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The Economics of Forest Fuel Removals on Federal Lands

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About the Authors

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His work has been recognized with national awards from the US Secretary of Agriculture, Chief of the US Forest Service, and Society of American Foresters. Wear's research focuses on linking economic choice and biophysical elements of natural resource systems to project resource conditions and illuminate policy options. He has written extensively on forest economics, forest carbon dynamics at broad scales, timber supply, the effects of risk on forest investments, and land use. He has led or participated in interdisciplinary initiatives to understand the influence of land use and forest management on a variety of ecosystem services, including biological diversity and water. As a federal scientist, he led or contributed to several national and regional natural resource assessments including the Southern Forest Resource Assessment, Southern Forest Futures Project, and National Climate Assessment.

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Abstract

Despite large recent investments by Congress, the costs of fuel removal and forest restoration needs in the western United States dramatically exceed available funding. Engaging the private sector may provide a means for enhancing the pace and scale of fuel removals to reduce wildfire hazard, but thus far this strategy—which has typically focused on increasing demand for small-diameter fuels—has not been broadly successful. To assess the economics of fuel treatments in the western United States, we develop a spatially explicit model of the revenues and costs of fuel removal in Idaho and Montana, under a variety of treatment scenarios. We find that fuel treatment sales would not be economically feasible across most of the study region unless prices of small-diameter material were to rise significantly, potentially via subsidies or another policy. Nevertheless, under current market conditions, bundling small amounts of sawtimber harvest with treatments is capable of dramatically expanding treatable area. Such an approach is a promising path to reducing fire hazard on public lands; however, a different approach will be necessary to encourage fuel removal on private lands, which make up a disproportionate share of forested lands near communities.

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1. Introduction

Public forest management in the western United States has recently shifted toward a dominant focus on mitigating wildfire hazards. The loss of life, property damage, air pollution, and suppression costs of wildland fires have converged in what the USDA Forest Service (USFS) now calls a wildfire crisis (USFS 2022), driven by changes in climate conditions (Abatzoglou and Williams 2016), growth in the wildland-urban interface (Balch et al. 2017; Higuera et al. 2023), and the accumulation of forest fuels—vegetation that has accumulated within fire-adapted forests due to a century of fire exclusion (Hessburg et al. 2005; Steel et al. 2015). Of these three factors, land management agencies can address only forest fuels. Therefore, the USFS has developed an aggressive strategy for reducing fuels on 50 million acres over 10 years (USFS 2022). With the Infrastructure Investment and Jobs Act (IIJA) of 2022, the US Congress has recently provided funding to allow the agency to take steps toward that goal. The IIJA provided more than $5 billion to address wildfire issues, mainly through projects to reduce forest fuels—more than two years of recent total base funding for the USFS.

Fuel management is accomplished through prescribed burning and mechanical thinning treatments, both of which are designed to remove or redistribute forest fuels to reduce the intensity of future fires and provide increased opportunities for containment (Vaillant and Reinhardt 2017). Prescribed fire treatments involve deliberately burning understory vegetation under favorable conditions, while mechanical thinning treatments involve selectively removing or redistributing small-diameter vegetation. While prescribed fires are less expensive to implement on a per-acre basis, mechanical thinning projects must often be performed first to implement prescribed fire safely in places with very dense fuels. Over the past several decades, numerous schemes have been proposed to lower the net cost of mechanical thinning through commercial utilization of harvested small-diameter material. However, thus far these strategies have not proven viable on a large scale, leaving policymakers with the challenge of funding expensive treatments across a broad area.

The USFS estimates that $5 billion to $6 billion annually would be needed for fuel treatment in the highest-priority areas (Clavet et al. 2021). While the IIJA represents a considerable step toward accomplishing the agency's stated needs, the $5 billion allocated by the IIJA for spending over three to five years will not be sufficient to achieve them. Moreover, in spite of the limitations, the IIJA will nevertheless provide an unprecedented increase to the scale of the federal fuel treatment program, raising several logistical challenges along with potential negative externalities. Work on the ground is accomplished mainly through contracts with private entities, and treatment needs may exceed local capacity. Labor supply may be especially restrictive for both local contractors and agency planners and administrators, at least in the short run (Rummer et al. 2005). Externalities relate mainly to disposal of the substantial wood waste generated by mechanical fuel treatments. Waste can be disposed of either by burning or through utilization of materials in the production processes for wood products. Burning generates air pollution, including especially harmful $PM_{2.5}$ particulates (Jaffe et al. 2020), and is restricted to relatively short fire-safe burn windows (Baijnath-Rodino et al. 2022).

This study explores the potential for various strategies to improve the pace and scale of fuel treatments in the United States, and limit externalities of waste disposal, by engaging markets in fuel removal. Most fuel treatments produce low-quality material that currently has no viable markets (Cabiyo et al. 2021; Hunter and Taylor 2022). Even where removals are more valuable, high harvest and transportation costs can make sales infeasible, highlighting how market potential is spatially variable among regions and within a region (Cabiyo et al. 2021; Hunter and Taylor 2022; Nielsen-Pincus et al. 2013; Rummer et al. 2005).

We address a set of questions about fuel treatment potential by building a case study of harvest economics in Montana and Idaho. We develop a spatially explicit method for estimating the economic feasibility of selling raw materials by using estimates of the potential costs of harvesting and transporting materials and the potential returns to material removals. Potential returns derive from spatially imputed estimates of FIA forest inventory data and market prices and depend on sale design parameters. Potential costs are based on a model of haul costs between existing road networks and processing facilities and estimates of harvesting costs that depend on topographic and other site features.

The case study allows us to evaluate the economic feasibility of fuel treatments under a range of scenarios. We examine the role of sawtimber and nonsawtimber prices and the potential role of treatment design—in this case defined as the amount of more valuable sawtimber bundled with low-value small-diameter material—in improving economic feasibility of treatments (Fried et al. 2017). We find that large increases in the price of small-diameter material would be required to make fuel removal economically feasible within much of the study area. Nevertheless, in some cases, bundling relatively small amounts of sawtimber is enough to tip the scales toward economic feasibility. Moreover, because our analysis is spatially explicit, we can intersect maps of economic feasibility with maps of fuel treatment priorities to examine the potential utility of market strategies for achieving priority fuel reductions. This analysis indicates that bundling sawtimber with low-value small-diameter material is likely to be an effective strategy for encouraging fuel removal on federal forestlands near communities exposed to fire hazard. However, because a significant portion of forest near these communities is privately owned, other strategies—including those that increase the price of small-diameter material—may be important as well.

This work relates to a body of literature studying the economic feasibility of fuel treatments. For example, timber market models (Prestemon et al. 2012) address how deployment of large-scale fuel treatment programs could affect material substitution, timber prices, and consumer and producer surplus. Detailed inventory models linked to growth simulators (Cabiyo et al. 2021; Fried et al. 2017) address how treatment design affects economic feasibility. All these studies use FIA forest inventory data to define forest conditions, but in distinct ways. Prestemon et al. (2012) use aggregates of plots across strata defined by biological and treatment schema to define regional timber supply relationships for their timber market simulations with locations specific to small regions. Cabiyo et al. (2021) and Fried et al. (2017) simulate treatments and costs for individual plot/condition records and then expand plots and cost estimates to population totals using area expansion factors that define the area frame of the inventory.

In contrast, we provide spatially explicit estimates of costs and returns, enabling us to address the coincidence of economic feasibility with fuel treatment priorities. We estimate treatment revenues using plot records and then use a spatial imputation of plots to grid cells to link forest conditions and potential revenues to each location. We then estimate costs of harvesting and hauling material for grid cells based on maps of topographic conditions, proximity to roads, and distance from processing mills. In so doing, we avoid the untenable assumption that the plots provide a representative sample of topographic and locational attributes within a region (implied by use of expansion factors). In effect, we apply an alternative means to "expand" the inventory to better account for cost variation related to a highly variable topography with highly variable access costs.

Our analysis of the relationship between economic feasibility and priority areas for fuel treatments also relates to the literature on fuel treatment prioritization. Most of this literature, reviewed by Chung (2015), focuses on methods for identifying fuel treatment locations that maximize risk reduction—that is, locations where the social benefits of fuel treatments are highest. In contrast, we identify high-wildfire-risk areas where it is economically feasible to reduce fuels through harvesting. In other words, we identify high-risk locations where the private costs of fuel treatments may, under some timber sale designs, be sufficiently low as to be outweighed by the private benefits of the project.

We use our case study to address three questions: (1) Where do forest and landscape conditions constrain the viability of selling fuel treatment removals? (2) How might changes to treatment design within the scope of agency decisionmaking alter viability? (3) Do economically viable harvest areas correspond with areas needing fuel treatment? Our results motivate a discussion of how administrative constraints, defined by contracting options available to the USFS, limit the ability to use subsidies in this context, even where social welfare gains are potentially high.

2. Institutional Details

Federal ownership dominates the forests of the northern Rockies, and while forest conditions on all lands influence the delivery of wildfire hazard to nearby communities, our policy discussion focuses on federal lands managed by the USFS. The agency controls about 82 percent of forestland in the region, and nearly all IIJA funding targets treatment needs on USFS land. The design of fuel treatments, absent congressional action, is limited to the contracting instruments available to the agency, and choices are constrained by economic feasibility tests.

Three instruments allow the USFS to contract with private firms for forest management. The first is a timber sale contract, which allows the USFS to auction rights to remove timber subject to management guidance and other conditions—generally through a sealed-bid process, with proceeds going to the US Treasury. The second is a service contract whereby the agency exchanges appropriated funds for services rendered, such as for thinning. The third is a stewardship contract, which allows the USFS to exchange the right to harvest timber in return for in-kind services in the vicinity of the timber harvesting. Timber sale proceeds thereby augment appropriated funding in the local area. Recent modifications to stewardship contracting authority allow for even more flexibility by spreading treatments across larger landscapes and over longer periods.[1] Stewardship contracts provide the most likely means by which the treatment designs we consider in this paper could be implemented. For simplicity, we focus on treatment designs in which proceeds from harvesting are exchanged for on-site fuel removal; however, it is likely that the ability to exchange harvest for services conducted across larger landscapes or longer periods would further increase potential for expanded fuel treatments (though at the expense of more intense sawtimber harvests in some locations).

Both timber sale and stewardship contracts require the management plan to generate revenues that at least cover their direct costs, as well as a formal economic analysis (Jackson 1989). In particular, the “suitability” requirements of the National Forest Management Act of 1976 require an assessment of economic feasibility to prevent subsidized sale of timber commodities. These feasibility tests require treatments to be funded either exclusively by timber proceeds (timber sale or stewardship contracts) or exclusively by appropriated funds (service contracts). While introducing criteria of economic efficiency to federal sale design, these tests preclude developing potentially beneficial sales where the returns to timber alone would not cover direct sale costs but public welfare gains from timber plus hazard reductions would. Our analysis is set within this institutional context, which we revisit in Section 6.

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[1] Section 604 (16 USC 6591c) of Public Law 108-148 as amended by Section 8205 of Public Law 113-79, the Agricultural Act of 2014, among other things, gives permanent authority to the USFS and BLM for stewardship contracting and extends the duration of stewardship contracts from 5 to 10 years. See Congressional Research Service (2022).

3. Theoretical Framework

Our analysis of timber sale feasibility focuses on the interaction between sellers and potential buyers of a timber sale (or stewardship) contract. A seller packages a sale—specific harvest quantities by species and size, with operational requirements—within a contract instrument. Potential buyers formulate bids for the rights to harvest the timber based on their assessment of expected revenues and costs implied by the contract. Because federal timber sales emphasize public good outcomes, such as mitigating fire hazard, they may differ substantially from those offered by a seller intent only on maximizing returns to timber. For example, public sales tend to be more complex than private sales in terms of the distribution of cutting units and treatment types and have more restrictive management standards (Jackson 1987; Munn and Rucker 1995). Nevertheless, a federal sale must pass a feasibility test whereby its revenues exceed direct costs, so the USFS seeks to design a sale offering that achieves multiple-use objectives yet is economically feasible based strictly on timber proceeds and has a reasonable likelihood of generating bids and being purchased.

The prospective buyer generates a bid for the offered timber based on information advertised by the seller, along with relevant market prices and auxiliary information. Both buyer and seller engage in an appraisal of a sale offering. The USFS uses an appraisal to estimate whether the timber sale offering is marketable (feasible) and to meet its legal requirement of receiving fair market value for the offering, while the buyer uses an appraisal to assign a bid that covers all costs incurred in the transaction and generates an acceptable profit.

Appraisals start with the value of logs delivered to a processing facility $P_D V_i$, where P_D is a vector of delivered log prices by species, V_i is a vector of volume offered for sale by species, and *i* indexes harvest locations. Reflecting the state of log markets, P_D is influenced by the prices of wood products made from the logs, as well as the costs of other inputs used in manufacturing them and the availability of material on the market. The market value of standing timber at a particular location ($P_s V_i$) is the difference between $P_D V_i$ and total costs incurred in harvesting and delivering logs from site *i* to the processing facility. Defining average per-unit costs of bringing timber at site *i* to market as c_i, the standing value of timber at location *i* can be defined according to

$$P_S V_i = (P_D - c_i) \times V_i \tag{1}$$

Per-unit costs can be divided into different categories: harvesting or stump-truck costs (c_i^H), transportation or hauling costs (c_i^T), and site development costs (c_i^D):

$$c_i \equiv c_i^H + c_i^T + c_i^D. \tag{2}$$

After accounting for costs, the appraised value of a sale may or may not be positive or above the legal minimum rates. However, the bid value must be positive with an upper bound of $P_D V_i$.

In practice, appraisals are based either on a residual value approach, using specific cost estimates as described here, or on a transaction-evidence approach that approximates costs and predicted bid values based on regression models (Jackson and McQuillan 1979).

4. Empirical Analysis

4.1. Study Area

For this analysis, we consider a study area that combines high wildfire hazard and relatively active timber markets: the states of Idaho and Montana. Within dry forests that prevail in much of the Rocky Mountain region, wildfire was historically limited by the availability of fuels, rather than by fuel moisture (Steel et al. 2015). As a result of a century of fire exclusion in the western United States, fuels have become more abundant, elevating fire hazard. A significant need now exists for forest restoration and fuel reduction treatments to both reduce wildfire hazard and increase forest resilience to disease (Stephens et al. 2018). While Idaho and Montana constitute a relatively small portion of overall timber harvest volume within the United States (3 percent) and the US West (12 percent), they contribute approximately 82 percent of total timber harvest from the Rocky Mountain region.[2]

Figure 1 describes the history of timber harvests in Idaho and Montana from 2000 to 2020, by ownership class. Between 2002 and 2018, timber harvesting generally declined in the region; average harvests between 2016 and 2018 were about 25 percent lower than average harvests between 2002 and 2004, with important differences between the two states. In Idaho, harvests dipped during the great recession (2009) but quickly recovered to prerecession levels. In contrast, harvests in Montana declined steadily between 2002 and 2008 and then fell to and remained at about half the 2002–2004 average values following the recession. Stable harvests in Idaho reflect a decrease in harvests from private lands (–18 percent) offset by expansion in public harvests (+33 percent), predominantly from state lands.

Timber harvesting is limited to about one-third of the area of the two states (Figure A.3), and harvests are strongly concentrated in the Idaho panhandle and northwestern corner of Montana. Six adjacent counties in the panhandle—Shoshone, Clearwater, Benewah, Bonner, Latah, and Kootenai—each represent more than 5 percent of total harvest and together account for a majority of the region's harvest (52 percent).

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[2] Percentages of timber production are based on harvest volumes in "Forest Products Industry and Timber Harvest Reports" from BBER (n.d.a) and total timber harvest volumes provided in Oswalt et al. (2019).

Adding two adjacent counties in Montana—Lincoln and Flathead—increases this to 64 percent of the region's total harvest. Harvest intensities are much lower throughout the remainder of the forested portion of the region, and change over time has not shifted the ranking of these counties to any great degree.

The history of timber production in this region indicates that the costs are variable, with harvesting being economically feasible in only a portion of forest areas. Consistent with equation (1), feasibility is determined by site-specific factors, including standing timber volume and the costs of bringing timber to market. Costs are influenced by mill locations and the transportation network connecting forests to mills. Economic fundamentals therefore determine where a market-based strategy for fuel treatments might be applicable. The development of treatment strategies and policies needs to start with a clear delineation of where market augmentation can work and where it cannot because of various economic limiting factors.[3]

4.2. Estimates of Timber Sale Value

Our objective is to estimate appraised values ($P_S V_i$) for hypothetical timber sales throughout our northern Rockies study region. This requires spatially explicit measures for all the elements of (1) and (2). To derive these measures, we divided forested area within the study region into 270 m grid cells, and we estimated timber values and per-unit costs of bringing timber to market from each cell. Estimates were based on USDA Forest Inventory Analysis (FIA) plot data, timber prices by species and product class, and the application of a state-of-the-art algorithm for interpolating gridded transport costs from a limited set of transportation cost observations. Data sources used in timber valuation are summarized in Table 1. We describe our data and methods for estimating each of the four components of timber sale value in turn below.

4.2.1. Delivered Value

Delivered value is the total amount paid for material at the mill gate ($\boldsymbol{P_D V_i}$); therefore, it is a function of the total volume of each species harvested and prices. For each 270 × 270 m plot in our study area, we define harvest volumes by applying assumed harvest intensities to measured volumes within representative FIA plots.

The FIA is a USFS program that has monitored the condition of public and private forests across the United States for over 90 years (Oswalt et al. 2019). FIA data include detailed measurements of trees on approximately 125,000 forest plots, with measurements of total tree volume by species and age/size class. Sampling protocols implemented in 1999 call for measuring plots every 10 years in the western United States. Plots are keyed to county, and exact plot locations are kept confidential. We use a 2018 extract of FIA data from Idaho and Montana, which reflects all plot measurements from the implementation of the modern FIA sampling protocols in 2003

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[3] Developing an effective fuel treatment strategy must also include a prioritization of treatment areas, ranked by their effects on wildfire and damage risks.

to 2018. For each plot, we calculate total sawtimber volume and total volume of small-diameter material for each species, where sawtimber is defined as trees greater than nine inches in diameter. We then use a mapping of FIA plots to 90 m grid cells using a k-nearest neighbor imputation algorithm that matches plots to grid cells based on sawtimber volumes and attributes from the National Land Cover Database (NLCD; for a description of the general procedure, see Rieman et al. 2010).[4] We then rescale these rasters to 270 m by summing inventory volumes.

Figure 2 shows total inventories of sawtimber and nonsawtimber in three ownership categories (USFS, private, and other public lands), calculated from volume rasters generated using the spatial imputation algorithm and converted from volume to weight as green tons..[5] Total biomass of small-diameter material tends to be substantially lower than that of sawtimber. Typically, total biomass would be calculated by applying expansion factors to individual plots and aggregating across them over a broad area. Figure A.3 plots volumes within the study area by product class, ownership, and state, calculated using the expansion factor approach. Based on the spatial imputation algorithm, total sawtimber on USFS lands within the study area departs from the total calculated using expansion factors by less than 0.5 percent. Our measurements compare favorably with measurements calculated using the standard approach, while having the advantage of characterizing the distribution of biomass in a spatially explicit manner.[6]

To calculate the total value of sawtimber and small-diameter material at each site, we multiply prices and quantities and sum across species groups within each class. For sawtimber, we use species group–specific prices reported by the University of Montana's Bureau for Business and Economics Research (Hayes and Morgan 2011). Prices are summarized in Table A.3 and range from $359/thousand board feet (BF) for subalpine fir to $550/thousand BF for western redcedar. We assume that all small-diameter material is delivered as chips produced by in-woods grinding and therefore assume a constant price for all species groups, which we initially set at $10 per green ton (GT). This is about 25 percent of sawtimber prices and provides a starting point for exploring alternative scenarios regarding future prices. After calculating the total value of sawtimber and small-diameter material at each site, we calculate effective sawtimber quantity by dividing total sawtimber value by a weighted average of sawtimber prices at each site, where weights are given by species group volumes, and convert the measure to green tons for consistent comparisons with quantities of nonsawtimber. In our analysis, calculating effective sawtimber quantity provides a

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[4] The specific coverage was provided by J. C. Coulston, Project Leader, Center for Integrated Forest Science, USDA Forest Service (pers. comm.).

[5] We convert volume to biomass using conversion factors of 0.07 green tons/cubic feet (GT/cf) for sawtimber and 0.035 GT/cf for nonsawtimber.

[6] Relative to expansion factor–based calculations, the spatial imputation algorithm substantially overpredicts volume on private lands. This is likely because expansion factors are calibrated to predict total volumes within private lands in forestland use, whereas because the spatial imputation algorithm relies on the NLCD, it maps private FIA plots to all private NLCD grid cells with forestland cover.

convenient means for testing the effects of changes in sawtimber prices. Rather than individually modifying the timber price for each species group, it allows us to simply multiply the weighted average sawtimber price at each site by a constant factor and to multiply effective sawtimber volume by the modified price.

Finally, the quantity of material for sale at each site depends on the assignment of a harvest–fuel treatment prescription. Prescriptions are assigned based on the range of removal intensities by product classes taken from the literature, and we explore various scenarios based on harvest intensities.

4.2.2. Harvesting Costs

Stump-to-truck costs (c_i^H) are defined based on the slope of each grid cell and the material being harvested. We assume that different harvesting technologies may be applied depending on site slope and define three slope classes: 0–20 degrees, 20–31 degrees, and greater than 31 degrees. We estimated the slope at each site based on a 30 m DEM from the National Elevation Dataset and aggregated to a 270 m raster based on modal slope class. We assume that ground-based logging systems can be applied up to a slope of 20 degrees and that cable systems are required at higher slopes.[7] On the steepest sites, skyline cable systems are required. We do not include costs of nascent logging systems (e.g., cut-to-length, tethered forwarder) that may reduce costs of high-slope logging.

We develop separate cost estimates for sawlogs and for small-diameter material. For sawlog harvesting, we use cost estimates from a semiannual survey of logging firms (Hayes et al. 2019). For small-diameter fuel treatment harvests, we develop average stump-to-truck costs based on logging cost studies conducted in the western United States (see Appendix A.1). As well, we assume that on-site grinding is required, with costs ($/GT) obtained from the same survey. Additionally, because drying that occurs during the chipping process reduces the weight of chipped material before hauling occurs, we reduce the cost per unit weight harvested by a factor of 34 percent.

4.2.3. Haul and Site Development Costs

We estimate timber haul costs following methods from Donaldson and Hornbeck (2016) and Araujo et al. (2020) for estimating spatially explicit costs of bringing products to market. In brief, their methods use Dijkstra's algorithm to calculate the minimum costs of transporting goods through a gridded landscape, where parameters determine the speeds at which different kinds of cells can be traversed. Speed parameters are identified by generating a grid of possible speed parameter combinations, then calculating predicted costs for a set of points with known transport costs. The best combination of parameters is the one that maximizes the R-squared from a regression of observed transport costs on predicted costs. These parameters are then used within Djikstra's algorithm to impute predicted

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[7] Cable systems may also be preferred because they can mitigate environmental damages and enhance crew safety.

transportation costs for all cells across the landscape. The regression that minimizes R-squared is used to convert predicted costs, which are initially unitless, into dollars.

To implement this strategy, we use data from the National Land Cover Database (NLCD), which we resample from a 30 m to a 270 m resolution (keeping the modal land use type in each cell) to improve processing speeds. Using US Census TIGER/Line road data, we buffer all paved and unpaved roads by 125 m and reclassify NLCD cells as paved or unpaved road if their centroid fell within either of the respective buffer types.[8] We group all nonroad NLCD cells into a single category, which we label "undeveloped," and we allow transport speeds to vary across undeveloped, paved, and unpaved roads.[9]

Using the R package gdistance (van Etten 2017), we calculate minimum haul costs from cells in 13 Montana counties to mills in those counties or in neighboring counties, under a variety of speed parameter combinations.[10] Mill locations were provided by the University of Montana's Bureau of Business and Economics Research (BBER).[11] Our speed parameter grid sets the speed of traversing a paved road equal to 1 and allows the speeds of traversing undeveloped cells and unpaved road cells to vary from 0.005 to 1 by increments of 0.005. To determine the best-fitting set of parameters, we regress combined haul and per-unit site development costs estimated for a set of 122 timber sales offered by the state of Montana between 2014 and 2022 (see Appendix A.2) on transportation costs (defined as the inverse of time traveled) predicted by the algorithm at each timber sale location.[12] These 122 timber sales, and the 13 Montana counties we use to parameterize transport speeds, are shown in Figure A.5.

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[8] We buffer roads so that masking the NLCD raster by the vector road layer yields a set of road cells that accurately represents the road network.

[9] We reclassify NLCD pixels in low-, medium-, or high-intensity developed use as paved road.

[10] While all of Idaho and Montana are included in timber value analysis, only timber sales from 13 counties in western Montana are used in haul cost estimation, with results then extrapolated for the entire study area (see Figure A.5).

[11] We restrict the set of Montana mill locations provided by BBER to active mills classified as a sawmill, pulp/paper mill, post/pole/piling mill, particleboard mill, or plywood/veneer mill.

[12] Haul costs are defined by applying a cost regression equation currently used for USFS timber sale appraisals (forest economist Mike Niccolucci, pers. comm.) to haul distance estimates assigned to each timber sale by state analysts. We add the estimated road construction and reconstruction costs from each sale's bid prospectus to define road/site development costs, a dominant component of transportation costs for undeveloped cells. We recognize that when roads are permanent, our variable cost measure may be misspecified—that is, permanent roads represent a fixed cost with subsequent returns.

The best-fitting set of parameters sets the speeds of transport across undeveloped and unpaved cells, relative to paved cells, at 0.015 and 0.2, respectively. This set of parameters predicts haul costs for our 122 timber sale observations with an R-squared of 0.136. Using the best-fitting parameters, we calculate predicted costs of transport to the nearest mill for all undeveloped, unpaved, and paved cells across Idaho and Montana. These costs are based on the assumption that paved road cells can be traversed at unit speed, so they are initially unitless. We convert the cost estimates to dollar values using parameters from the regression of observed haul costs on predicted costs.

The resulting haul cost raster is shown in Figure 4. Costs are lowest near roads and in northern Idaho and western Montana, regions with a relatively high density of mills. Costs are highest in large, roadless areas of Idaho and Montana—including the Frank Church Wilderness, Bob Marshall Wilderness, and Glacier National Park—and in eastern Montana, regions with a low density of mills (and clearly no option to harvest timber).

5. Results

5.1. Economic Feasibility of Fuel Treatments

We begin by examining the economic feasibility of two simplified timber sale scenarios: a sawtimber harvest scenario and a fuel treatment scenario. Scenario 1 represents a sawtimber harvest scenario: no small-diameter material is harvested, and 80 percent of the total volume of sawtimber is harvested from each site. Scenario 2 represents a fuel reduction treatment scenario: 100 percent of the small-diameter material is harvested from each site, and no sawtimber is harvested. Under each scenario, we apply a screen based on the USGS Protected Area Database (USGS 2022) to exclude areas in national parks and wilderness areas where timber harvesting is precluded by rule.

Figure 5 plots the distributions of delivered and standing values by ownership category for both scenarios (the third panel shows distributions for a third scenario, which we discuss in Section 5.2). In the harvest scenario, delivered values are widely distributed, with values at the highest volume sites exceeding 1 million acres on other public land, 1.5 million acres on USFS land, and 2 million acres on private land. After subtracting harvest and transportation costs, standing values are lower. However, harvest at 90.4 percent of sites remains economically feasible. In the treatment scenario (scenario 2), delivered values are dramatically lower than in the harvest scenario, owing to the lower volumes of small-diameter timber (Figure 5) and to the lower prices per green ton for small-diameter timber. As a result, fuel treatment is economically feasible at fewer than 0.01 percent of sites under the treatment scenario.

Next, we examine the range of nonsawtimber prices under which the pure fuel treatment scenario (scenario 2) would become economically feasible across the study area. Strategies to develop technologies to enhance utilization of small-diameter material are intended to increase fuel removal by the private sector by increasing demand, and therefore prices paid, for this material. Our results shed light on the size of price increases that would be necessary for such an approach to be feasible.

Figure 6 plots the relationships between the percentage of land treatable and total treatable land for each of the three landownership categories. Approximately zero acres are economically treatable within the study area until nonsawtimber prices reach nearly four times the base level ($10/GT). Between prices of $40 and $60/GT (price indices 4–6), the share of total treatable area expands steadily within all landownership type (but fastest on private lands), eventually reaching 80–90 percent. Above a price of $60/GT, much larger marginal increases in nonsawtimber prices are required to increase economically treatable area. Overall, these results indicate that a sizable increase in demand for nonsawtimber would be required to make pure fuel treatment scenarios economically feasible throughout a significant portion of the study area.

5.2. Effects of Treatment Design on Economic Feasibility

As an alternative to the pure treatment scenario, we consider a third, hybrid scenario (scenario 3) in which 100 percent of the small-diameter material is harvested from each site and the treatment is subsidized by the sale of 20 percent of the site's sawtimber. The third panel of Figure 5 shows the distributions of delivered and standing values under the hybrid scenario. In comparison with the harvest scenario, delivered values are lower; however, in comparison with the treatment scenario, a substantially higher percentage of sites (29.5 percent) are economically feasible to treat.

The spatial distribution of economically feasible sites in the harvest and hybrid scenarios can be seen in Figure 8, panels A and B, respectively. The treatment scenario is not plotted because Figure 5 reveals few sites with positive standing values under the treatment scenario. The harvest scenario is economically feasible throughout much of the study area. While Figure 5 illustrates that a significant portion of the study area is economically feasible to treat under the hybrid scenario, panel B of Figure 8 shows that this area is concentrated in northern Idaho and western Montana. This finding is consistent with Figure 3, which indicates that this portion of the study area contains the highest density of sawtimber, and with Figure 4, which shows relatively low transportation costs in this portion of the study area.

While the hybrid scenario assumes a sawtimber harvest intensity of 20 percent, and that prices remain constant at levels described in BBER (n.d.b.), the total amount of economically treatable land within the study area depends critically on these variables. Figure 7 explores how the supply of treatable land within the study area varies with changes in sawtimber price and sawtimber harvest intensity levels. To vary price, we multiply the weighted average price of sawtimber at each site by factors between 0.6 and 1.6. In practice, sawtimber prices could be affected by changes in wood product demand (for example, due to new technologies) or by policies such as subsidies. We also experiment with augmenting treatments with some sawtimber harvest at each site, a variable that can be altered in the design of timber sale contracts.

As expected, the total area of economically treatable land is increasing in both sawtimber price and sawtimber harvest intensity. At lower sawtimber harvest intensity levels, a higher sawtimber price is needed to treat a similar area of land. At a given price, the greatest gains in treatable area come from increasing sawtimber harvest intensity from 0 to 20 percent. Beyond that point, additional sawtimber harvest results in somewhat smaller increases in treatable area.

5.3. Treatments within Wildland-Urban Interface Areas

Based on the preceding analysis, bundling sawtimber harvest with treatments appears to have potential as a strategy to increase the economic feasibility of fuel treatments at a broad scale. However, a separate question is whether these treatments would be implemented in areas of significant need—that is, in high-hazard areas with populations in harm's way. To examine this question, we overlay maps of standing timber values under a variety of price–intensity scenarios with maps of wildfire hazard and the wildland-urban interface (WUI).

Data on wildfire hazard come from the 2018 USFS Wildfire Hazard Potential (WHP) data product (Dillon et al. 2020). WHP provides a wall-to-wall measure of the potential for large and difficult-to-contain fires at any given location in the United States, based on fuel, vegetation, and fire ignition data and fire behavior modeling. While WHP is an ordinal, unitless measure, values above approximately 400 (the 84th percentile of the national WHP distribution) are generally considered to indicate high wildfire hazard potential.

Data on the WUI come from 2020 iteration of the University of Wisconsin SILVIS Lab's WUI data set (Radeloff et al. 2018). Using this data set, we identify census blocks that are categorized as either intermix (those where housing intermingles with vegetation) or interface (those where housing lies directly adjacent to large areas of wildland vegetation). Fuel reduction treatments are expected to most significantly reduce risk to homes when they are implemented in areas near the WUI. To encourage projects in these areas, the Healthy Forests Act of 2002 reduced requirements for environmental review for fuel reduction projects occurring within 1.5 miles of the WUI. Consistent with this, we buffer WUI intermix and interface areas by 1.5 miles. We examine the potential for economically feasible treatments within this area near the WUI and within high-fire-hazard (WHP > 400) areas near the WUI.

Figure 9 shows how the percentage of economically treatable land varies as a result of changes in sawtimber price across the full study area, WUI areas, and high-hazard WUI areas for the 20 percent sawtimber harvest intensity scenario (scenario 3). The left column shows how the relationship between the share of feasibly treatable acres and price differs within WUI areas compared with the full study area. Across the full range of prices, WUI and high-hazard WUI areas have a higher share of feasibly treatable land than the study area overall. In part, WUI areas may be more amenable to treatment because transportation costs are lower, since they are near roads. High-hazard WUI areas may be more costly to treat because they tend to be in areas that are more remote and have more rugged terrain, resulting in higher harvesting costs.

The right column of Figure 9 shows the relationship between feasibly treatable acres and price. Despite the high share of forested lands within the study area owned by the USFS, forestland near the WUI is more evenly split across the three ownership categories (USFS, private, and other public), and increases in feasibly treated acres as sawtimber prices increase are fairly similar across these categories. While subsidizing treatments with sawtimber is a viable strategy on those high-hazard public lands in close proximity to the WUI, a significant share of forestland close to the WUI is privately owned. On these lands, a different strategy will be needed to encourage treatment.

6. Conclusions

Fuel treatments are a means to restore resilience to wildfire in forest ecosystems, mitigate property losses and smoke emissions, and reduce the costs of wildfire suppression. However, current budget outlays severely restrict the scale of these activities on federal lands. One way to expand the scale of fuel treatments would be through policies that engage the private sector by improving the economic feasibility and marketability of fuel treatments.

Much of the research pursuing this goal has sought to increase private sector engagement in fuel removal by increasing demand for small-diameter material through development of new technologies (e.g., biochar or mass timber) that enable greater utilization of small-diameter material. But demand stimulus may not be enough. Our results indicate that absent policies that would strongly subsidize material utilization, such strategies may face an uphill battle: a nearly fourfold increase in the price of small-diameter material would be required to move the needle on fuel removal in our study area. Any successful strategy would need to overcome the high cost of delivering this low-quality material—perhaps by attaching subsidies for wildfire mitigation or carbon sequestration.

An alternative means for improving economic feasibility of fuel treatments, one we find to be somewhat more promising, is treatment design. Our analysis indicates that under current price levels, bundling treatment with just 20 percent of a site's sawtimber would expand the area on which it is economically feasible to treat from nearly zero if no sawtimber is harvested to 8 million acres of the study region's USFS lands (29 percent of the total). This amounts to subsidizing fuel treatments with federal sawtimber assets rather than with federal appropriations. Such a policy is capable of enhancing feasibility on high-hazard forestlands close to WUI communities, where treatment is needed most; however, the mix of ownerships near WUI communities means that agency-designed timber sales may be only part of the solution in these areas.

A strategy that would not require increasing sawtimber harvests would be to have federal agencies directly account for the nontimber benefits of fuel treatments using a direct subsidy that could make the sale feasible. One approach would be to allow for negative sale bids, with the agency selecting the least negative bid. Agencies would set maximum subsidies (minimum bids), based on either the estimated benefits associated with the sale's wildfire hazard reduction or the cost of the alternative service contract. If the resulting costs to the government were less than the costs for a service contract that achieved the same outcome, the subsidized sale would extend the effect of fuel treatment budgets. While such a strategy would be more costly from the agency's perspective than increasing sawtimber harvests, our findings—that only small increases in sawtimber harvests are necessary for economic feasibility in many cases—indicate that the private sector might require relatively small inducements to expand its role in fuel treatments in the study region.

A subsidy or a hybrid of sawtimber bundling and subsidy could offer a means for the USFS to offer marketable material at a scale that could encourage investment in the wood products sector and build demand for traditional or alternative products. But congressional authority to sell timber and USFS administrative directives (manual and handbook) do not allow for negative-bid (below-cost) timber sales. Implementation would therefore require congressional action to modify existing authorities or grant new ones. Recent authorization of new stewardship contracting authorities suggests that such congressional action, while not likely expeditious, is plausible.

Yet another approach would involve a shift in the point of timber valuation. That is, where timber on the stump may be economically infeasible, the same timber sold from the roadside or a sorting yard could be feasible. In this case, timber delivered to a roadside location would be auctioned while harvesting, and development costs would be paid for by appropriated funds using service contracts—not unlike the structure of existing fuel treatment contracts. Economic analysis would still be required to determine feasibility of sales, but bidders would not need to overcome the high costs of harvesting and pay a portion of transportation costs. To our knowledge, these strategies could be deployed within existing contracting authorities.

Demand for both sawtimber and small-diameter material derives from demand for wood products and is organized by the infrastructure of transportation networks and processing facilities (mills). Future research could use the framework we have developed in this paper to explore how the addition of new mills could enhance opportunities for fuel treatments by increasing the net value of mixed sawtimber/small-diameter harvest plans. Future work might also look at policy approaches that span all forest ownerships or expand these analyses to other regions where fuel treatment needs are substantial.

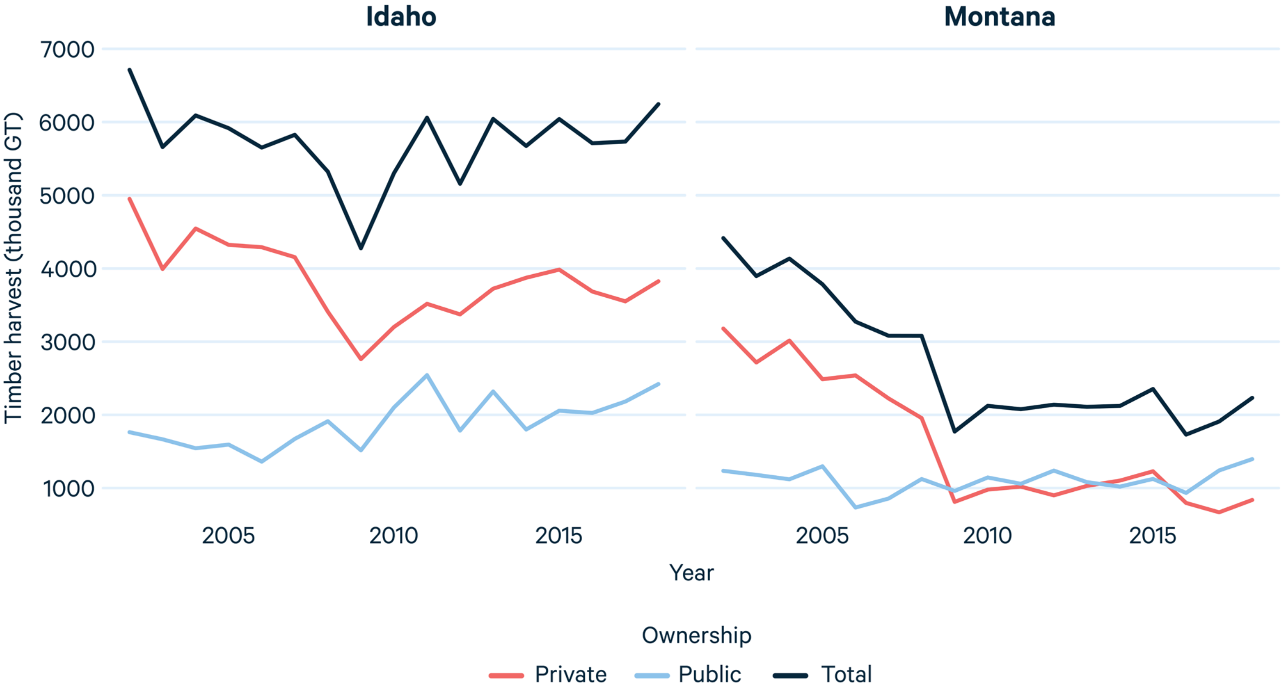
We expect that these policy proposals will be controversial. Timber harvesting on federal lands has long been at the center of public debates regarding multiple-use forest management. The persistent controversy over below-cost timber sales, which defined a contentious public land debate in the 1980s, centered on these same feasibility issues and the appropriate accounting of costs and benefits associated with sale planning and road development (Gorte 2004). On one side was the argument that with a full accounting of costs, revenues from most sales in places like the northern Rockies did not cover all costs and therefore provided a tacit federal subsidy to the wood products industry. On the other side was the argument that additional costs of sale design provided for other unpriced multiple-use improvements, such as wildlife habitat and recreation access, so timber sales paid their way. Essentially, the debate focused on the appropriate allocation of costs and the full accounting of benefits, and in some cases, it served as a proxy battle for excluding forest management from federal lands.

The current wildfire crisis likely represents a case where certain timber sales would clearly yield important nontimber benefits in the form of hazard reductions for surrounding communities, thereby justifying subsidized or below-cost sales. A full accounting of timber and nontimber benefits and costs should be used to guide strategies for managing the federal forest estate. We find that the greatest challenge to effectively engaging the private sector in fuel treatments is found on the supply side and dominated by high transportation costs. Encouragingly, costs may be less prohibitive in high-risk areas close to the WUI. Proposals for building demand for treatment material, for either conventional or novel products, need to simultaneously address the high costs of delivering that material.

Table 1. Input data and sources of revenue and cost components of timber valuation (equation 1)

Variable	Description	Inputs	Sources
P_D	Value of timber at the mill	Prices of delivered timber	• Sawlog prices from BBER by species and product class • Small-diameter material prices estimated by scenario
V_i	Product volumes	Inventory tree volumes by size class	• Volumes from USFS FIA plot data • Spatially imputed to grid cells (Coulston, pers. comm.) • Assumptions regarding removal intensity based on treatment strategy
c_i^H	Cost of harvesting (stump-to-truck costs)	• Average slope of site • Logging cost estimator • Products	• DEM coverage • Logging cost by technology (slope) from the literature
c_i^{SD}	Cost of road development	• Distance to road • Average slope of site	• Road coverage • DEM coverage • Road development cost estimates from timber sale observations (state of Montana)
c_i^T	Cost of transportation (hauling)	• Minimum distance along roads to mill • Average haul costs	• Road coverage • Map of mill locations (by type) • Haul cost estimates from timber sale observations (state of Montana)
c_i^O	Other costs	• Sale size • Sale complexity	• Unmodeled, assigned as an average cost based on timber sale observations with differences among ownership groups

Figure 1. Timber harvest over time, by state and ownership category, 2002–20



Data source: BBER (n.d.a.)

Figure 2. Sawtimber and nonsawtimber inventories, by state and ownership, within Idaho and Montana

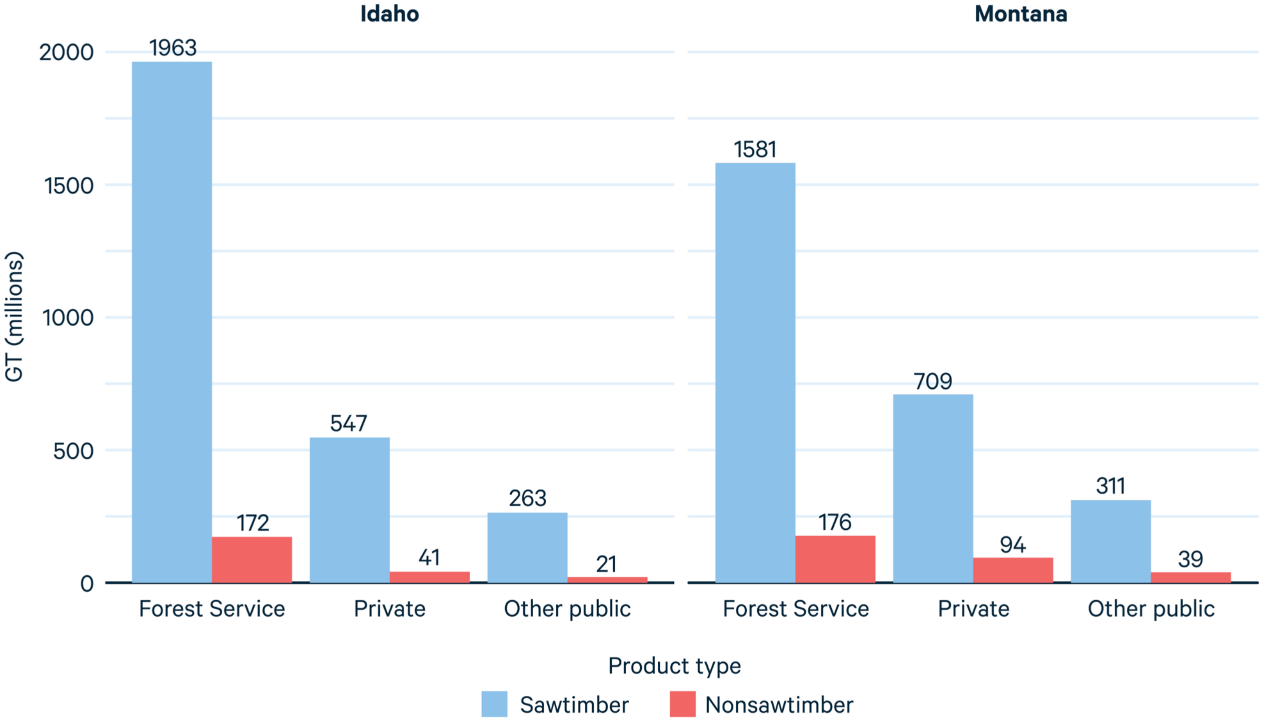
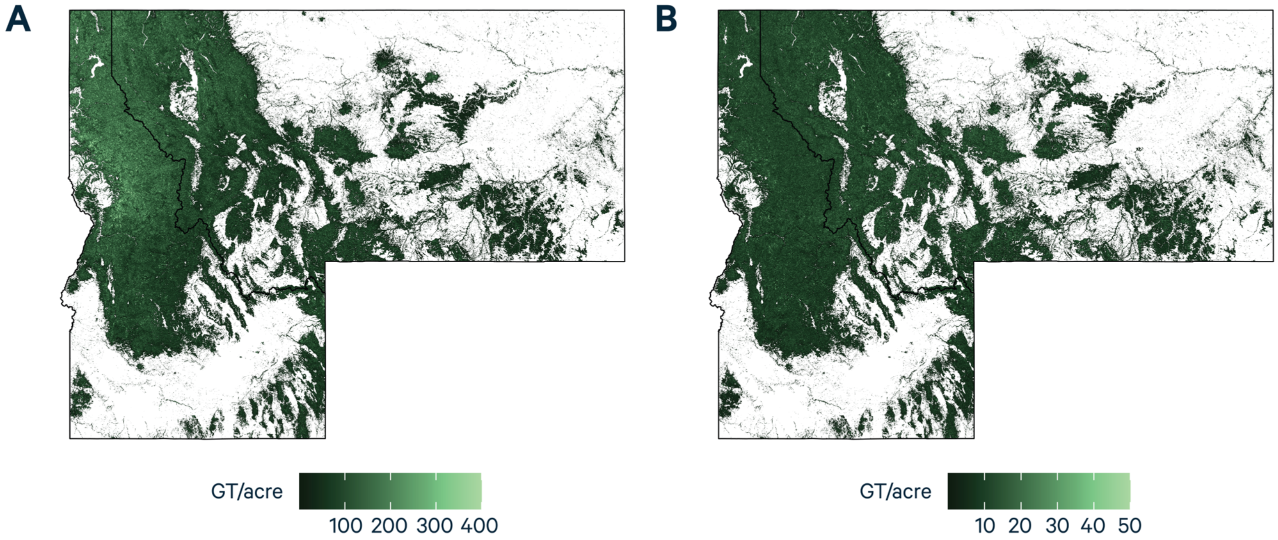
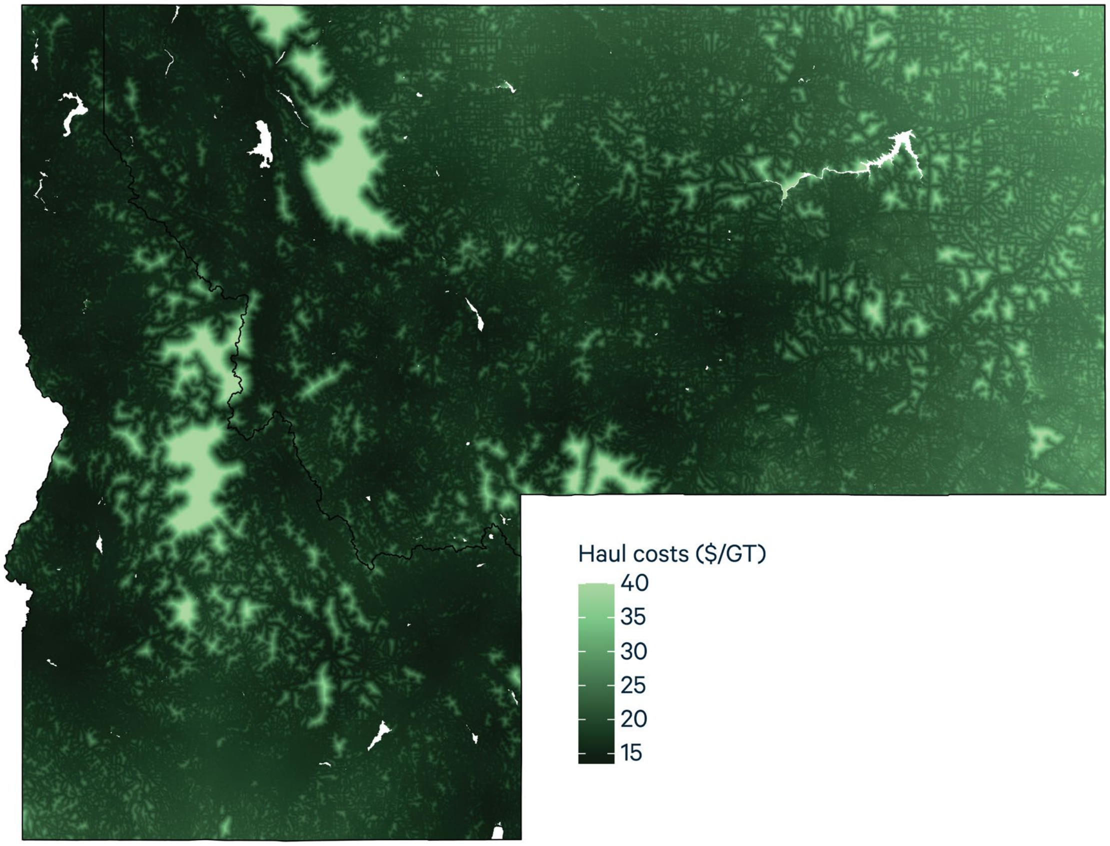


Figure 3. Per-acre inventories of sawtimber (panel A) and small-diameter material (panel B)



Note: Values are top-coded at 10,000 GT/acre (panel A) and 1,000 GT/acre (panel B).

Figure 4. Estimated transportation costs for sawtimber and small-diameter material within Idaho and Montana



Note: Values are top-coded at $40/GT for visualization.

Figure 5. Distributions of delivered and standing timber values per acre across harvest, treatment, and hybrid scenarios

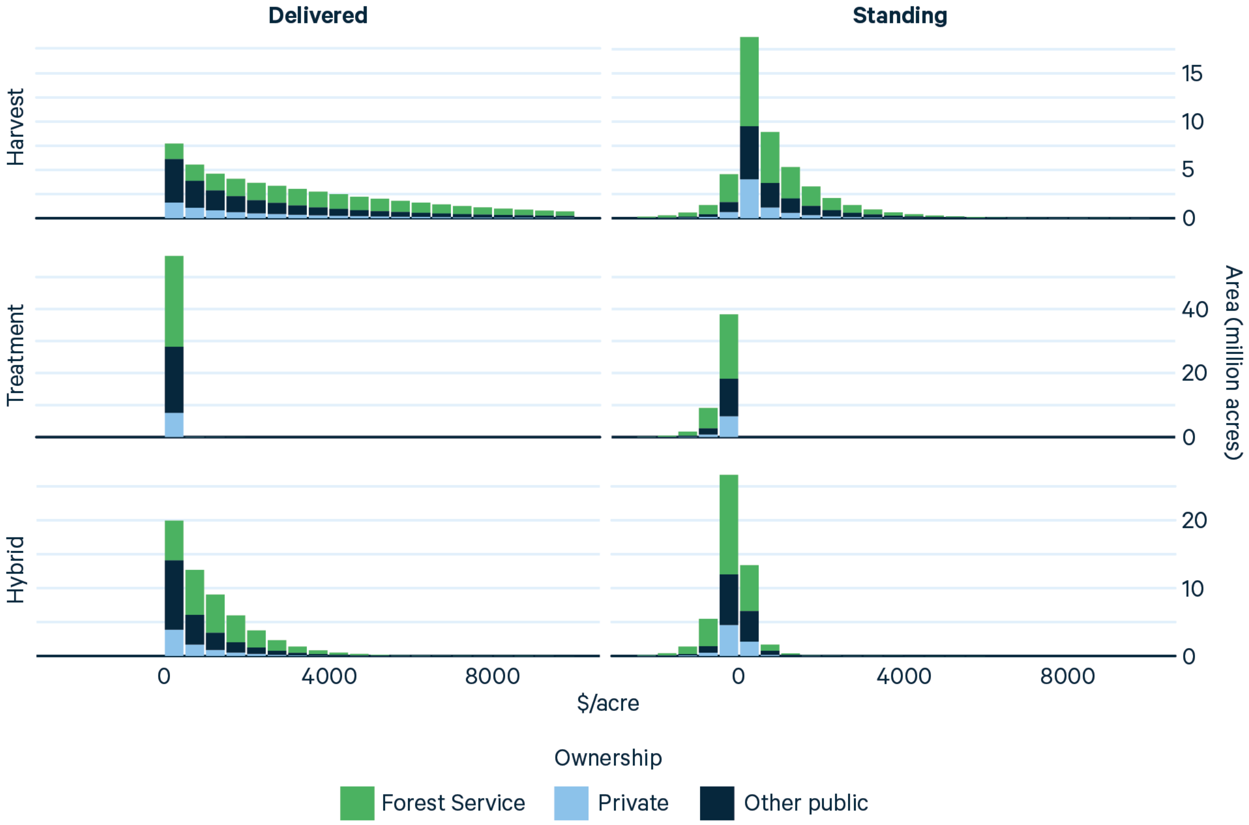


Figure 6. Supply of feasibly treated area (percentage treatable of total and total treatable area) under the treatment scenario (scenario 2), by ownership class

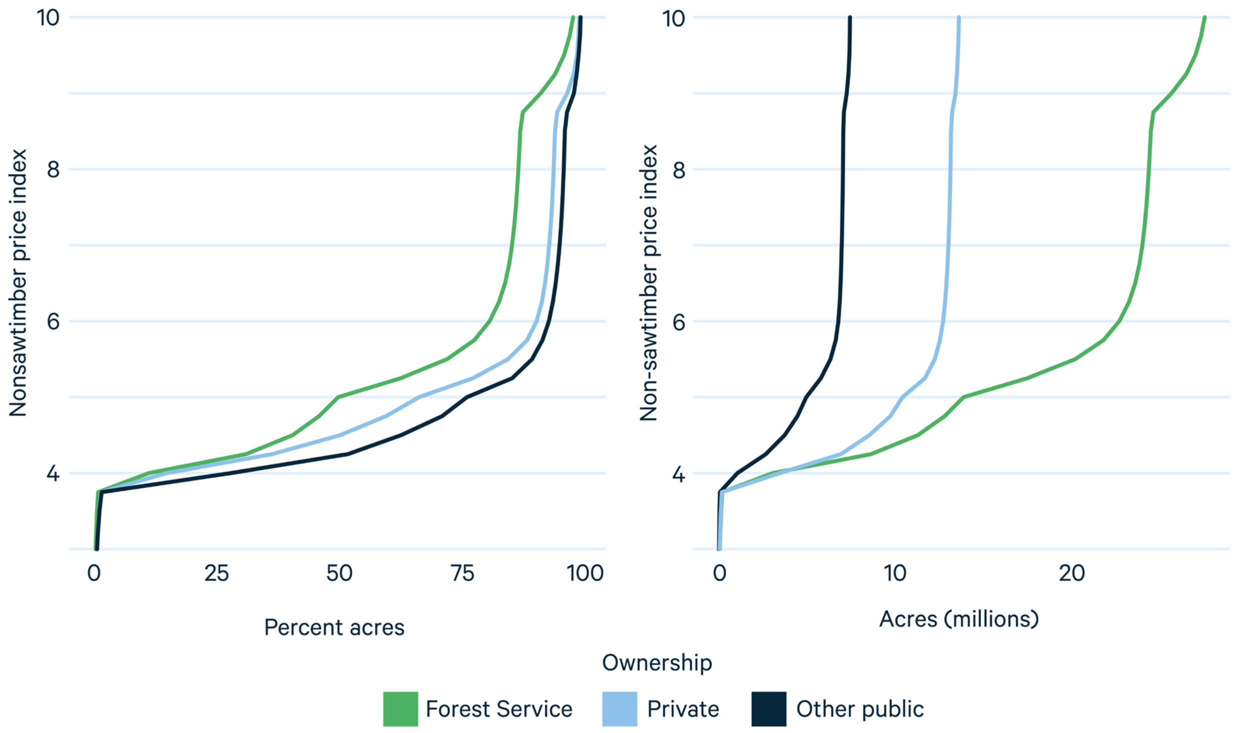
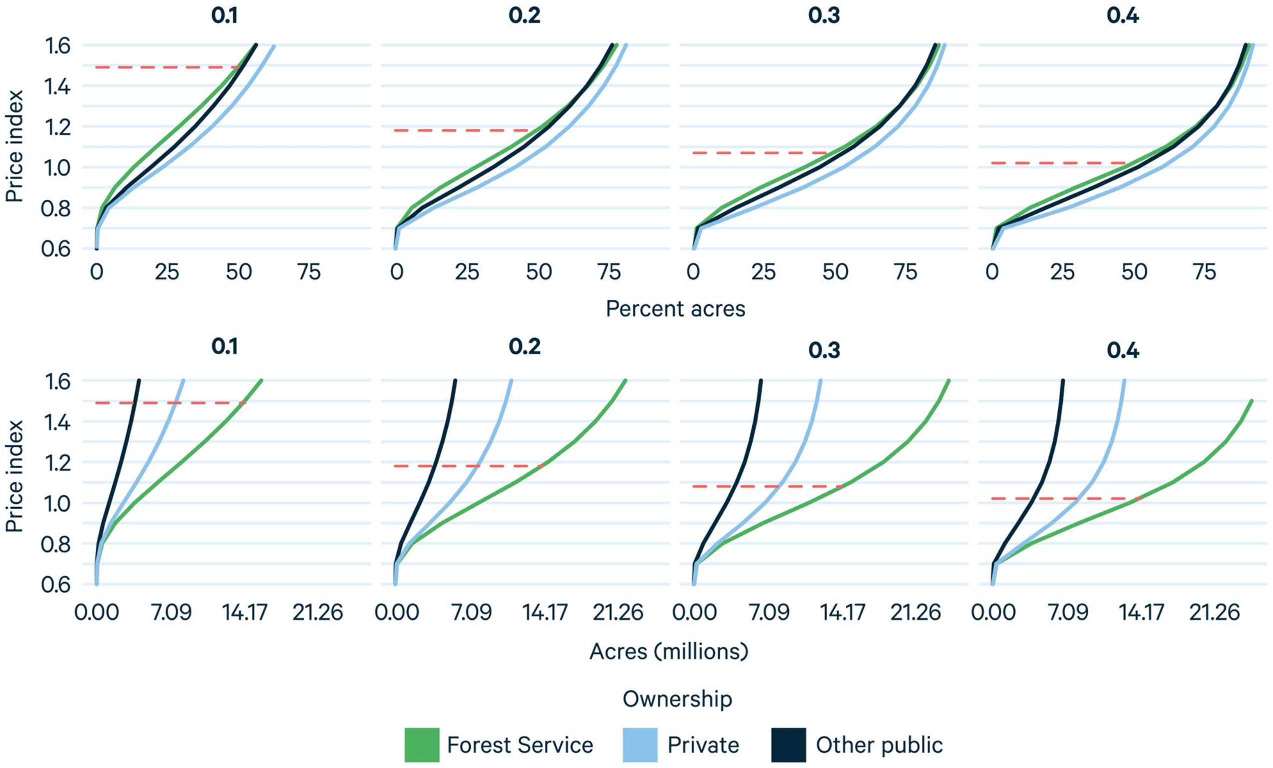


Figure 7. Supply of feasibly treated land (percentage treatable of total and total treatable area) under hybrid scenarios with varying sawtimber prices (*y*-axis) and sawtimber harvest intensities (panels)



Note: Dashed lines indicate the price index at which 50% treatment of USFS land is economically feasible to treat. Ticks on x-axis of the lower plot indicate acreages corresponding to 25%, 50%, and 75% of USFS land.

Figure 8. Maps of economically feasible sites under the harvest (panel A) and hybrid (panel B) scenarios

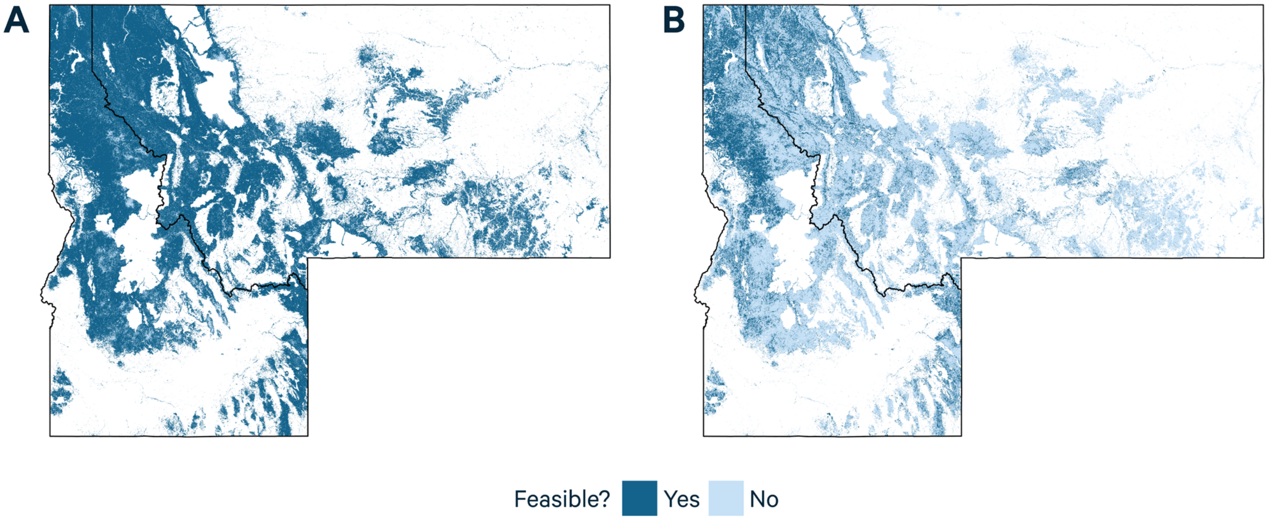
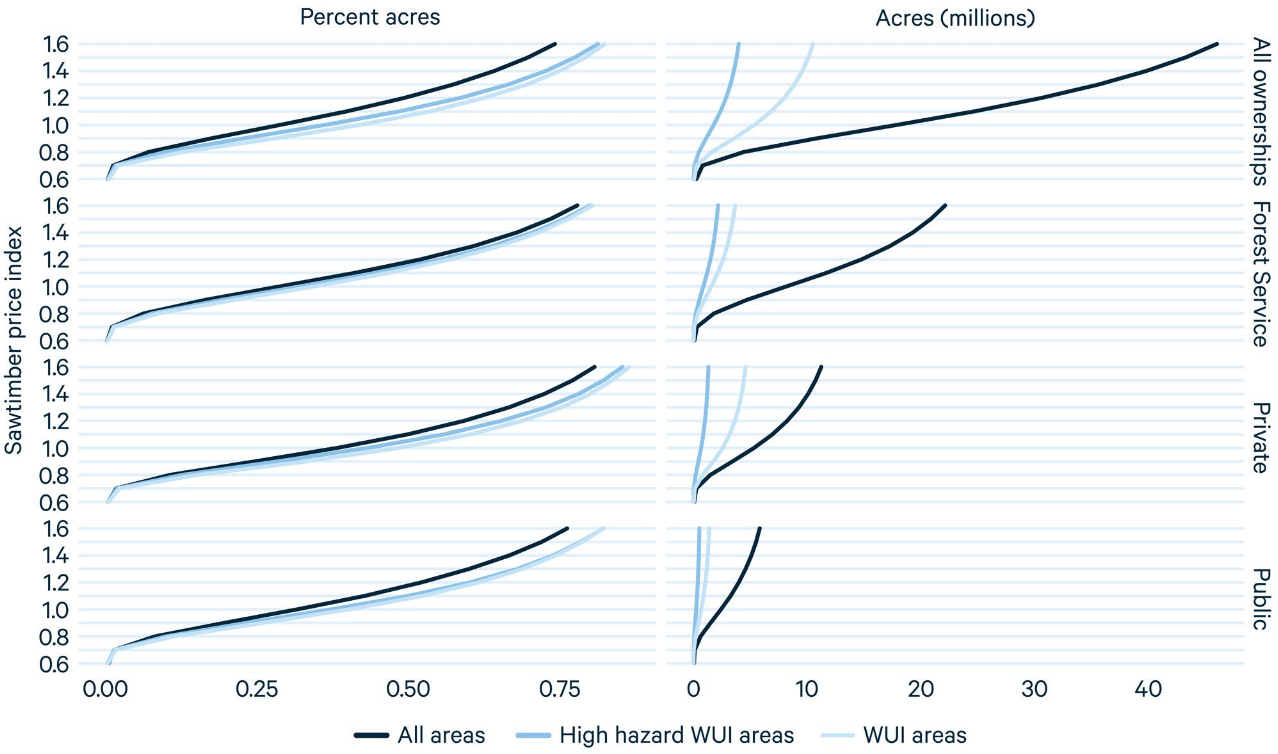


Figure 9. Supply of feasibly treated WUI areas (percentage treatable of total and treatable area) under the 20 percent sawtimber harvest scenario (scenario 3) and varying sawtimber prices



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Appendix

A.1. Logging Estimates

We survey the literature on logging costs for small-diameter materials (thinning or fuel treatments) to generate estimates of stump-to-truck costs (Han et al. 2017; Han and Han 2020; Harrill 2010; McIver et al. 2003; Pan et al. 2008; Petitmermet et al. 2019; Townsend et al. 2019). Costs are adjusted to 2012$ values using the GDP price deflator. Small-diameter materials are often processed in the field with a grinder (rather than a chipper), and some studies include these grinding costs (average of $10.47), which we subtract to define a common value across all studies (Table A1, Figure A1).

Table A1. Estimates of stump-to-truck costs (2012$) for small-diameter harvesting from the literature

Source	Material	System	Total cost	Grinding cost	Stump-to-truck cost
			$/GT		
Pan et al. (2008)	Small	Ground	$22.97	$14.35	$8.62
Harrill et al. (2010)	Small	Ground	$36.86	$11.41	$25.45
Townsend et al. (2019)	Small	Ground	$28.08	$7.59	$20.48
Townsend et al. (2019)	Small	Ground	$37.22	$7.78	$29.44
Han et al. (2017)	Small	Ground	$33.37	$11.24	$22.14
Han and Han (2020)	Small	Cable	$37.34	$0.00	$37.34
Han and Han (2020)	Small	Cable	$34.31	$0.00	$34.31
McIver et al. (2003)	Small	Ground	$27.48	$0.00	$27.48
McIver et al. (2003)	Small	Ground	$28.17	$0.00	$28.17
McIver et al. (2003)	Small	Ground	$32.27	$0.00	$32.27
McIver et al. (2003)	Small	Skyline	$90.51	$0.00	$90.51
McIver et al. (2003)	Small	Skyline	$71.92	$0.00	$71.92
McIver et al. (2003)	Small	Skyline	$56.74	$0.00	$56.74
Petitmermet et al. (2019)	Small	Tethered	$30.10	$0.00	$30.10
Petitmermet et al. (2019)	Small	Tethered	$25.47	$0.00	$25.47
Petitmermet et al. (2019)	Small	Ground	$20.48	$0.00	$20.48
Petitmermet et al. (2019)	Small	Ground	$17.36	$0.00	$17.36
Hayes et al. (2019)	Sawlog	Ground	$30.56	$0.00	$30.56
Hayes et al. (2019)	Sawlog	Ground	$32.28	$0.00	$32.28
Hayes et al. (2019)	Sawlog	Ground	$34.75	$0.00	$34.75
Hayes et al. (2019)	Sawlog	Cable	$41.66	$0.00	$41.66
Hayes et al. (2019)	Sawlog	Cable	$48.06	$0.00	$48.06

Note: Stump-to-truck costs for small material often include costs of chipping/grinding material, and the net cost is defined by backing out these costs. Where studies use $/bone dry ton (BDT), we apply a conversion of 1.5 BDT/GT. For the conversion to 2012$, we use a GDP price deflator based on year of study.

Figure A1. Stump-to-truck costs across studies

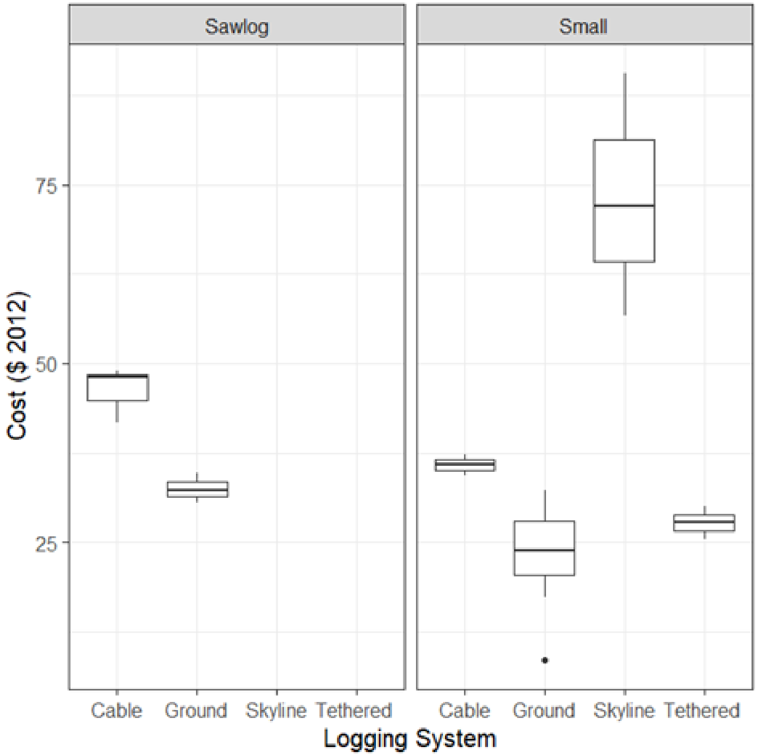


Table A2. Stump-to-truck cost estimates (2012$/GT) by system based on literature survey

	Slope class	Small diameter	Sawlog
	Percentage	$/GT	
Ground systems	0–35	$24.81	$32.28
Cable	36–60	$35.82	$41.66
Skyline	>60	$73.06	$48.94

Note: Cost of ground systems for small-diameter material is the average of observations absent the outlier in Pan et al. (2008). Cost of cable systems (both ground lead and skyline) for small-diameter material is the average across all studies. For sawlogs, we use the average cost of ground-based systems from BBER. Because BBER cost estimates for cable systems include skyline, we use the low bound for nonskyline cable and the high bound for skyline costs.

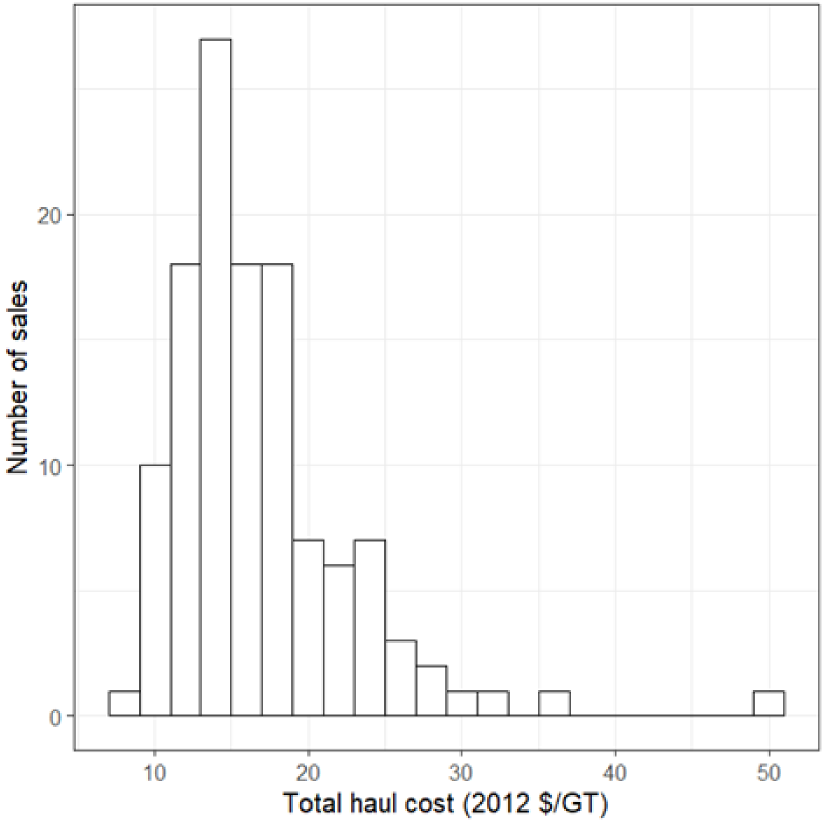
A.2. Stump-to-truck cost estimates (2012$/GT) by system based on literature survey

We develop a dataset of haul cost estimates for a sample of timber sales sold by the state of Montana between 2018 and 2022 (MT DNRC 2022). We extract data from individual sale prospectus documents, including sale location using the United States Public Land Survey System (i.e., township, range, and section ids) to connect haul cost estimates to specific locations. We then compile the data for each completed sale using the following approach:

1. Review “notice/prospectus/maps” document.
2. If sale includes cutting units in more than two sections, then discard.
3. If sale includes cutting units in two sections, inspect map. If units are dissimilar across sections, then discard; otherwise, record two entries for sale (one for each township, range, and section location).
4. If sale includes cutting units in one section, then enter data.
5. Record sale name, section, township, range, year of sale, paved and unpaved haul distance, tons/thousand board feet (mbf) harvested, purchaser’s share of road development costs, and purchaser’s share of road maintenance costs ($/GT).

Haul costs ($/GT) are estimated by applying a cost regression equation currently used for USFS timber sale appraisals (forest economist Mike Niccolucci, pers. comm.) to recorded haul distances. Estimated total transportation costs are the sum of estimated haul cost and recorded road construction and maintenance costs from each sale prospectus.

Figure A2. Distribution of haul cost estimates for sales within state of Montana timber sale data



A.3. Sawtimber Prices

Sawtimber prices (Q1 2018) are based on prices for sawlogs delivered to mills as reported by the University of Montana's Bureau of Business and Economic Research. We link reported prices by species group from western Montana to individual species codes in the FIA database tree records, as shown in Table A3.

Table A3. Delivered sawlog prices ($/mbf, Scribner decimal rule) by species from BBER (n.d.b)

Species code	Common name	Price ($/mbf)
242	Western redcedar	$550.00
93	Engelmann spruce	$409.00
108	Lodgepole pine	$409.00
73	Western larch	$407.00
202	Douglas-fir	$407.00
17	Grand fir	$384.00
122	Ponderosa pine	$378.00
119	Western white pine	$369.00
263	Western hemlock	$369.00
264	Mountain hemlock	$369.00
19	Subalpine fir	$359.00

Source: BBER (n.d.b)

A.4. Additional Figures

Figure A3. Timber harvest by county, 2002–5 and 2014–7

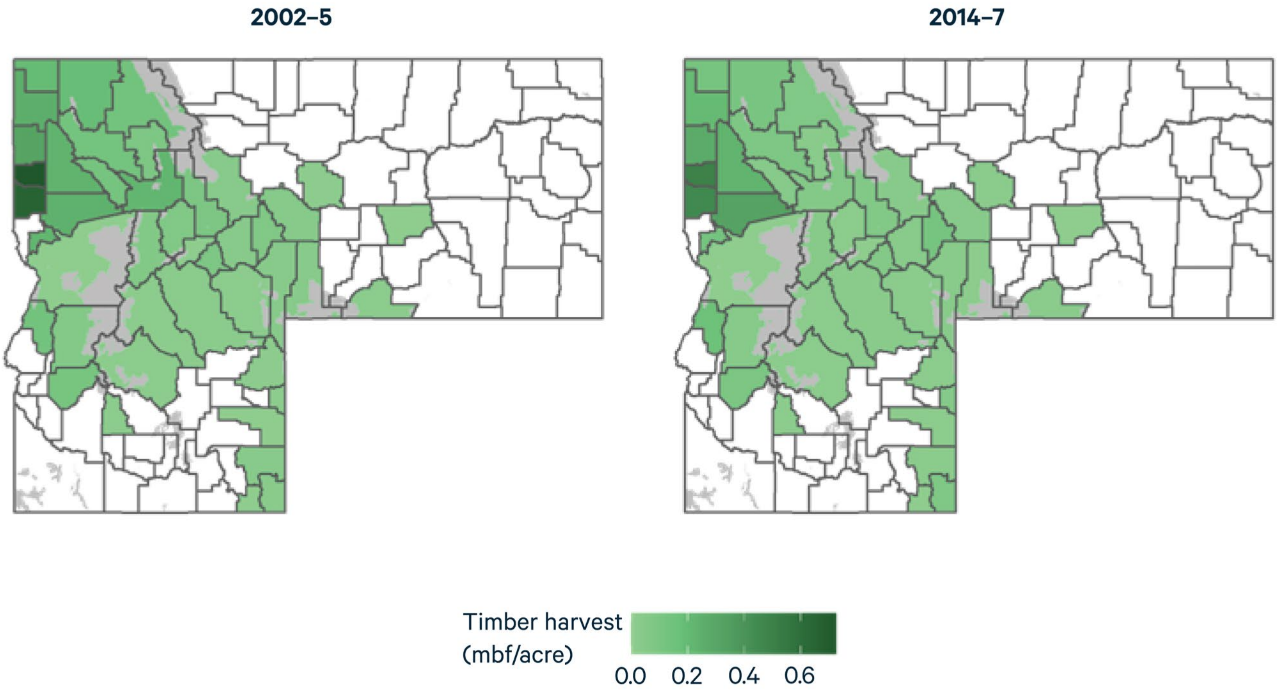


Figure A4. Sawtimber and nonsawtimber inventory in Idaho and Montana, calculated based on applying expansion factors to FIA plot observations, by state and ownership

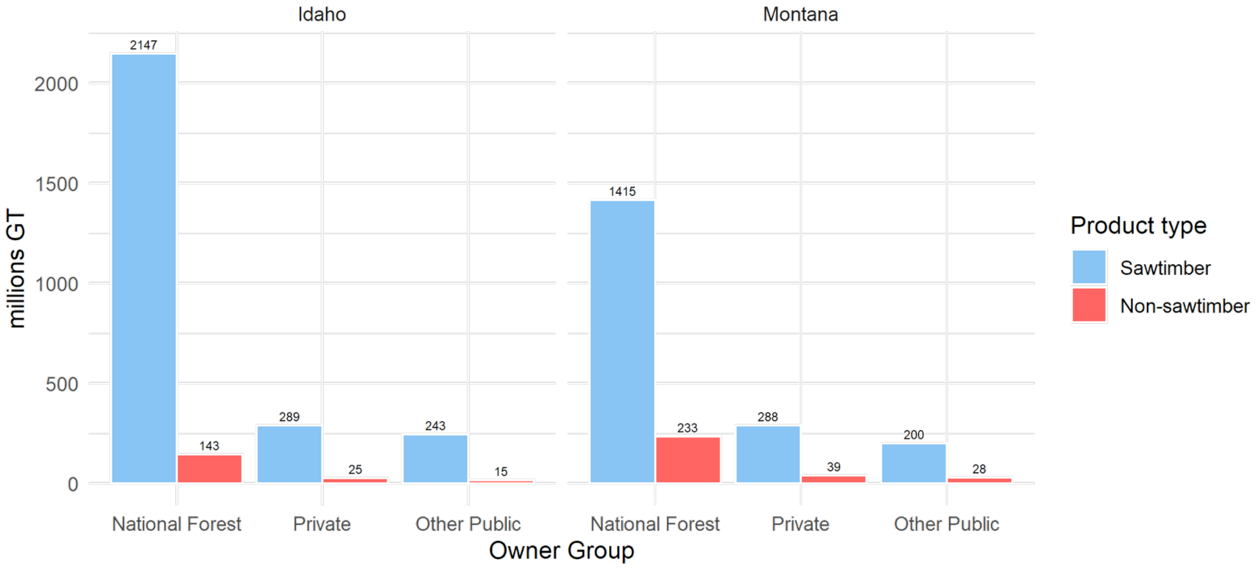
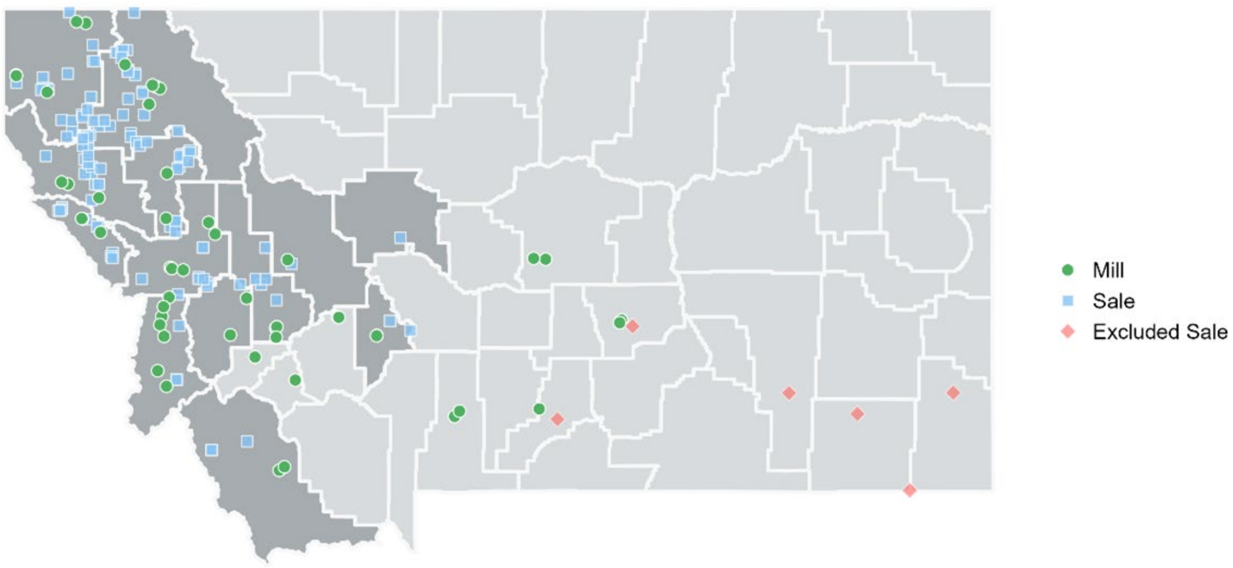


Figure A5. Map of Montana mills, wood product sales, and counties used in parameterization of transportation costs



Note: Counties used in transport speed parameterization are shaded.