U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Appendix B. Appendix to Chapter 4: Biomass from the Forested Land Base

March 2024

Disclaimer

Availability

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

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

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Appendix B. Appendix to Chapter 4: Biomass from the Forested Land Base

Appendix B.1: Biomass from the CONUS Forested Land Base

B.1.1. Data Updates

Stumpage Prices

An input to assessing cost for forest woody biomass in the conterminous United States (CONUS) includes stumpage prices, which in the 2016 analysis were provided by the U.S. Forest Service (USFS) by zone (North, South, and West) and tree type (softwood and hardwood). These data have been updated to reflect 2021–2022 costs, derived from RISI biomass.

USFS Revises Woody Biomass Estimates

Wood resources are routinely quantified by the USFS through the Forest Inventory and Analysis (FIA) program, other federal agencies, states, and private forest land managers. Statistical models are commonly used to estimate standing timber volume (e.g., Schumacher and Hall 1933). This FIA dataset used a Component Ratio Method until 2021 (Woodall et al. 2011; Domke et al. 2012), and currently uses a species-specific volume and biomass estimation approach (Westfall et al., 2023). The FIA released a national-scale volume and biomass framework to assess species identified by FIA, excluding woodland species, that is specific to the species, attribute, and geographic location. Across the CONUS, minor differences in total merchantable bole volume and biomass have been estimated, and an increase in limb biomass is shown (USFS 2022). This dataset is being tested for billion-ton analyses for future research.

National and Regional Outlook of Roundwood Markets

The modeled woody biomass available for energy in this section was based on the projected futures (2020–2070) (Johnston, Guo, and Prestemon 2023) of U.S. aggregate national and regional demands for roundwood for conventional wood products production reported in the 2020 USFS Resources Planning Act (RPA) assessment report (USFS 2023), which were first met in the Forest Sustainable and Economic Analysis Model (ForSEAM) before solving for additional woody biomass feedstock available from U.S. timberland at the county level. The trajectories of demand for roundwood were provided for four alternative scenarios of economic, demographic and climate changes adopted by the USFS in its 2020 RPA assessment. Market clearing quantities of production, consumption, trade, and prices of forest products were solved by the Forest Resource Outlook Model (FOROM), a global partial market equilibrium model of the forest sector, in conjunction with the RPA Forest Dynamics Model (FDM), which accounts for land use change, forest type change, and net growth and harvests at fine spatial scales. The combinations of Representative Concentration Pathways and Shared Socioeconomic Pathways were consolidated into the four distinct scenarios labeled as LM (lower warming and moderate U.S. income and population growth; RCP4.5-SSP1), HL (high warming and low U.S. income and population growth; RCP8.5-SSP3), HM (high warming and moderate U.S. income and population growth; RCP8.5-SSP2), and HH (high warming and high U.S. income and population growth; RCP8.5-SSP5). This analysis utilized the projected roundwood production in the HM scenario to satisfy the baseline (business-as-usual) conventional wood demand in ForSEAM.

B.1.2. CONUS Constraints

CONUS sustainability constraints have been relaxed in a sensitivity exercise, with results discussed in Chapter 6.

B.1.3. National and Regional Outlook of Roundwood Markets

Under the four alternative scenarios adopted in the 2020 RPA assessment, and with 2015 as the starting point, the FOROM-FDM system projected varying levels of U.S. aggregate production, consumption, trade, and prices of roundwood (sum of industrial roundwood and other roundwood) (Table B-1). The HL and HH scenarios provided the lower and upper bounds of projected U.S. aggregate roundwood market activity through 2070. The HH scenario, which depicts a high economic and high population growth combined with an unconstrained future greenhouse gas emissions path, projected the highest future roundwood production levels, with a projected 55% increase by 2060 compared to the 2015 observed levels (370 million m^3). In contrast, the HL scenario, which depicts a low economic and population growth combined with an unconstrained future greenhouse gas emissions path, generated the lowest roundwood production levels, with a 12% increase by 2060 compared to the levels observed in 2015. The next largest volume of roundwood production was projected for the LM and HM scenarios, with 43% and 25% increases by 2060, respectively. Thus, the HL and HM scenarios, where roundwood harvests for conventional wood products were lowest, would serve as the largest source of roundwood input to wood energy generation, provided that current policies and programs favoring the use of wood for energy continue.

Projected U.S. aggregate consumption levels of roundwood were lower than the projected production levels in all scenarios, suggesting that the United States would continue to remain a net exporter of roundwood in all scenarios, with similar trajectories of increases as their projected production. Projections of U.S. roundwood production were accompanied by higher average roundwood prices, and this result was common to all scenarios, with the HH and HL scenarios showing the largest and smallest increases (85% and 19% increases by 2060 compared to 2020 price levels, respectively).

Regionally, the U.S. South was shown to remain a dominant roundwood producing region, with a projected share of more than 60% of the U.S. aggregate roundwood production by 2060 in all scenarios, followed by the West and North RPA regions, with about 20% and 18% shares, respectively.

Table B-1. Projected U.S. Aggregate Production, Consumption, Net Exports, and Prices of Total Roundwood under Four Alternative Scenarios of Emissions and U.S. Socioeconomic Growth, Adopted in the USFS's 2020 RPA Assessment, 2020–2060 (Johnston, Guo, and Prestemon 2023)

Market Variable	Scenario	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
Production (million m^3)	LM	370	407	421	435	450	464	481	497	511	527
	HL	370	395	397	399	401	403	405	407	410	413
	HM	370	400	408	417	426	434	442	449	456	462
	HH	370	407	424	441	457	477	498	522	546	571
Consumption (million m^3)	LM	359	395	407	420	433	445	461	475	487	501
	HL	359	383	385	386	387	388	390	391	393	395
	HM	359	387	395	402	410	417	422	428	433	438
	HH	359	394	409	424	438	455	473	495	520	546
Net export (million m^3)	LM	10	13	14	15	17	19	20	22	24	25
	HL	10	12	13	13	14	15	15	16	17	18
	HM	10	13	14	15	16	18	19	21	22	23
	HH	10	13	15	17	19	22	24	27	26	25
Price ($/$m^3$)	LM	-	75	79	85	90	98	103	108	113	117
	HL	-	76	80	84	86	87	89	89	90	91
	HM	-	79	84	90	94	99	104	108	113	118
	HH	-	79	84	92	100	111	121	132	140	145

Note: Roundwood quantities equal the sum, and prices equal the averages of industrial roundwood and other industrial roundwood by softwood and hardwood categories.

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Appendix B.2. SubRegional Timber Supply (SRTS) Analysis Illustrates Regional Variation

B.2.1 Methods Summary

SRTS is an empirical bioeconomic model that was utilized in BT16 and BT23. For a full write-up on the SRTS modeling approach and assumptions, please see BT16 and other SRTS documentation.[1] To investigate the potential impacts of demand for bioenergy with carbon capture and storage (BECCS) on biomass availability and roundwood prices, we also show the results from an additional set of scenarios that simulate a boost in pine pulpwood demand resulting from the hypothetical introduction of a BECCS facility (not shown in the table). However, the new pulpwood demand is assumed to be localized to the southwest Arkansas region, where pine inventory is expected to expand rapidly through 2050.

Table B-2. Demand Scenarios for SRTS Projections

Pine Sawtimber Residue Factor [a]	Baseline Pine Sawtimber Demand	Pine Sawtimber Boost (Low)	Pine Sawtimber Boost (High)
Low	Current annual demand of 54.6 million dry tons with 10% of sawmill residues used to offset growth in pine pulpwood demand	Annual demand of 63.0 million dry tons by 2025 with 10% of sawmill residues used to offset growth in pine pulpwood demand	Annual demand of 67.0 million dry tons by 2025 with 10% of sawmill residues used to offset growth in pine pulpwood demand
Medium	Current annual demand of 54.6 million dry tons with 30% of sawmill residues used to offset growth in pine pulpwood demand	Annual demand of 63.0 million dry tons by 2025 with 30% of sawmill residues used to offset growth in pine pulpwood demand	Annual demand of 67.0 million dry tons by 2025 with 30% of sawmill residues used to offset growth in pine pulpwood demand
High	Current annual demand of 54.6 million dry tons with 50% of sawmill residues used to offset growth in pine pulpwood demand	Annual demand of 63.0 million dry tons by 2025 with 50% of sawmill residues used to offset growth in pine pulpwood demand	Annual demand of 67.0 million dry tons by 2025 with 50% of sawmill residues used to offset growth in pine pulpwood demand

[a] Preferences for mill residues as a feedstock.

B.2.2. Background on Southern Forest Resource Market

In the southern forest resource market analysis prepared for BT16, the demand for bioenergy was driven by the emerging use of wood pellets produced in the U.S. South. This demand was primarily driven by Drax UK to meet European renewable energy standards. At the time, a common thread in the popular and research press was how EU policy uncertainty could affect long-term demand for pellets from the U.S. South. Since the 2016 study, the EU's Renewable Energy Directive in 2018 clarified its standards for the sustainable use of forest-based biomass energy, allowing for forest-based biomass from working forests to contribute to Europe's

[1] https://github.com/NCState-SOFAC/SubRegionalTimberSupply/blob/master/SRTS_Documentation.pdf

renewable energy goals. Further, the United States' Inflation Reduction Act of 2022 has expanded a tax credit available to energy producers capturing and permanently storing CO_2 (Clean Air Task Force 2023). This federal subsidy has been raised from $50/ton of CO_2 stored to $85/ton stored from industrial and power generation facilities and to $180/ton from direct air capture technology (Clean Air Task Force 2023). Further, the United States' Bipartisan Infrastructure Law of 2021 and the Inflation Reduction Act of 2022 have provided $43 million in grants intended to bolster the domestic utilization of forest biomass for energy production and building construction, which may be effective in lowering the cost of investment into carbon capture and storage operations.

These initiatives serve to support further growth of the emerging wood bioenergy industry in the U.S. South. From 2015 to 2019, wood pellet capacity in the U.S. South increased by 20%. Pellet mill roundwood consumption in 2019 was approximately 6% of paper mill pulpwood consumption, and 12% of paper mill consumption of sawmill residues. Pellet capacity is expected to continue growing (Mendell 2019). The next decade of bioenergy demand in the South may also be driven by interest in BECCS. Beyond simply improving the efficiency of energy generation compared to traditional coal-fired power plants, the BECCS technology relies on renewable forest biomass and without contributing to atmospheric carbon concentration (Drax 2023; Larson et al 2021). These facilities will likely consume 4–5 times the amount of wood fiber than a typical pellet mill, leading to an increase in demand for byproducts from timber harvesting and lumber manufacturing activities, as well as small-diameter roundwood.

Domestic Wood Pellet Production and Exports

The U.S. South currently accounts for 78.6% of the nationwide densified biomass production capacity (EIA 2023). All wood pellets produced in the U.S. South are exported, and 76% of North American pellet production across the U.S. and Canada is shipped overseas (Forisk Consulting 2019). Wood pellet exports from the U.S. increased by an annual average of 9% from 2012 to 2021, from no exported volume in 2008 to over 7 million metric tons (or 8 million dry short tons) by the year 2021 (USDA 2022). In 2021, the value of these exports exceeded $1 billion, and approximately 96% of this exported volume was shipped to Europe for energy production (USDA 2022). Nearly all exported volume of pellets produced in the U.S. South had historically been shipped to Europe. However, exports to Japan have recently grown such that 13% of total pellet production during the fourth quarter of 2022 was shipped to Japan (Ekström 2023).

An international harmonized trade code for wood pellets was not adopted until 2012. However, Eurostat adopted a code independently in 2009. To obtain U.S. export data from 2012–2012, we calculated the average capacity utilization as 78% and applied this figure to the mill capacity data found by Forisk Consulting (2014). These data are reported in Figure B-1. The remaining export data reported in Figure B-1 are available from FAOSTAT and the U.S. International Trade Commission. These sources report that U.S. exports have gained an increasing share of the global trade of wood pellets. In 2012, U.S. exports accounted for 28% of total global imports. By 2021, this percentage rose to 45%.

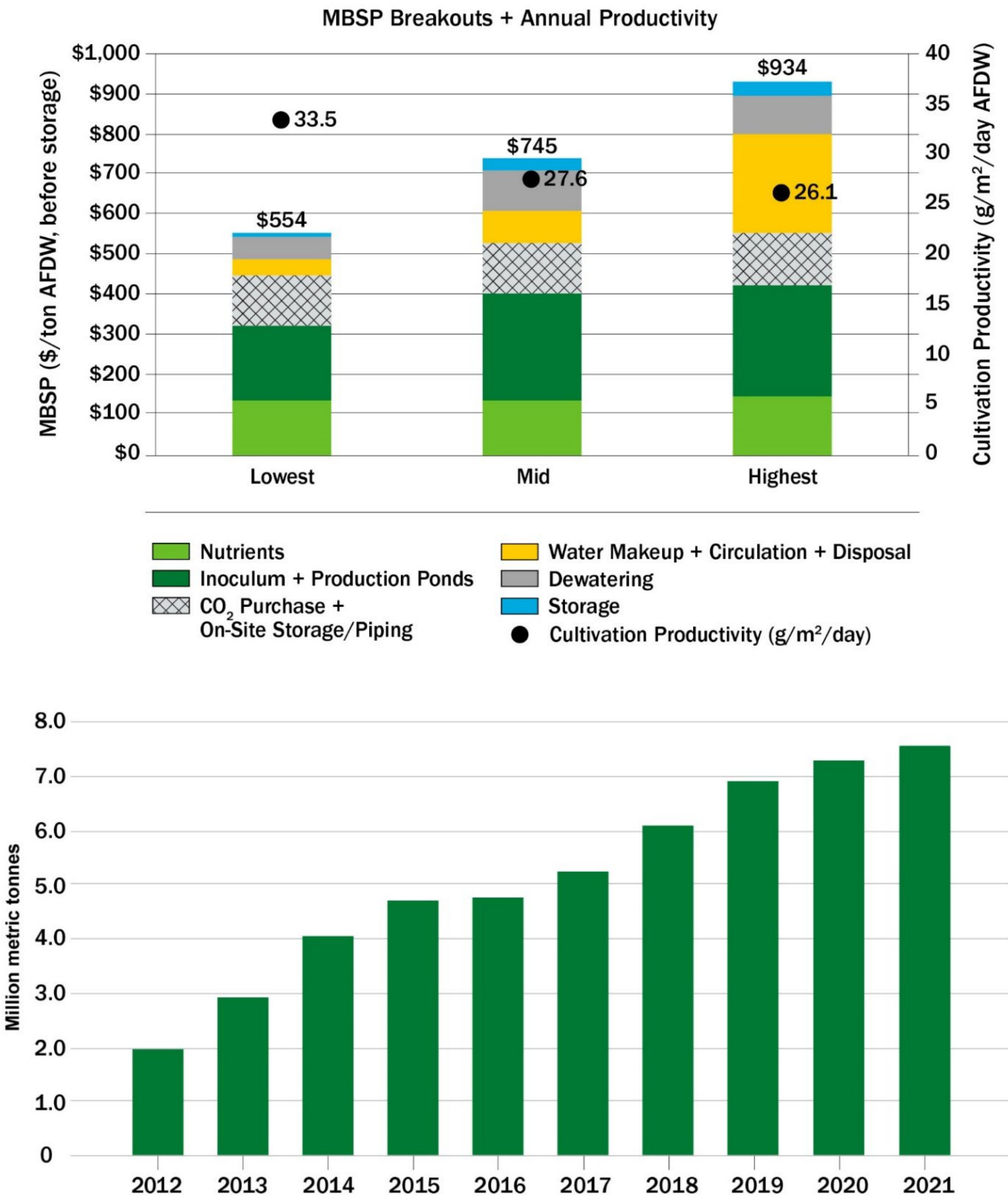

Figure B-1. Top: minimum biomass selling price (MBSP) and the cultivation productivity of woody biomass in a lowest, mid, and highest BECCS scenarios. Bottom: U.S. wood pellet exports (2012–2021)

However, wood pellets remain a relatively small percentage of total U.S. exports of forest products. In 2022, wood pellet exports accounted for only 10.3% of the total volume of exported wood products (FAO 2023).[2] Wood pellet production for export, while comparatively small, represents a significant source of income for the U.S. forest sector. A 2017 estimate of 256 wood pellet mills distributed across the U.S. South found that annual production generated $5.7 billion in income and contributed 35,990 jobs to the economy (Henderson et al. 2017). As the export demand for wood pellets increases, the derived demand for small-diameter roundwood and logging residues is also likely to increase. Therefore, we expect the economic impacts attributable to wood pellet exports to grow as the demand for roundwood harvested from forests in the U.S. South increases alongside a growing end use demand for renewable energy (Henderson et al. 2017). However, as we explore in this report, higher preferences for mill residues as a substitutable feedstock to pellet production may limit the wood pellet sector's derived demand for harvested roundwood and logging residues.

Historical Utilization of Feedstocks for Wood Pellet Production

Wood pellet production in the U.S. South relies on forest-based biomass from three primary sources: (1) small roundwood harvests (i.e., "whole-tree biomass"); (2) residues from wood processing, which includes bark (primarily used as boiler fuel rather than as a pellet feedstock), dry lumber shavings, and wood chips; and (3) nongrowing stock biomass, which includes slash, foliage, and rough and rotten trees not suitable for lumber or veneer production. A 2008 estimate of wood pellet feedstocks reported that 69% of fiber used for pellet production was sourced from sawmill residues, whereas only 16% of fiber for pellets was sourced from chips, small roundwood, and logging residues (Spelter and Toth 2009). Feedstock sources have since shifted more toward roundwood use. Excluding logging residues, around 21% of the feedstock for wood pellet production in the U.S. South is sourced exclusively from dry sawmill residues (see Table B-2). Pellet mills utilized only 2.3 million dry tons of both softwood and hardwood mill residues in 2021, which is 4.7% of total mill residue production across the U.S. South. Pellet producers also utilized 10.7 million dry tons of roundwood as a feedstock in 2021, which represented 15.1% of total pulpwood roundwood harvested in that year. Dry sawmill residues are relatively cheaper to transport and have physical properties desirable for pellet production (Pokhrel, Han, and Gardner 2021). However, as pellet production capacity has expanded, more direct use of roundwood has been the key contributor to pellet plants. This utilization of roundwood can support an increased balance between pellet supply and demand (Spelter and Toth 2009). However, as we explore in this report, recent announcements to expand lumber production capacity may generate cheaper sources of feedstocks in the form of dry mill residues; contributing to a shift in pellet feedstocks away from small roundwood and back toward mill residues.

[2] For context, the largest volumes of exported forest products in 2022 were recovered paper (17.1%), other paper products including newsprint and packaging (12.9%), and industrial roundwood (10.5%). Unprocessed wood chips and particles accounted for an additional 9.5% of exports volume.

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Appendix B.3: Methods Summary: Bioregional Inventory Originated Simulation Under Management (BioSum)

B.3.1. Methods

Stand Inventory Data

FIA data for Washington and Arizona were downloaded from the FIA Datamart, the online warehouse that allows users to select and download FIA data.[3] These data are selected by state, then subsetted later in the workflow to inventory plots within the priority investment landscape eligible for treatment under the Wildfire Crisis Strategy. Additional information on how FIA data are collected, compiled, and analyzed can be found at the USFS FIA data website.[4]

Silvicultural Simulations

The Forest Vegetation Simulator (FVS) is a distant independent, individual tree growth and yield model designed to project forest stands through time under management, with the capacity to simulate the effects of very detailed silvicultural prescriptions on future stand conditions and outputs of harvested wood (Dixon 2023). Users are responsible for providing plot data representing the area of forest to be simulated and specifying and parameterizing the forest management activities to be applied in the projection of each modeled stand via the interface provided with the software or via key control programs (.KCP files). Prescription parameters were determined for Arizona Four Forests Restoration Initiative (4FRI) priority investment landscape (PIL) based on consultations with the Fort Valley Experimental Forest's Research Silviculturist Keith Moser, national forest staff in the USFS Region 3 and insight attained from publications such as the Final Environmental Impact Statement (FEIS) (USFS 2014a, 2014b). Prescriptions and treatment effectiveness metrics for the Central Washington Initiative (CWI) PIL were derived from consultations with silviculturists in that region. FVS was used to project 13 cycles beginning with a pre-year, a 1-year projection to a management year at which treatment is modeled, then a 1-year projection to a post-management year (to simulate treatment of activity fuels resulting from the thinning treatment), followed by an 8-year projection to the beginning of the next decade; this is repeated three more times.

In the 4FRI area, the desired conditions sought a reduction in the potential for crown fire realized by increasing the canopy base height and/or reducing the canopy bulk density. The goal is to reduce canopy bulk density below 0.05 kg/m^3 and to raise stand canopy base height above 18 feet (USFS 2014a). In the CWI, the Composite Resistance Score is used to judge to the likelihood of a crown fire initiating in a stand. This score combines subscores generated by thresholding each of crown base height, crown bulk density, predicted volumetric tree mortality under a 6–8-foot flame length surface fire, and proportion of fire-resistant species comprising the stand basal area. Each subscore ranges from 0 to 3, and when all four subscores are summed, the result is a Composite Resistance Score ranging from 0 to 12 (Fried et al. 2017).

[3] https://apps.fs.usda.gov/fia/datamart/datamart.html
[4] https://www.fia.fs.usda.gov/

Modeling Biomass Removals

The BioSum development began in 2002 when the USFS began to examine changes in wildfire suppression and mitigation policy with the goal of "forest biomass summarization." Mitigation of wildfire hazard often entails the removal of "ladder fuels" that consist of often innumerable sub-merchantable-sized trees, which can incur high costs to implement with poor prospects for any financial return from sales of removed material unless merchantable-sized trees of commercial species are also part of the removals. The BioSum framework supports the evaluation of treatment effectiveness at stand level in terms of changes to hazard and resistance metrics and characterizes the area of forest on which effective treatment by one or more prescriptions is possible and economically feasible, subject to assumptions about costs of treatment implementation and delivery of harvested wood to potential utilization sites. BioSum can also identify optimal silvicultural prescriptions for each acre, compute the volume and mass of merchantable and unmerchantable wood generated by treatment activities, by time period, and identify the wood processing facilities to which that wood could be feasibly directed.

The BioSum framework is typically configured to model four analysis periods of 10 years each, for 40 years total, to simulate the management of forests in the area of interest. Using the Control Numbers from the FIA database, the stands (derived from FIA condition-level data—either full or partial FIA plots) included in the CWI and 4FRI regions were selected via a spatial overlay on the PIL polygons (each composed of an aggregation of fire sheds). Treatment packages are the programmatic description of the management actions taken on the forestland in the simulation. The treatment "packages" (each a sequence of silvicultural prescriptions and operations performed over time, typically contingent on stand density or size triggers evaluated by FVS during the simulation) were crafted from information obtained by reading Environmental Impact Statements and discussions with forest researchers and managers for the two PILs and were matched to real-world management design. The treatments are coded as FVS keyword control programs that guide the projection of the forested lands under the selected management strategies. The FVS results are then uploaded to the BioSum framework for processing (calculating biomass and volume per tree, estimating treatment costs and computation of wood volumes and values by size and species, and selecting the best treatment for each acre under one or more optimization scenarios). A processor scenario is developed and applied, before the optimization, to define tree species groups and diameter size classes, set up the GIS-based calculation parameters for estimating wood haul costs, specify the price and usage of every species and diameter grouping, establish the real inflation rate to discount future revenues and costs to the present day, and to define to specify additional costs above and beyond harvesting and transport (e.g., for disposal of surface fuels generated by the treatment operation). The treatment optimizer module utilizes these processor results to select the best treatment package for each forest stand in the analysis based on the metrics of interest to the user and how the model should interpret the changes in those metrics (Fried et al. 2023). The simulation produced by BioSum has more acres than are planned for the PILs, and the results are scaled down to match the reported acreage for each PIL.

Funding to enhance fire resistance in the CWI and 4FRI landscapes, among others, has been appropriated under the Bipartisan Infrastructure Law and Inflation Reduction Act. These funds may fully fund the management activities required to achieve the desired resistance. The woody material that can be transmuted into bioenergy feedstock is inseparable from merchantable timber during harvesting because the purpose of the activity is to reduce fire hazard—something that would not be achieved were harvested wood allowed to remain in the forest. In most cases, mechanical fuel treatment removes whole trees, so the residues arrive at the forest landing as attached branches or as sub-merchantable-sized trees or trees of noncommercial species bundled in a twitch. Those residues can be chipped in preparation for destruction in an air curtain destroyer (covered by special funding), but such destruction would only impose an additional cost on top of harvesting, and if a buyer for the material can be sourced, the only costs that have not been paid for by the Congressional funds targeted at fire resistance are those associated with transporting residues from the forest landing to a buyer's facility. The meta-supply curves are created from the haul cost data from a forest landing to the nearest facility, and the quantity of material that is produced at that forest landing and transportation prices to the purchaser's facility are collected into $5 price increments. Further documentation of the BioSum model is available at biosum.info/

B.3.2. Post-BioSum Analysis

To shape the data into the format used in the databases provided in the billion-ton repositories and the Bioenergy Knowledge Discovery Framework (KDF) (https://bioenergykdf.ornl.gov/bt23-data-portal), scripts using Jupyter Notebooks were developed for post-processing the results of BioSum. These scripts also generate the images used in this chapter and provide the statistical analyses used in the results of the BioSum analysis. These scripts are provided in a GitLab repository for users to use or adapt as desired. The Python scripts were developed to automate and provide transparency into the operations needed to perform this analysis. This includes steps that allow the user to download the GIS road layers used in the transportation step of this analysis, select the FIA points used in the BioSum analysis, and develop the properly formatted input file for later use. BioSum and FVS operations were not scripted with Python in this analysis, but the post-processing steps after those operations were. The post-processing steps include extracting data from the BioSum outputs into a single database with relevant data for the billion-ton analysis and developing statistics, charts, and images to explain the data that have been produced.

Repository availability: The repository for the code used in the post-processing of BioSum results, the FIA databases, the code used to generate the data charts used in this report, and the KCP files used for the FVS simulation are provided at github.com/EERE-Biomass/BT23BioSUM.

B.3.3. Sustainability and Environmental Constraints

- No harvesting on reserved lands.
- Private, state, tribal, and federal forestland included in volume estimates.

- The analysis also assumes that merchantable-sized wood from commercial species, removed during treatment operations, for which there is a market would be delivered to the nearest sawmill fetching the market price for that kind of wood.
- The list of species considered valuable and merchantable for lumber and other traditional wood products was verified through publications and discussions.
- The analysis limited the diameter of trees available for biomass to smaller than merchantable size, the tops and limbs of merchantable-sized trees, and the entirety of all trees of species with little to no commercial value at the scale of production that these treatments would entail (e.g., juniper).
  - 7-inch-DBH cutoff in Washington and 9 inches in Arizona.
  - Trees as small as 1 inch in diameter could be harvested in both landscapes, but utilization minimums differ by slope class (3 inches on gentle slopes [<40°] and 5 inches on steep slopes [>40°]).
- Removals *may* temporarily exceed growth across the PILs in order to achieve fire resistance and restore forest density to levels consistent with historic ranges of variability and/or to levels compatible with future climate parameters.
- Costs do not limit harvesting—in all cases, the most effective treatment is assumed to be implemented, not the one that returns the most net revenue or incurs the least net cost.

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