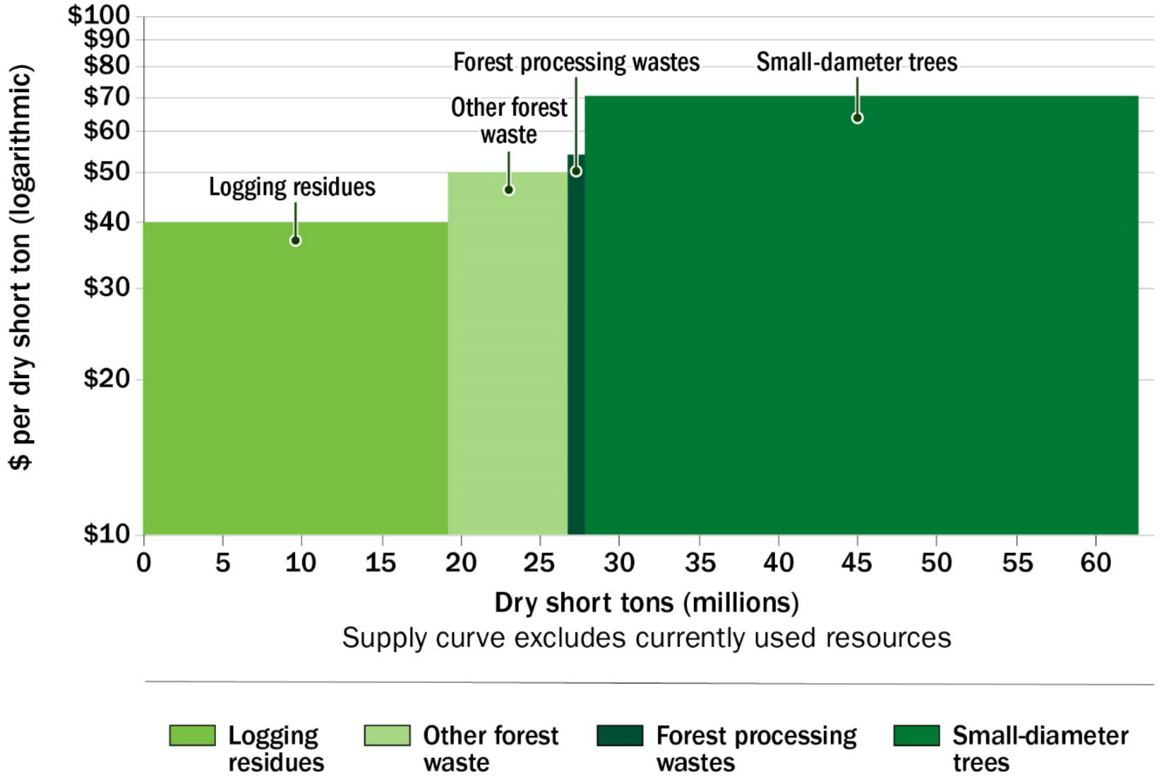

Figure 4.2. Stepwise supply curve of resources from forested lands, mature-market medium scenario

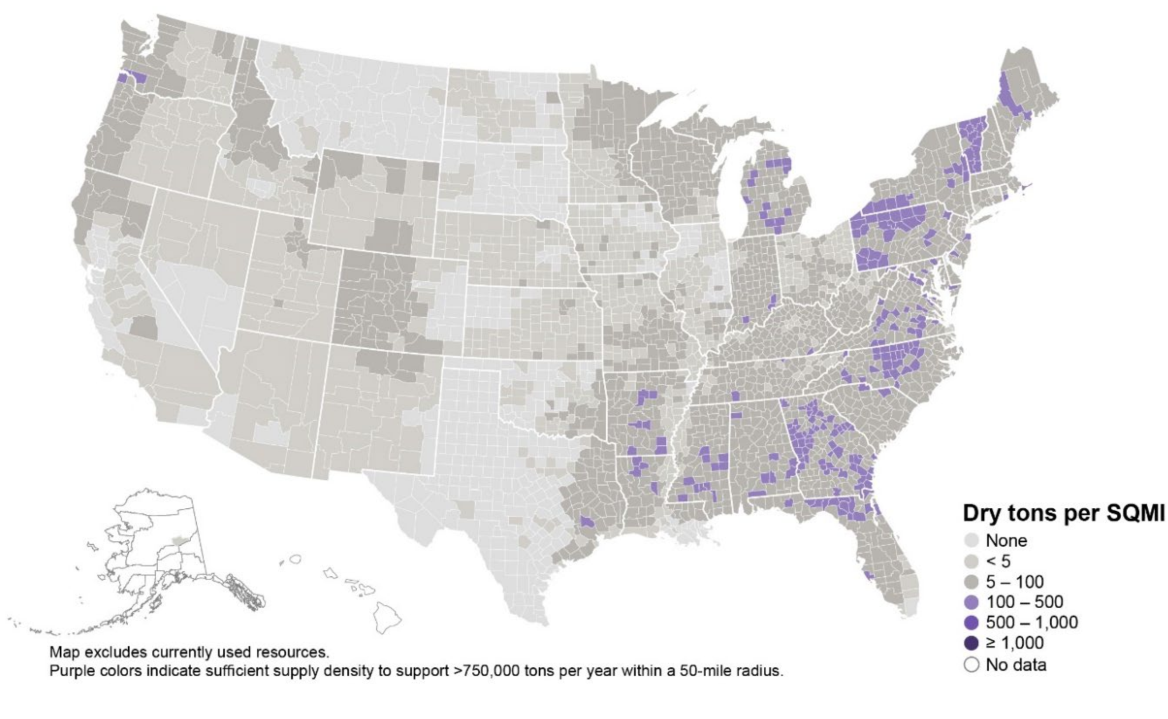

Figure 4.3. Spatial distribution of resources from the forested land base, mature-market medium scenario

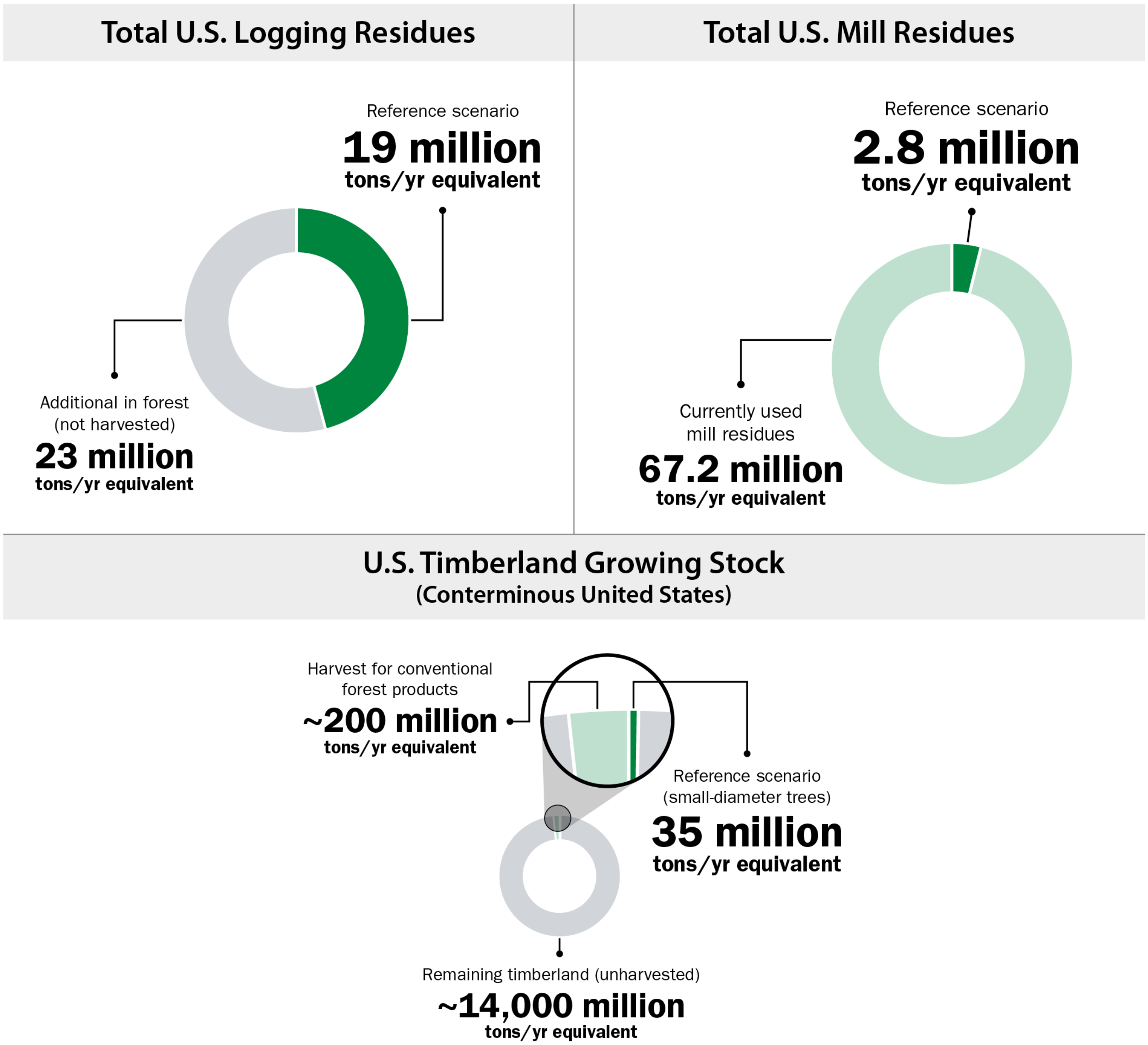

Figure 4.4. Logging residues reported as available in mature-market medium scenario at up to $40 per dry ton in proportion to total residues in forest, not harvested; small-diameter trees and conventional forest products harvest annually in proportion to timberland left unharvested annually; and forest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

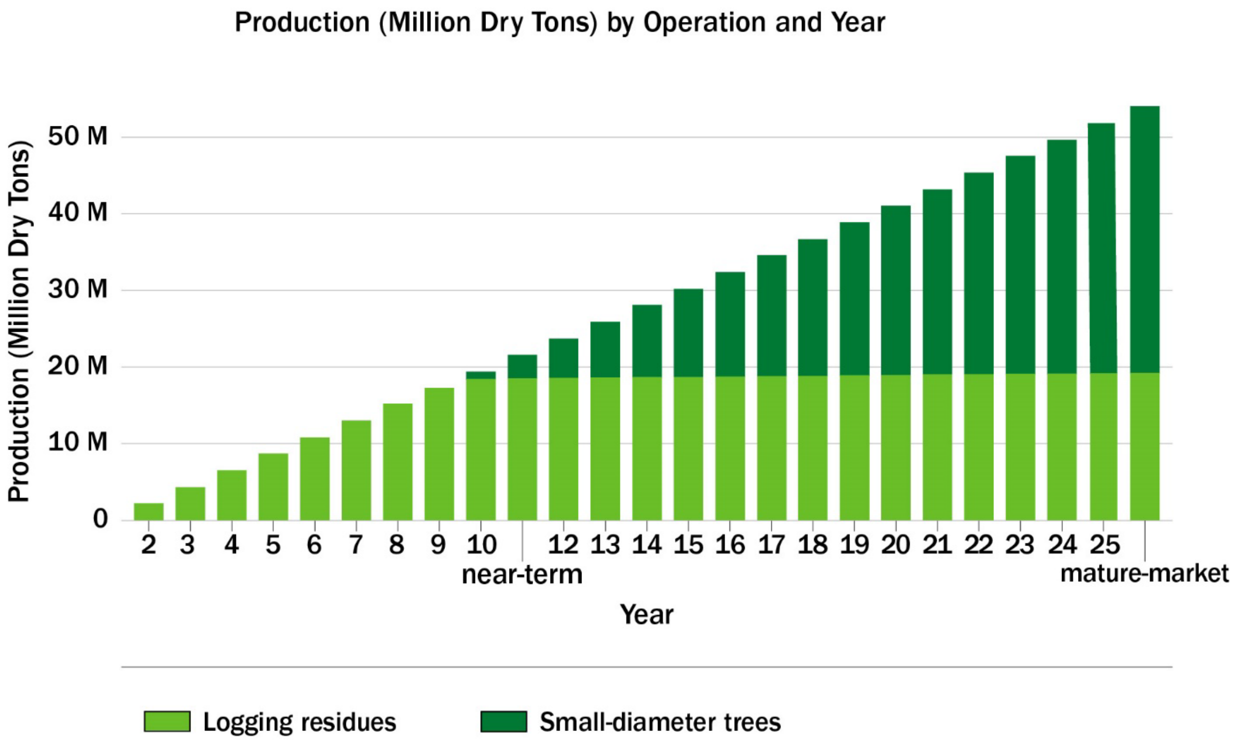

Figure 4.5. Production (million dry tons) by operation and year of the analysis, including highlighted near-term and mature-market scenarios. Biomass production trajectory used in this this analysis adds incremental biomass demand, beginning in Year 2 of the simulation at less than 5 million dry tons 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.

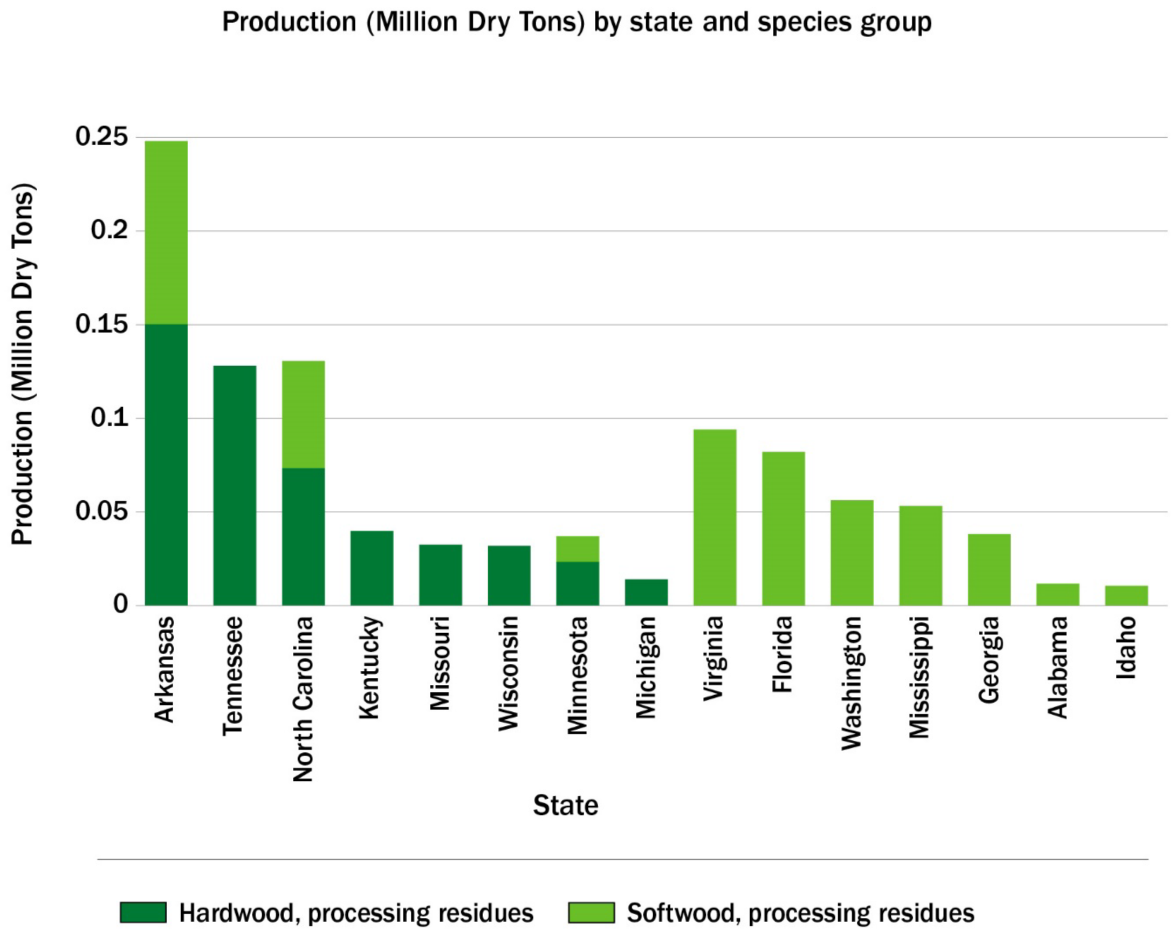

Figure 4.6. States producing more than 10,000 dry tons per year of mill residues that are left unused. Mill residues that are left unutilized total 1.1 million dry tons annually, with a concentration of residues unused in the South, with growth expected in softwood (e.g., pine) sawmills. Additional growth 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).

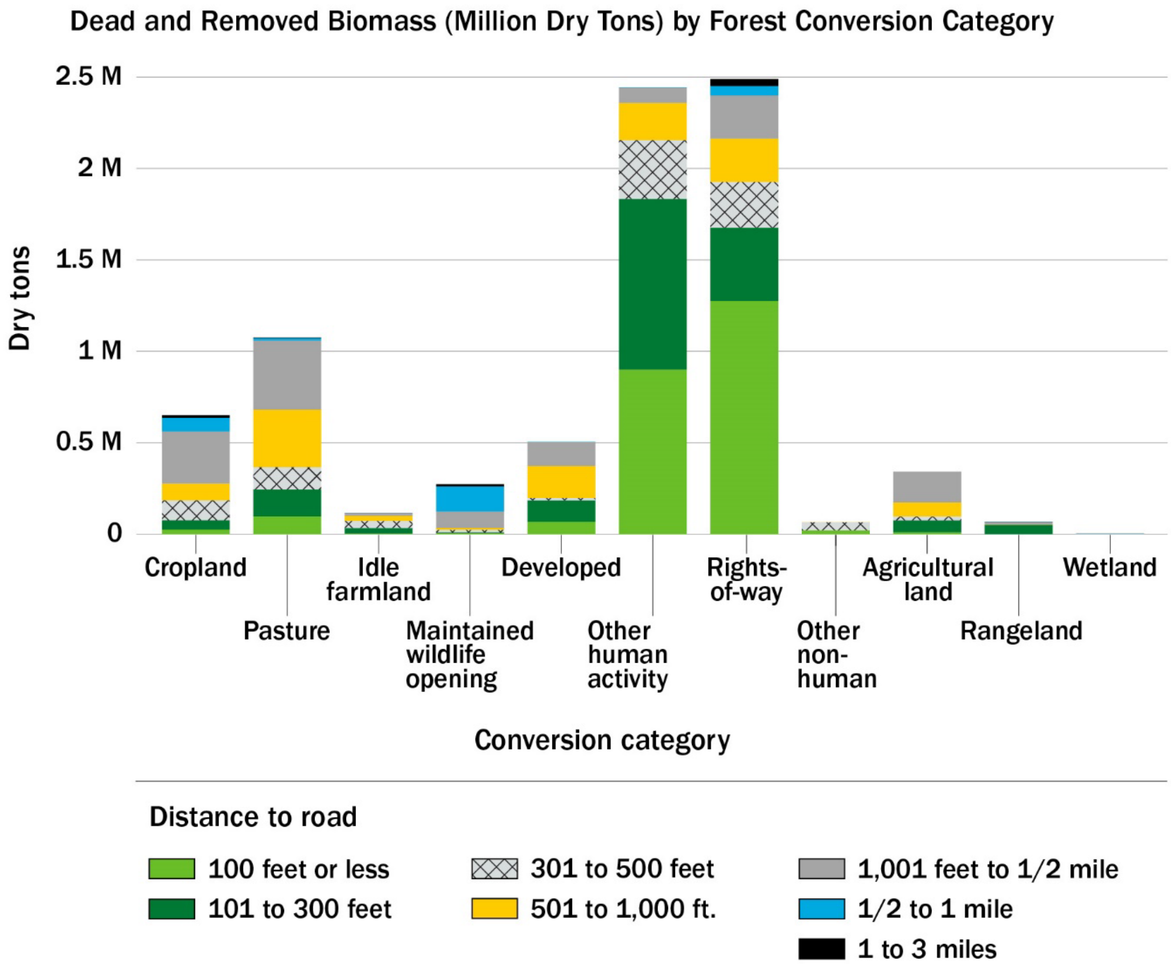

Figure 4.7. Potential forest waste from land conversion to various non-forest uses that are potentially left unutilized totals 7.5 million dry tons annually. Haul distance is expected to limit availability of biomass beyond 3 miles to a road. A price similar to hog fuel of $50 per dry ton is assumed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

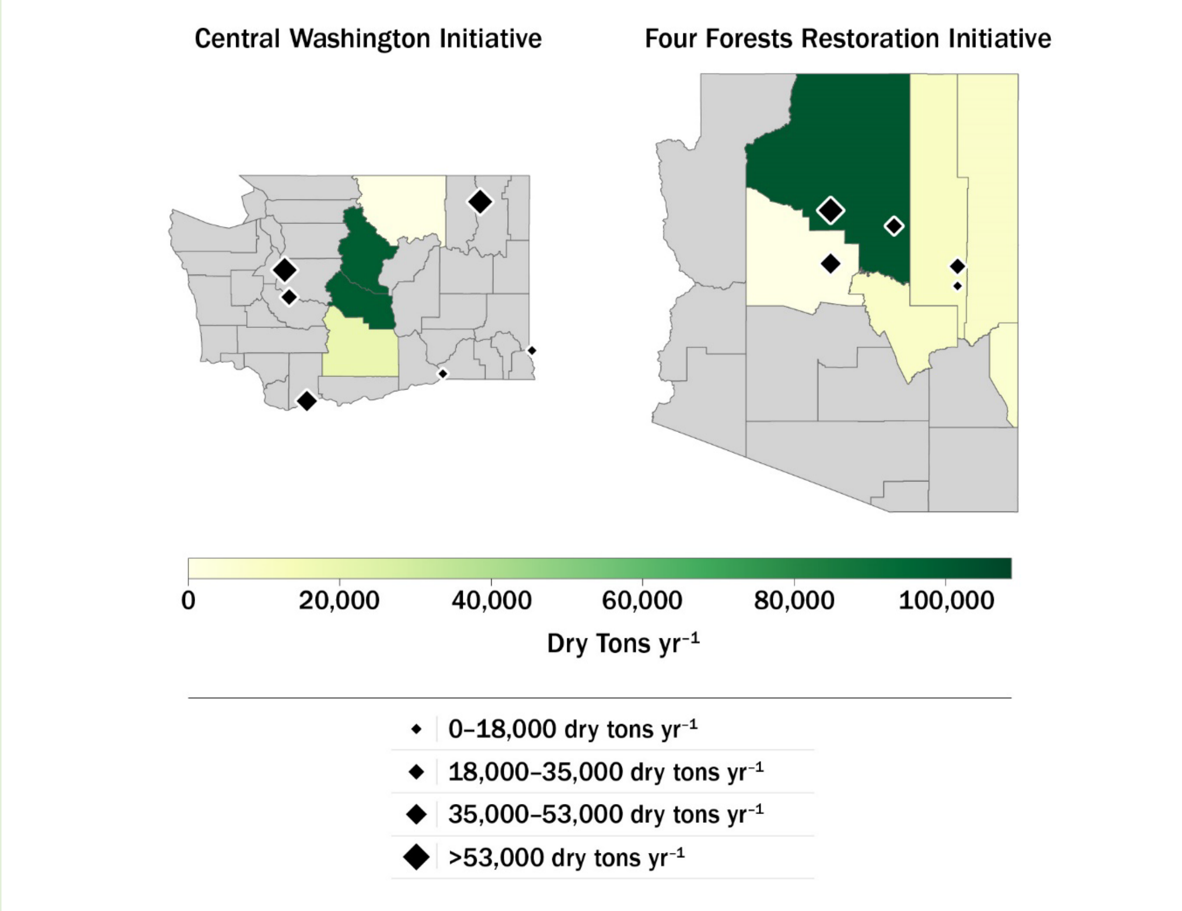

Figure 4.8. County-level woody biomass feedstock quantities produced, and facilities receiving those feedstocks (sized by quantity delivered), for the 0.13 million dry tons per year generated by the 4FRI PIL and the 0.3 million dry tons per year generated by the CWI PIL at a facility gate price payment 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.

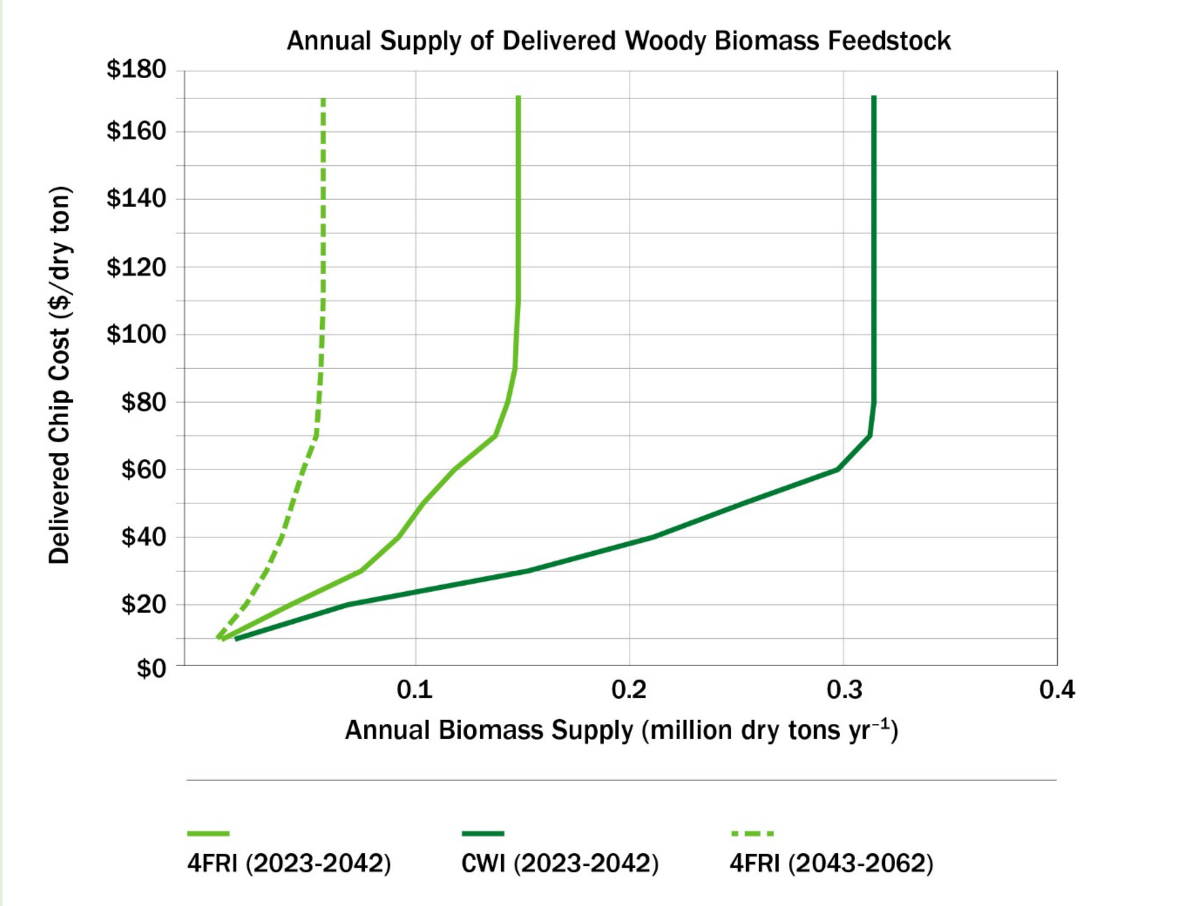

Figure 4.9. The 4FRI PIL's supply curve for woody biomass feedstock indicates considerably greater supply in both two-decade periods than the CWI PIL in 2023–2042. In both landscapes, prices over $70 generate very little additional feedstock, and prices above $110 per dry ton deliver no increase in additional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

References

Chudy, R., R. Abt, R. Jonsson, J. Prestemon, and F. Cubbage. 2013. "Modeling the Impacts of EU Bioenergy Demand on the Forest Sector of the Southeast U.S." *Journal of Energy and Power Engineering* 7: 1073–1081.

Ekström, Håkan. 2023. "US Woodchip Exports Up 40% Thanks to Growing Asian Demand." ResourceWise, May 16, 2023. resourcewise.com/forest-products-blog/us-woodchip-exports-up-40-thanks-to-growing-asian-demand.

Favero, Alice, Adam Daigneault, and Brent Sohngen. 2020. "Forests: Carbon sequestration, biomass energy, or both?" *Science Advances* 6 (13). doi.org/10.1126/sciadv.aay6792.

Food and Agriculture Organization of the United Nations. 2023. "Forestry Production and Trade." Accessed July 11, 2023. fao.org/faostat/en/#data/FO.

Fried, Jeremy S., Theresa B. Jain, Sara Loreno, Robert F. Keefe, and Conor K. Bell. 2017. "A framework for evaluating forest restoration alternatives and their outcomes, over time, to inform monitoring: Bioregional inventory originated simulation under management." *Proceedings of the 2017 Forest Vegetation Simulator (FVS) e-Conference*. fs.usda.gov/research/treesearch/55072.

Innovative Natural Resource Solutions. 2023. *McNeil Station Carbon Overview*. Portland, ME: Innovative Natural Resource Solutions. burlingtonelectric.com/wp-content/uploads/McNeil-Carbon-6.2023.pdf.

Lang, Amanda. 2022. "Sawmill Investment Update: Map of U.S. South Expansions." Forisk Blog, June 22, 2022. forisk.com/blog/2022/06/22/sawmill-investment-update-map-of-u-s-south-expansions/.

Mendell, Brooks. 2019. "Risk and Context in the Forest Industry: Lessons from Wood Pellets, Part I." Forisk Blog, March 12, 2019. forisk.com/blog/2019/03/12/risk-context-forest-industry-lessons-wood-pellets-part/.

North Carolina State University. 2023. "SubRegionalTimberSupply." GitHub. github.com/NCState-SOFAC/SubRegionalTimberSupply.

RISI. 2023. "North American Woodfiber & Biomass Markets: Understanding the Key Drivers of North American woodfiber and Biomass Markets." *Fastmarkets* 9 (4).

Stokes, Bryce J., Colin Ashmore, Cynthia L. Rawlins, and Donald L. Sirois. 1989. *Glossary of Terms Used in Timber Harvesting and Forest Engineering*. New Orleans, LA: USFS Southern Forest Experiment Station. SO-73. srs.fs.usda.gov/pubs/gtr/gtr_so073.pdf.

TimberMart-South. 2023. "Quarterly Market Bulletin – 3rd Quarter 2023." timbermart-south.com/pdf/3Q2023%20TMS%20Bulletin.pdf.

University of Tennessee. 2023. "Analysis Models." arec.tennessee.edu/research/beag/analysis-models/.

U.S. Department of Agriculture (USDA). 2022. "Global Agricultural Trade System (GATS)." Accessed Nov. 9, 2022. apps.fas.usda.gov/gats/default.aspx.

U.S. Department of Energy (DOE). 2016. *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks*. Washington, D.C.: DOE. ORNL/TM-2016/160. energy.gov/eere/bioenergy/articles/2016-billion-ton-report-advancing-domestic-resources-thriving-bioeconomy.

U.S. Energy Information Administration (EIA). 2023. "Monthly Densified Biomass Fuel Report." Accessed April 13, 2023. eia.gov/biofuels/biomass/

U.S. Forest Service (USFS). 2016. "FIA DataMart." apps.fs.usda.gov/fia/datamart/datamart.html.

———. 2022a. *Confronting the Wildfire Crisis: A Chronicle from the National Fire Plan to the Wildfire Crisis Strategy*. Washington, D.C.: USFS. FS-1187c. fs.usda.gov/sites/default/files/fs_media/fs_document/WCS-Chronicle.pdf.

——— 2022b. *Confronting the Wildfire Crisis: Initial Landscape Investments to Protect Communities and Improve Resilience in America's Forests*. Washington, D.C.: USFS. FS-1187d. fs.usda.gov/sites/default/files/WCS-Initial-Landscape-Investments.pdf.

——— 2022c. *Forest Atlas of the United States*. Washington, D.C.: USFS. FS-1172. fs.usda.gov/sites/default/files/fs_media/fs_document/Forest-Atlas-of-the-United-States.pdf.

———. 2023a. *Confronting the Wildfire Crisis: Expanding Efforts To Deliver on the Wildfire Crisis Strategy*. Washington, D.C.: USFS. FS-1187f. fs.usda.gov/sites/default/files/fs_media/fs_document/WCS-Second-Landscapes.pdf.

———. 2023b. "FIA BioSum." biosum.info/.

———. 2023c. "Forest Products." fs.usda.gov/research/forestproducts.

———. 2023d. *Future of America's Forests and Rangelands: Forest Service 2020 Resources Planning Act Assessment*. Washington, D.C.: USFS. GTR-WO-102. https://doi.org/10.2737/WO-GTR-102.

———. 2023e. "Timber Products Output Studies." fia.fs.usda.gov/program-features/tpo/.

———. 2023f. "United States Forests at a Glance." experience.arcgis.com/experience/82dcef460b1a470db0f8f4dd7cf6f9b7/.

Acknowledgments

Charles J. Barnett provided a customized FIA dataset for this analysis on behalf of the USFS Northern Research Station.

Research forester Dr. Demetrios Gatziolis of the USFS Pacific Northwest Research Station developed and executed a geoprocessing analysis that provided the haul cost data used to construct the supply curves in this report.

Research forester (retired) Dr. Terrie Jain of the USFS Rocky Mountain Research Station contributed significantly to the silvicultural prescription development and fire resistance modeling framework used for the CWI landscape under the BioSum-modeled case studies.

Thomas M. Schuler, USFS National Program Lead - Silviculture Research, supported this analysis through scoping guidance and supporting USFS assistance in dataset compilation and modeling.

Bibliography

Abt, K., R. Abt. C. Galik, and K. Skog. 2014. *Effect of Policies on Pellet Production and Forests in the U.S. South: A Technical Document Supporting the Forest Service Update of the 2010 RPA Assessment*. Asheville, NC: USFS Southern Research Station. General Technical Report SRS-202. srs.fs.usda.gov/pubs/gtr/gtr_srs202.pdf.

Abt, R., F. Cubbage, and K. Abt. 2009. "Projecting southern timber supply for multiple products by subregion." *Forest Products Journal* 59 (7/8): 7–16. srs.fs.usda.gov/pubs/ja/2009/ja_2009_abt_002.pdf.

Achat, David L., Simon Martel, Delphine Picart, Christophe Moisy, Laurent Augusto, Mark R. Bakker, and Denis Loustau. 2018. "Modelling the nutrient cost of biomass harvesting under different silvicultural and climate scenarios in production forests." *Forest Ecology and Management* 429: 642–653. doi.org/10.1016/j.foreco.2018.06.047.

Aguilar, F., A. Mirzaee, R. McGarvey, S. Shifley, and D. Burtaw. 2020. "Expansion of US wood pellet industry points to positive trends but the need for continued monitoring." *Scientific Reports* 10: 18607. doi.org/10.1038/s41598-020-75403-z.

Brandeis, C., and K. Abt. 2019. "Roundwood Use by Southern Pellet Mills: Findings from Timber Product Output Mill Surveys." *Journal of Forestry* 117 (5): 427–434. doi.org/10.1093/jofore/fvz042.

Clean Air Task Force. 2023. "Carbon Capture and the Inflation Reduction Act." Feb. 16, 2023. catf.us/resource/carbon-capture-inflation-reduction-act/.

Dixon, G. 2023. *Essential FVS: A user's guide to the Forest Vegetation Simulator*. Fort Collins, CO: USFS Forest Management Service Center. fs.usda.gov/fmsc/ftp/fvs/docs/gtr/EssentialFVS.pdf.

Drax. 2023. "Bioenergy with carbon capture, use and storage (BECCS) and negative emissions." Accessed April 14, 2023. drax.com/about-us/our-projects/bioenergy-carbon-capture-use-and-storage-beccs/.

Forisk Consulting. 2014. "Wood bioenergy US." Volume 6 (1). forisk.com/products/category/bioenergy-2/.

Forisk Consulting. 2021. "Forest Bioenergy US Free Summary." Forisk Research Quarterly: Q1 2021. forisk.com/resources/resources-from-forisk-wood-bioenergy-us-free-summary/.

Gray, J., J. Bentley, J. Cooper, and L. Cyprian. 2021. *Southern Pulpwood Production, 2019*. Asheville, NC: USFS Southern Research Station. Resource Bulletin SRS-230. srs.fs.usda.gov/pubs/rb/rb_srs230.pdf.

Hardie, I., P. Parks, P. Gottlieb, and D. Wear. 2000. "Responsiveness of Rural and Urban Land Uses to Land Rent Determinants in the U.S. South." *Land Economics* 78 (4): 659–673. doi.org/10.2307/3146958.

Henderson, J., O. Joshi, R. Parajuli, and W. Hubbard. 2017. "A regional assessment of wood resource sustainability and potential economic impact of the wood pellet market in the U.S. South." *Biomass and Bioenergy* 105: 421–427. doi.org/10.1016/j.biombioe.2017.08.003.

"Inflation Reduction Act of 2022: H.R.5376 – 117th Congress (2021–2022)." congress.gov. Accessed Aug. 8, 2023. congress.gov/bill/117th-congress/house-bill/5376/text.

"Infrastructure Investment and Jobs Act: H.R.3684 – 117th Congress (2021)." congress.gov. Accessed Aug. 8, 2023. congress.gov/bill/117th-congress/house-bill/3684.

Jacobson, R.A., Jeremy Fried. n.d. "Biomass Potential from Wildfire Crisis Strategy Fuel Reduction: Two Case Studies." In preparation.

Jain, T.B., J.S. Fried, and S.M. Loreno. 2020. "Simulating the Effectiveness of Improvement Cuts and Commercial Thinning to Enhance Fire Resistance in West Coast Dry Mixed Conifer Forests." *Forest Science* 66 (2): 157–177. doi.org/10.1093/forsci/fxz071.

Johnston, Craig M.T., Jinggang Guo, and Jeffrey P. Prestemon. 2023. "Chapter 7: Forest Products." In *Future of America's Forest and Rangelands: Forest Service 2020 Resources Planning Act Assessment*. Washington, D.C.: USFS. Gen. Tech. Rep. WO-102. doi.org/10.2737/WO-GTR-102-Chap7.

Kanieski da Silva, B., F. Cubbage, and R. Abt. 2019. "Structural Changes on Pulpwood Market in the US South: Wood Pellet Investments and Price Dynamics." *Forest Science* 65 (6): 675–687. doi.org/10.1093/forsci/fxz043.

Larson, E., C. Greig, J. Jenkins, E. Mayfield, A. Pascale, C. Zhang, J. Drossman, et al. 2021. *Net-Zero America: Potential Pathways, Infrastructure, and Impacts*. Princeton, NJ: Princeton University. netzeroamerica.princeton.edu/the-report.

Markowski-Lindsay, M., C. Brandeis, and B. Butler. 2023. "USDA Forest Service Timber Products Output Survey Item Nonresponse Analysis." *Forest Science* 69 (3): 321–333. doi.org/10.1093/forsci/fxad003.

Mendell, Brooks. 2019. "Risk and Context in the Forest Industry: Lessons from Wood Pellets, Part II." Forisk Blog, March 26, 2019. forisk.com/blog/2019/03/26/risk-context-forest-industry-lessons-wood-pellets-part-ii/.

Muhammad, A. 2021. “Green Energy Globalization: The Connection Between EU Climate Policy and U.S. Wood Pellet Trade.” 2023 Rod Ziemer Lecture, Athens, GA, April 21, 2023.

Pokhrel, G., Y. Han, and D. Gardner. 2021. “Comparative Study of the Properties of Wood Flour and Wood Pellets Manufactured from Secondary Processing Mill Residues.” *Polymers* 13 (15): 2487. doi.org/10.3390/polym13152487.

Schumacher, F.X., and S.H. Hall. 1933. “Logarithmic expression of timber-tree volume.” *Journal of Agricultural Research* 47: 719–734.

Spelter, H., and D. Toth. 2009. “North America’s Wood Pellet Sector.” Madison, WI: USFS Forest Products Laboratory. Research Paper FPL-RP-656. doi.org/10.2737/FPL-RP-656.

U.S. Forest Service (USFS). 2014a. *Final Environmental Impact Statement for the Four-Forest Restoration Initiative, Volume 1*. Washington, D.C.: USFS. MB-R3-04-23.

———. 2014b. *Final Environmental Impact Statement for the Four-Forest Restoration Initiative, Volume 2*. Washington, D.C.: USFS. MB-R3-04-24.

———. 2022. *Forest Inventory and Analysis National Core Field Guide, Volume I: Field Data Collection Procedures for Phase 2 Plots*. Washington, D.C.: USFS. Version 9.2. fia.fs.usda.gov/library/field-guides-methods-proc/docs/2022/core_ver9-2_9_2022_SW_HW%20table.pdf.

———. 2023. *Future of America’s Forest and Rangelands: Forest Service 2020 Resources Planning Act Assessment*. Washington, D.C.: USFS. Gen. Tech. Rep. WO-102. Washington, DC. 348 p. https://doi.org/10.2737/WO-GTR-102.

Wall, D., J. Cooper, J. Bentley, and J. Gray. 2018. *North Carolina Harvest and Utilization Study, 2015*. Asheville, NC: USFS Southern Research Station. e-Resource Bulletin SRS-216.

Winn, M., L. Royer, J. Bentley, R. Piva, T. Morgan, E. Berg, and J. Coulston. 2020. *Timber Products Monitoring: Unit of Measure Conversion Factors for Roundwood Receiving Facilities*. Asheville, NC: USFS Southern Research Station. e-General Technical Report SRS-251.