Trees, Forests and People 26 (2026) 101417

Contents lists available at ScienceDirect

Trees, Forests and People

journal homepage: www.sciencedirect.com/journal/trees-forests-and-people

Economic impacts of mass timber production using small-diameter wood from fuel reduction and restoration treatments in eastern Oregon

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ARTICLE INFO

Keywords:
Wildfire resilience
Mass timber
Fuel treatments
Small-diameter logs
Economic impacts assessment

ABSTRACT

The Blue Mountains ecoregion of eastern Oregon, encompassing the Malheur, Umatilla, and Wallowa–Whitman National Forests, faces escalating wildfire risk driven by historical fire exclusion and fuel accumulation. This study integrates spatially explicit fuel reduction and restoration treatment planning with mass timber production to simultaneously enhance fire resilience and stimulate rural economic development. Using TreeMap 2022 data and potential operational delineations, we found that 69% of forests exceed fire-resilient desired future conditions, with 31% prioritized as potential treatment units for mechanical thinning across three national forests. The small-diameter wood volume (10–23 cm diameter) for Ponderosa pine and Lodgepole pine, typically unmerchantable in conventional markets, was evaluated for mass timber production under three treatment scheduling scenarios: *basecase20* (20 years), *accelerated10* (10 years), and *extended30* (30 years). Input–output modeling through IMPLAN revealed substantial regional economic impacts, generating 365 total jobs (direct, indirect, and induced) and $105 million in total output under the *basecase20* scenario. Ripple effects were concentrated in logging, sawmilling, and transportation sectors along the I-84 corridor, demonstrating that each dollar invested in mass timber processing generates an additional 31 cents in the regional economy. These findings highlight a scalable pathway to offset restoration costs, reduce wildfire hazard, and revitalize rural communities through the utilization of small-diameter wood for value-added forest products.

1. Introduction

Wildfire activity has been steadily increasing across the western U.S., with measurable rises in frequency (Kenward et al., 2016), economic expense (USDA Forest Service, 2015, 2018), and ecological and social impacts (Palaiologou et al., 2020). The cumulative toll of lives lost, property damage, smoke-related health issues, and rapidly mounting suppression expenditures has led the USDA Forest Service (USFS) to declare a “wildfire crisis” (Huerta Sanchez, 2024). This crisis is driven by three main, interacting factors: (1) climate change, which increases the frequency of extreme fire weather events (Abatzoglou and Williams, 2016); (2) the continued expansion of the wildland–urban interface (Balch et al., 2017; Higuera et al., 2023); and (3) the legacy of fire exclusion, which has produced heavy fuel accumulation in historically fire-adapted forests (Hessburg et al., 2005; Steel et al., 2015). Consequently, policy and management discourse have shifted toward developing more effective strategies for wildfire control and mitigation through proactive forest restoration (Rice, 2017).

Eastern Oregon exemplifies these dynamics, where historically fire-adapted forests now face both ecological vulnerability and economic barriers to restoration. The Blue Mountains ecoregion, which includes the Umatilla, Malheur, and Wallowa–Whitman National Forests (NFs) on the east side of the Cascade Range, represents a landscape where restoration treatments are needed to enhance forest fire resilience (Vernon et al., 2023). The region is characterized by dry forest types, particularly susceptible to high-severity fires. Current restoration efforts in this region focus on selective thinning, prescribed fire, and other vegetation management techniques designed to build more fire-resilient landscapes and promote long-term ecological recovery (Hessburg et al., 2015; Spies et al., 2010).

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https://doi.org/10.1016/j.tfp.2026.101417

Available online 21 July 2026

Among the strategies available, mechanical thinning and prescribed burning for fuel reduction purposes are the most widely implemented. Prescribed burning typically involves controlled ignition of understory vegetation, reducing surface fuels. Mechanical thinning, by contrast, involves the selective removal of small-diameter trees and dense vegetation, reducing ladder fuels to create conditions under which prescribed burning can be conducted safely and effectively. Furthermore, thinning treatments can also reduce pest outbreaks, indirectly increasing forest resilience (Agee and Skinner, 2005; North et al., 2009).

However, the financial burden of these restoration operations remains a substantial obstacle to widespread implementation (Chang et al., 2023). Specifically, the high cost of harvesting and transportation is rarely offset by the low market value of the resultant small-diameter timber and residues. Despite efforts to develop markets for small-diameter and low-value wood, widespread economic success has remained limited, highlighting the continued need for innovative approaches to utilization (Porter and Longcor, 2020).

Implementing fuel reduction restoration treatments at scale requires high-quality information to guide planning, prioritization, and resource allocation. Advanced strategies, such as Potential Operational Delineations (PODs) (Dunn et al., 2020), and physically based fire behavior models (Finney, 2006), enhance the ability to identify and reinforce fire management opportunities. However, the effectiveness of these tools depends on accurate, fine-resolution, and spatially explicit terrain and vegetation data, which are often scarce or costly to generate (Carbone et al., 2016; Elshawi et al., 2018). Moreover, a core technical challenge in accurately estimating treatment needs and biomass delivered costs lies specifically in how spatial data are stored and analyzed. Most existing approaches rely on vector datasets of polygons for individual stands. While this format aligns with traditional silvicultural practice, it complicates fine-scale spatial analysis and consequently constrains the extent of landscape assessment (Keefe et al., 2014; Wells et al., 2016). Raster data, in contrast, divides landscapes into small grid cells, providing greater analytical flexibility. Raster systems streamline storage, reduce processing time (Möller and Nielsen, 2007), and easily combine multiple data layers using map algebra (Hogland and Anderson, 2017). Integrated with ground plot data, remote sensing, and data imputation techniques further enhance raster-based analysis, providing detailed, grid-based information on forest structure and biomass estimates for broad-scale landscape assessments (Hogland et al., 2014).

Identifying and prioritizing areas for restoration treatments requires an ecological planning framework that integrates fuel reduction objectives with goals for forest structure and other land management priorities. We adopt the framework of desired future conditions developed by Hogland et al., (2021), which synthesizes ecological principles into explicit criteria for stand density, species composition, and spatial heterogeneity to promote wildfire resilience across large landscapes. The application of this framework requires high-resolution spatial data, such as raster-based biomass mapping (Hogland and Anderson, 2017; Houtman et al., 2025) integrated with strategic fire control points defined by PODs (Dunn et al., 2020), to guide restoration treatment and intensity.

Forest restoration treatments often generate large volumes of small-diameter trees that lack traditional sawtimber value, creating a fundamental economic challenge for implementing these treatments on scale. The costs associated with feedstock procurement, including harvesting, collection, and transportation, constitute a major portion of the overall treatment expenses and are critical variables due to factors such as the spatial distribution of biomass, transport logistics, and market availability (Campbell et al., 2018; Keefe et al., 2014). The low value of the small-diameter wood compounded by high handling and transportation costs makes it difficult to justify treatments economically without identifying additional revenue sources or cost offsets (Yue et al., 2014; De Meyer et al., 2014; Zhang et al., 2011).

In the Blue Mountain region, these logistical and economic challenges are further compounded by a shrinking sawmill infrastructure. Multiple facilities have closed in recent years, leaving only one sawmill remaining operational in the southern region and just two sawmills to the north. While these three remaining facilities are technically capable of processing logs down to a 15 cm small end diameter, their preferred minimum diameter is currently 23 cm. This operational preference stems from both the efficiency of the existing equipment and the lack of established markets for smaller dimension lumber (personal comm). Ultimately, addressing this dual economic constraint is essential to expanding the adoption of restoration treatments as a landscape-scale wildfire mitigation strategy.

One potential pathway for utilizing small-diameter wood from restoration is the production of mass timber, a category of engineered wood products designed for sustainable construction (Ramage et al., 2017). Products such as Cross-Laminated Timber (CLT) and Glue-Laminated Timber (GLT) are manufactured by assembling dimension lumber into high-strength structural components (Fini et al., 2017). Mass timber offers significant benefits. It stores carbon (Robati and Oldfield, 2022) while serving as a lightweight structural alternative to steel and concrete in mid- and high-rise construction (Kremer and Symmons, 2015). Mass timber demand is growing rapidly in the U.S. market and globally. For instance, U.S. Pacific Northwest (PNW) consumption is projected to grow by a 20% compound annual growth rate, from 60,500 m^3 in 2024 to 182,000 m^3 by 2030 (Anderson et al., 2025). Small-diameter softwood is not currently the primary feedstock for mass timber manufacturing, but a growing body of evidence indicates it holds technical promise as an alternative source of dimension lumber. European research has demonstrated that with optimized sawing techniques, small-diameter logs can yield structurally viable lumber for CLT production (Fredriksson et al., 2015), and recent work on Ponderosa pine harvested specifically from restoration programs has shown that resulting CLT layups meet the bending performance characteristics required for structural applications (Jahedi et al., 2024). Building on this evidence, the successful utilization of small dimension lumber sawn from small-diameter restoration wood for mass timber manufacturing presents a promising, though as yet commercially unrealized, economic mechanism that could both develop new markets and offset the financial costs of forest restoration. In the PNW, however, CLT and GLT manufacturing predominantly relies on large dimension lumber, with production largely concentrated on Douglas-fir species. The utilization of smaller dimension materials, especially from pine species, the main tree species in dry, mixed conifer forests where fire risks are high, remains an emerging practice (USDA Forest Service, 2023).

The primary objective of this study is to conduct an economic impact analysis quantifying the potential regional benefits of establishing a mass timber supply chain based on small-diameter restoration material. This analysis specifically targets the pine-dominated Blue Mountain region, using feedstock harvested from the Malheur, Umatilla, and Wallowa–Whitman National Forests. Our analysis is based on the assumption that new, commercially viable technology will emerge to efficiently convert these small Ponderosa pine and Lodgepole pine logs into lumber for mass timber manufacturing.

Our methodology integrates ecological planning (Raster Tools developed by Hogland et al., (2021)) with economic modeling using Impact Analysis for Planning (IMPLAN). We first assess current forest conditions across the three National Forests and establish desired future conditions (DFCs) that define structural benchmarks for fire-resilient forests. Forest stands exceeding these resilience thresholds are identified as candidates for restoration treatment, representing areas where fuel and density reduction is necessary. For these areas, we quantify the merchantable wood volume derived from the removable trees, categorized by softwood species of interest (i.e., Ponderosa pine (PP) and Lodgepole pine (LP)) and small-end diameter classes. To minimize market disruption, we assume that only the log proportion between 10 cm and 23 cm diameters would be utilized for new mass timber production, and this volume is allocated to the three existing sawmills in the region. Mass timber production is also assumed to occur at current sawmill locations, with finished products then shipped to a prefabricated modular housing panel manufacturing facility planned near Portland, Oregon (Anderton and Gunn, 2025).

We employ the IMPLAN system, a widely used input–output model, to evaluate the resulting economic effects (Henderson et al., 2017). IMPLAN tracks monetary flows among industries, government, and households, capturing imports and exports at the regional level (Clouse, 2023). IMPLAN-based economic contribution analysis has been increasingly applied across the forest products industry in recent years, including comprehensive national-level assessments of the sector's overall economic footprint (Poudel and Dahal, 2025), underscoring the suitability of this modeling framework for evaluating emerging, forest-products-based value chains such as the one considered here. Impacts are categorized as direct (i.e., industry expenditure), indirect (i.e., supply-chain effects), and induced (i.e., spending from increased household income). Economic outcomes are reported through measures such as employment, labor income, value added, and industry output (Thapa et al., 2025a; Clouse, 2021).

2. Materials and methods

2.1. Study landscape and input data

Our study focuses on three national forests (NFs): Malheur (688,000 ha), Umatilla (570,000 ha), and Wallowa–Whitman (930,000 ha) located within the Blue Mountain ecoregion (Fig. 1). This region is characterized by dry grasslands, shrublands, and pine-dominated forests (Simpson, 2007).

The core spatial inputs required for ecological restoration planning utilized a raster framework composed of several datasets. These layers included tree-level estimates (e.g., tree size, species, density) assigned to each grid cell, a topographic map, road networks, fire management boundaries, and the locations of sawmill facilities. We utilized TreeMap 2022 CONUS (Houtman et al., 2025) to generate the necessary tree-level estimates for forest composition and structure at a 30 × 30 m resolution across the study landscape. This dataset combines Forest Inventory and Analysis (FIA) plot data (USDA Forest Service, 2019) with topographic, climatic, and disturbance variables through a random forest modeling framework, offering high spatial precision for ecosystem assessments. Topographic information, including slope, aspect, and elevation, was derived from the U.S. Geological Survey's 3D Elevation Program (3DEP) (Gesch et al., 2002). These variables are important determinants of vegetation patterns, fire behavior, and harvest feasibility in mountainous terrain. Geospatial detail on road networks, rivers, and other hydrological elements critical for assessing accessibility, fuel breaks, and logistical planning was sourced from OpenStreetMap (OSM) data (Haklay and Weber, 2008). Fire management boundaries were defined using PODs (Thompson et al., 2011). PODs partition the landscape into practical units delineated by natural and built features such as ridges, rivers, roads, and fuel breaks, serving as spatial references for aligning restoration objectives with wildfire suppression strategies. Finally, data on existing sawmill locations and IMPLAN economic data were incorporated to connect the spatially explicit restoration planning and timber outputs with regional economic modeling.

2.2. Data analysis

The spatial datasets were analyzed to prioritize areas and quantify timber outputs and supply chain costs. This analytical process was structured into three main steps: (1) Characterization of current and desired future conditions at a 30 × 30 m grid cell resolution; (2) Estimation of removable tree volume by species and top diameter classes; and (3) Delineation of potential treatment units (PTUs) and calculation of harvesting and transportation costs.

2.2.1. Existing and desired future forest conditions

TreeMap 2022 CONUS provided the statistically similar Forest Inventory and Analysis (FIA) plot data for each forested grid cell. Using the

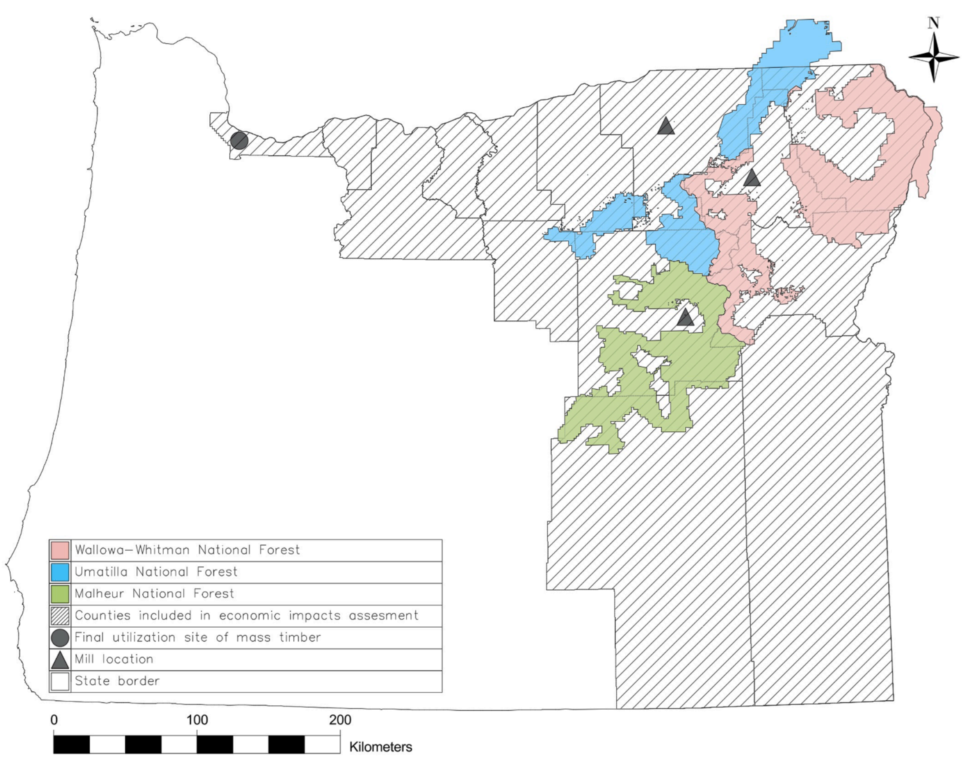

Fig. 1. Study area map, showing the Malheur, Umatilla, and Wallowa–Whitman National Forests in eastern Oregon as the feedstock source for restoration thinning material. The map also delineates the county boundaries, sawmill locations, and the proposed mass timber market location near Portland, Oregon, included in the economic impact assessment.

tree list and tree-level attribute data associated with a given cell, we first calculated the basal area per hectare (BAH) measured in m^2 ha^{-1}. The BAH was determined for each 30 × 30 m grid cell by calculating the basal area for individual trees (t) in the tree list, using the tree's diameter at breast height in inches (D_t) and its trees per hectare (TPH_t), and subsequently summing these values for all trees within the cell (Eq. 1).

$$BAH = \sum \left(0.0005065 \times D_t^2 \times TPH_t\right) \quad (1)$$

We adopted the desired future conditions (DFCs) framework from Hogland et al., (2021), which defines target BAH thresholds for stand structure. These thresholds are based on key landscape gradients, including slope, aspect, elevation, proximity to water, and distance from PODs (Table 1). Areas near water bodies or on steep slopes were retained in their existing structural state to protect ecological integrity and hydrologic stability. In contrast, drier and south-facing slopes were specifically targeted for greater canopy reduction to increase heterogeneity and fuel discontinuity.

2.2.2. Removable tree volume estimation

We identified potential restoration treatment areas where the current BAH exceeded the target BAH threshold defined by the DFCs. The excess BAH was calculated and applied to estimate the removable tree volume for each grid cell. Specifically, we calculated the proportion of the stand basal area requiring reduction by dividing the excess BAH by the grid cell's total BAH. This proportion was then multiplied by the grid cell's total merchantable tree volume to estimate potential removal, based on the assumption that volume removal is proportional to the reduction in basal area.

To determine species and top diameter-specific removals, the total individual tree volume in cubic feet (from base to top) was first estimated using species-specific volume equations developed for the Pacific Northwest region (Waddell et al., 2014) (Table 2). Assuming the merchantable portion includes volume up to the 10 cm top diameter, we then calculated the tree height at that 10 cm top diameter using taper equations for softwoods (Czaplewski et al., 1989) (Eq. 2) and hardwoods (Bluhm et al., 2007) (Eq. 3) along with the bisection method (Burden et al., 2016). The final merchantable tree volume from base to 10 cm top diameter was calculated by subtracting the cone volume of the treetop (above 10 cm base diameter) from the total volume.

Table 2
Examples of the species-specific volume equations documented in (Waddell et al., 2014) used for major softwood species in the study region to estimate total tree volume (ft^3) from tree base to top. CVTS is the cubic feet volume of a tree from base to top, DBH is the diameter at breast height in inches, and HT is the total tree height in feet.

Species	Volume equations
Ponderosa pine	$CVTSL = -8.521558 + 1.977243 \times \ln(DBH) - 0.105288\,\{ln(HT)\}^2 + \frac{136.0489}{HT^2} + 1.99546 \times ln\,(HT)$ $CVTS = \exp(CVTSL)$
Lodgepole pine	$CVTSL = -2.615591 + 1.847504 \times \log(DBH) + 1.085772 + log(HT)$ $CVTS = 10 * *(CVTSL)$
Douglas-fir	$CVTSL = -6.110493 + 1.81306 \times \ln(DBH) + 1.083884 + ln(HT)$ $CVTS = \exp(CVTSL)$

For calculating section volumes (e.g., between 10 cm and 23 cm), the same height estimation method was used, and the section volumes were calculated as truncated cone volumes defined by the two end diameters and the height difference between those two end diameters. These sectional volume estimates, particularly those derived from Ponderosa pine and Lodgepole pine, were then used to evaluate the economic impact of small-diameter wood utilization. This analysis assumes the adoption of optimized small-log sawing and milling technology capable of efficiently converting small-end diameter softwood logs (down to 10 cm) into dimension lumber suitable for mass timber production. This assumption is supported by demonstrated technical feasibility in prior research: optimized sawing of small-diameter logs has been shown to yield structurally viable lumber for CLT manufacturing (Fredriksson et al., 2015), and CLT panels produced from small-diameter Ponderosa pine sourced from restoration treatments have met required structural performance standards (Jahedi et al., 2024). As such processing capacity is not yet widely deployed at commercial scale in the Pacific Northwest, this represents a forward-looking assumption of the study rather than a description of current industry practice. All removable volumes, initially calculated in cubic feet, were converted to cubic meters using the conversion factor of 0.0283168.

$$d_s(h) = D\cdot\sqrt{b_1\cdot(x-1) + b_2\cdot(x^2-1) + b_3\cdot(a_1-x)^2\cdot I_1(x < a_1) + b_4\cdot(a_2-x)^2\cdot I_2(x < a_2)} \quad (2)$$

where, $d_s(h)$ is the diameter (in inches) at a specific height (h) in feet for softwood species, D is the diameter at breast height in inches, H is the total tree height in feet, x is the relative height (h/H), and b_1, b_2, b_3, b_4, a_1, and a_2 are species-specific coefficients, and I_1 and I_2 are binary indicators (1 if the conditions $x < a_1$ and $x < a_2$ are true, respective; 0 otherwise).

$$d_h(h) = D\cdot X^C \quad (3)$$

where, $d_h(h)$ is the diameter (in inches) at a specific height (h) in feet for hardwood species, X is a relative height transformation and calculated as $\frac{1-\sqrt{Z}}{1-\sqrt{P}}$, with $Z = h/H$ and $P = 4.5/H$, and C is the variable exponent calculated as $a_3 \cdot (C_1 + C_2)$, where $C_1 = 1.364409 * D^{1/3}\cdot\exp(a_4\,Z)$ and $C_2 = exp(a5 \cdot CR \cdot a_6 \cdot \left(\frac{D}{H}\right)^{a_7} \cdot Z)$, CR is crown ratio, and coefficients a_3, a_4, a_5, a_6, a_7 are species-specific coefficients.

Table 1
Spatially explicit target basal area per hectare (BAH) thresholder for restoration treatment.

Feature	Characteristic	Threshold (Metric)	Desired BAH (m^2 ha^{-1})
Deferred	Area	NA	Existing BAH
Water	Distance From	< 30.5 m	Existing BAH
Water	Distance From	> 30.5 m	See Aspect Feature
Elevation	Slope	< 50%	See Aspect Feature
Elevation	Slope	> 50%	Existing BAH
Elevation	Aspect	290° < Aspect < 360° or 0° < Aspect < 70°	19.5
Elevation	Aspect	70° < Aspect < 290°	14.9
PODs	Distance From	< 610 m	4.6

Table 3
Criteria used to spatially define harvesting systems and treatment costs. Machine rates ($ hr^{-1}) and payload are adopted from Hogland et al., (2021) and modified for volume units and updated to reflect operational rates specific to this study.

Component	System	Rate	Rate of travel	Payload	Where it can occur
Offroad	Rubber tire skidder	$165 h^{-1}	2.4 km h^{-1}	5.6 m^3	Slopes ≤ 35% and next to roads (distance < 460 m from a road).
	Skyline	$400 h^{-1}	3.2 km h^{-1}	4.3 m^3	Slopes > 35% and within 30 m of a road.
	Helicopter	$8,000 h^{-1}	3.9 km h^{-1}	7.1 m^3	Areas not covered by the other two and distance < 914 m from landing area.
Felling	Feller buncher	$7.06 m^{-3}	NA	NA	Slopes ≤ 35%
	Hand Felling	$12.36 m^{-3}	NA	NA	Slopes > 35%
Processing	Delimbing, bucking, and loading	$24.72 m^{-3}	NA	NA	NA
On road	Log Truck	$115 h^{-1}	Vary*	28.3 m^3	NA
Additional treatments	Prescribed fire	$519 ha^{-1}	NA	NA	Forested areas

* Road type and maximum speed: Residential 40 km h^{-1}, unclassified 24 km h^{-1}, tertiary 56 km h^{-1}, secondary 72 km h^{-1}, primary 88 km h^{-1}, and motorway 105 km h^{-1}.

2.2.3. Potential treatment units (PTUs) and feedstock cost

A potential treatment unit (PTU) was defined as a contiguous area of at least 5 ha in size, consisting of grid cells with a minimum of 38 m^3 per hectare removals. Using these thresholds, we analyzed each NF to develop PTUs that represent restoration units for further costs and logistics planning.

The final delivered feedstock cost at mill gates was estimated following the approach developed by Hogland et al. (2018), which encompasses all expenses related to felling, processing, and transporting wood from the forest to the mill (Table 3).

For transportation cost estimates, the model employed a least-cost path algorithm (ESRI, 2025). This algorithm converts on-road travel distances into round-trip travel times based on the average driving speed which varies with road type, to identify the least-cost sawmill destination (Louis and Kizha, 2021; Hogland et al., 2018). Timber was assumed to be processed at landings, including delimbing, bucking and loading, before transport. Additionally, the analysis included post-harvest treatments, such as hand piling and prescribed burning, and accounted for the lumber processing costs of $120.22/$m^3$ at each sawmill (Anderson, 2024).

Cost inputs in this study were drawn from several sources spanning 2017–2024 (Table 3, Table 4) and were not deflated to a common price year prior to use in the 2023 IMPLAN model. We note, however, that our dominant dollar-denominated cost inputs, the lumber processing cost (Anderson, 2024) and the CLT market price range used in our producer-surplus comparison (Atkins et al., 2023) are contemporaneous or near-contemporaneous with our 2023 base year. The comparatively older sources (Oregon BEST, 2017; Anderson et al., 2020) inform the proportional intermediate input shares in Table 4 rather than absolute cost levels, and such relative expenditure shares are inherently less sensitive to price-level drift than dollar-denominated inputs, consistent with standard input–output practice of applying fixed-weight technical coefficients across data vintages. We further evaluate the sensitivity of our results to the largest related assumption (the 50% lumber input share) in Section 4.

Table 4
Customized industry spending pattern for mass timber manufacturing in Oregon.

IMPLAN sector	Code	Proportion	Source
Electric power transmission and distribution	3042	3.5	(Anderson et al., 2020)
Fabric coating mills	3111	3.7	(Oregon BEST, 2017)
Dimension lumber and boards	3124	50.0	(Anderson et al., 2020)
Plastic material and resin manufacturing	3156	8.9	(Oregon BEST, 2017)
Paint and coating manufacturing	3167	0.9	(Oregon BEST, 2017)
Adhesive manufacturing	3168	15.0	(Anderson et al., 2020)
Hand tool manufacturing	3226	2.2	(Oregon BEST, 2017)
Machine shops	3239	3.0	(Khanal et al., 2024)
Packaging machinery manufacturing	3282	1.7	(Anderson et al., 2020)
Wholesale services, machinery, equipment, & supply	3378	2.9	(Oregon BEST, 2017)
Truck transportation	3399	1.5	(Oregon BEST, 2017)
Management of companies and enterprises	3451	6.7	(Oregon BEST, 2017)
Total		100.0	

Note: Percentages represent shares of intermediate input expenditure (summing to 100% of total intermediate input), not shares of gross industry output. The value-added share of Sector 127 (Engineered Wood Member and Truss Manufacturing) retained from the 2023 IMPLAN data for the custom Oregon region is approximately 37% of total industry output.

2.3. Treatment scheduling

Restoring the three NFs in the Blue Mountain region within a single year is impractical due to the scale of the landscape and associated costs. Since fuel reduction treatments remain effective for 10–20 years in general before retreatment is required (Stephens et al., 2012), we phased treatments over time using three scheduling scenarios: the base case 20-year (*basecase20)*, the accelerated 10-year (*accelerated10)*, and the extended 30-year (*extended30*) plans. For each scenario, the total treatable area was divided by the schedule duration (i.e., 10, 20, or 30 years) to define the annual treatment area target. For yearly simulations, PTUs were randomly selected until the annual area target was met, ensuring an unbiased spatial allocation of treatments. The volume of wood obtained in the first year of treatment in these scenarios was then used in the economic impact assessments.

2.4. Lumber and mass timber production

Lumber production efficiency was estimated using a 56% recovery factor, producing 56 m^3 of lumber per 100 m^3 of logs, with the remainder converted to chips, sawdust, or other byproducts (Wagner et al., 2009). A 15% loss rate during mass timber manufacturing was applied to calculate the final mass timber volume (Bebard et al., 2010). Mass timber production was assumed to be co-located with existing sawmill facilities. Therefore, the transportation costs associated with moving lumber between these two processing stages were not included in the analysis (Atkins et al., 2022). Transportation costs from each of sawmill to the mass timber product market near Portland, Oregon were included in the economic impacts assessment: $48.85/$m^3$ from the mill in Southern region and $33.16/$m^3$ from the mills in Northern region, determining the final delivered cost of mass timber products.

2.5. Economic impacts assessment

The economic impacts associated with mass timber manufacturing that utilizes small-diameter wood were assessed using the IMPLAN input-output model. The analysis focused on operational impacts, excluding construction-phase effects, and assumed all mass timber was shipped to Portland, Oregon, for final use. A custom IMPLAN region was defined by combining the following counties: counties where the three NFs reside (Baker, Grant, Harney, Malheur, Morrow, Umatilla, Union, Wallowa, Wheeler), I-84 corridor counties (Gilliam, Hood River, Sherman, Wasco), and Portland (Multnomah), to capture wood flows and economic effects from production to end use (Fig. 1).

Since IMPLAN lacks a specific mass timber sector, we customized Sector 127 (Engineered Wood Member and Truss Manufacturing) to reflect mass timber input structures, following I. Thapa et al. (2025) and Khanal et al. (2024) (Table 4). This sector has also been identified as one of the fastest-growing forest products subsectors nationally in terms of output and value-added (Poudel and Dahal, 2025), further supporting its relevance for mass timber-related economic modeling. Specifically, the absorption coefficients (intermediate input shares) of Sector 127 were replaced with the values shown in Table 4, which represent the best available estimates of the intermediate input spending pattern for a mass timber manufacturing facility. The value-added structure of the default Sector 127, comprising labor income, other property income, and taxes on production and imports was retained unchanged from the 2023 IMPLAN database. The percentages in Table 4 represent shares of intermediate input expenditure (summing to 100% of intermediate input); they do not represent shares of total gross industry output. Based on the 2023 IMPLAN dataset for our custom region, the value-added share of Sector 127 is approximately 37% of total industry output, with the remaining ~63% constituting intermediate inputs to which the spending pattern in Table 4 applies.

The economic impacts of mass timber production were assessed across the three NFs under the three scheduling scenarios: *basecase20, accelerated10*, and *extended30*. Only small-diameter wood between 10 cm and 23 cm obtained from restoration thinning treatments was considered for mass timber production, focusing on Ponderosa pine and Lodgepole pine. Although treatment scenarios span 10–30 years, we used the initial annual wood volume to model a single year of full operation. This approach aligns with the static nature of Input-Output models like IMPLAN, which capture economic effects for a single period.

2.5.1. Estimating direct output of mass timber industry

The direct output (T) of the mass timber industry for each scenario was calculated using unit mass timber production costs, with lumber inputs comprising 50% of total intermediate production cost (Anderson et al., 2020). Specifically, if the unit lumber production cost from restoration treatment is denoted as L ($ m^{-3}), then the total unit mass timber production cost is derived as twice the lumber cost (i.e., C = 2L), because lumber constitutes approximately 50% of total production expenditure. To this is added the unit transportation cost from sawmill to the final utilization site in Portland, yielding the total unit cost U_i. This represents the producer's total unit expenditure and is used as the IMPLAN direct output shock consistent with the prospective cost-based approach of Khanal et al. (2024) and Thapa et al. (2025b). The 50% figure from Anderson et al. (2020) refers to lumber's share of total intermediate production cost for mass timber (operating expenditure on intermediate inputs). The total industry output per scenario was then computed as shown in Eq. 4.

$$T_i = U_i * V_i, \tag{4}$$

where T_i is the total industry output for a particular scenario i, U_i is the unit mass timber production cost for scenario i, and V_i is the total volume of mass timber being produced for scenario i.

It should be noted that in a prospective analysis of an as-yet non-existent mass timber industry based on a novel feedstock pathway, no established market sales price exists for the resulting product. We therefore follow the approach of Thapa et al. (2025b) and Khanal et al. (2024), both of which analyzed prospective mass timber facilities using IMPLAN in constructing the direct output shock from full unit production cost rather than a hypothetical market price. This cost-based shock is explicitly conservative: it captures the intermediate expenditure necessary to operate the industry (feedstock, processing, transport) and therefore provides a lower-bound estimate of the industry's economic footprint. The gap between the estimated production cost ($492–$616 m^{-3}) and prevailing CLT market prices ($1,483–$1,554 m^{-3}; Atkins et al., 2023) represents substantial potential producer surplus available to cover stumpage, profit, capital recovery, and market risk; the resulting economic impacts at realized market prices would be proportionally larger.

2.5.2. Estimating direct employment in mass timber industry

Labor needs for mass timber production vary with facility size, capacity, and product type. Industry data reflect this variability, showing employment ranging from 20 workers for a small facility (Redmore et al., 2021) to about 100 for a large facility with 100,000 m^3 annual capacity (Ridgeway, 2025). Following Thapa et al., (2025b), we categorized manufacturing facilities by annual production capacity and adjusted workforce requirements accordingly. We defined four production scales: small-scale facilities (up to 20,000 m^3) employing 28 personnel; medium-scale operations (20,000 to 34,492 m^3) requiring 48 employees; large-scale facilities (34,492 to 62,000 m^3) supporting a workforce of 86; and mega-scale plants exceeding 62,000 m^3, which generate approximately 180 direct jobs.

The facility-scale employment figures (28/48/86/180 direct jobs for small, medium, large, and mega-scale facilities, respectively) were implemented in IMPLAN as direct employment specifications within the industry output impact event for Sector 127. This approach overrides the default IMPLAN employment-to-output ratio for the sector, which is calibrated to a broad average across all engineered wood products and does not adequately capture the labor intensity of mass timber (CLT/GLT) manufacturing specifically. Direct employment specification is the recommended approach for emerging industries where sector averages are not representative and is consistent with the methodology of Thapa et al. (2025b) and Khanal et al. (2024). Indirect and induced employment effects were then computed through the standard IMPLAN multiplier process, applied to the specified direct employment levels and the associated industry output shock.

3. Results

3.1. Potential treatment units (PTUs) and removal volume

3.1.1. Existing basal area per hectare (BAH)

The raster analysis of the 2.19 million ha forested area across the three NFs estimated the average existing BAH at 15.1 m^2 ha^{-1}, ranging from 0.0 to 89.5 m^2 ha^{-1} (Fig. 2). Average BAH varied slightly by forest: 16.2 m^2 ha^{-1} in Malheur, 15.7 m^2 ha^{-1} in Umatilla, and 13.9 m^2 ha^{-1} in Wallowa–Whitman. A substantial portion of the landscape exceeded the DFC targets, indicating a high need for treatment. Approximately 72% of the forested area in Malheur, 64% in Umatilla, and 70% in Wallowa–-Whitman surpassed their respective DFC thresholds.

3.1.2. PTUs and volume output

The analysis aggregated areas whose BAH exceeds DFC into 8,828 PTUs, after excluding areas that did not meet the minimum timber volume and harvest unit size requirements. The total area included in these PTUs, was 678,747 ha, representing approximately one-third of the forested land across the three NFs (Table 5). This treatable area was distributed as 217,129 ha in Malheur (32%), 174,275 ha in Umatilla

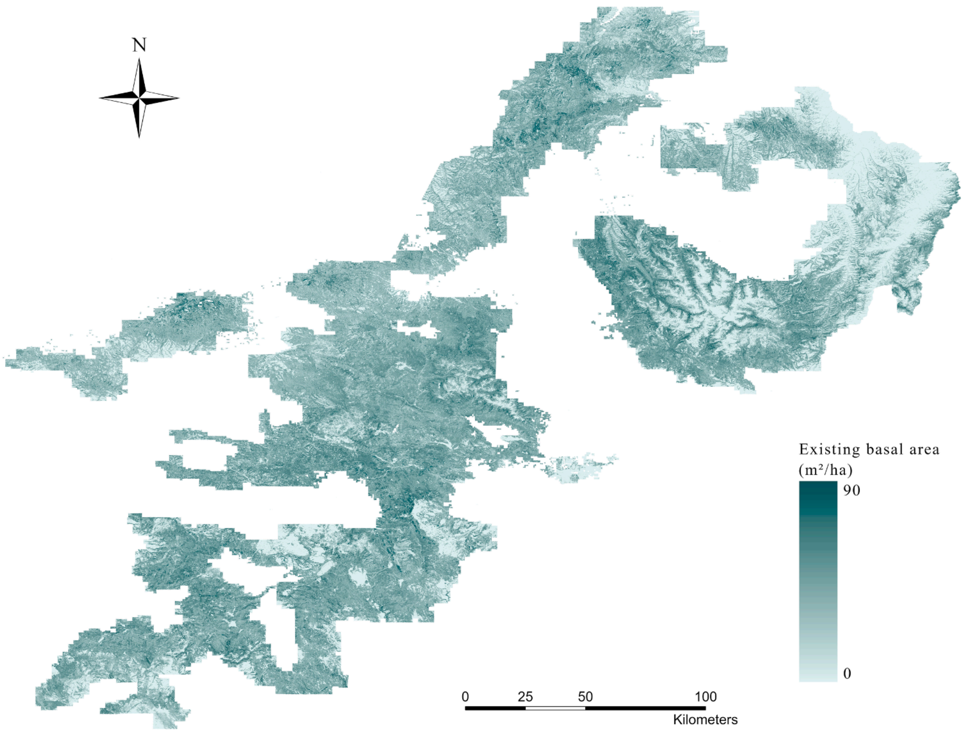

Fig. 2. Spatial distribution of current basal area (m^2/ha) across the study area.

Table 5
Treatment area (ha) and estimated volume output (in 1000 m^3) from Potential Treatment Units (PTUs) by national forest (Malheur (MNF), Umatilla (UNF), and Wallowa–Whitman (WWNF)) and scheduling scenarios. The sectional volume of PP and LP represents the small diameter section volume between 10 and 23 cm available for mass timber feedstock, categorized by Ponderosa pine (PP) and Lodgepole pine (LP).

		PTUs	Scheduling scenario (first-year treatments)		
			Basecase20	Accelerated10	Extended30
MNF	Total area (ha)	217,129	11,264	21,722	7252
	# of PTUs	2941	215	306	152
	Removals per ha (m^3/ha)	97	94	95	95
	Merchantable volume	21,000	1064	2053	687
	Sectional volume of PP	1952	115	178	79
	Sectional volume of LP	380	16	55	7
UNF	Total area (ha)	174,275	8762	18,001	6017
	# of PTUs	2693	173	368	161
	Removals per ha (m^3/ha)	95	91	95	94
	Merchantable volume	16,602	799	1714	564
	Sectional volume of PP	628	38	85	18
	Sectional volume of LP	571	21	36	24
WWNF	Total area (ha)	287,343	14,514	29,173	9587
	# of PTUs	3194	264	399	75
	Removals per ha (m^3/ha)	94	90	91	89
	Merchantable volume	27,034	1310	2649	853
	Sectional volume of PP	1275	66	122	32
	Sectional volume of LP	1259	55	130	46

(31%), and 287,343 ha in Wallowa–Whitman (31%) (Table 5). The PTUs were spread across the NFs: 2,941 in Malheur, 2,693 in Umatilla, and 3,194 in Wallowa–Whitman. Spatially, these PTUs covered a wide range of topography, with merchantable volume removal (up to 10 cm top diameter) ranging from 38 to 210 m^3 ha^{-1} (Fig. 3).

The total merchantable volume was estimated at 64.6 million m^3, including 21.0 million m^3 in Malheur, 16.6 million m^3 in Umatilla, and 27.0 million m^3 in Wallowa–Whitman (Table 5). The average removal rate per hectare was highly consistent across the three NFs, ranging from 94 to 97 m^3 ha^{-1}. The small-diameter portion of this merchantable volume defined as 10 cm to 23 cm for PP and LP species totaled approximately 6.1 million m^3 across the three NFs, constituting the available feedstock for mass timber (Table 5). Of this 6.1 million m^3, PP accounted for 3.9 million m^3, while LP contributed 2.2 million m^3. The Wallowa–Whitman National Forest provided the largest share of this volume (42%), followed by Malheur (38%) and Umatilla (20%).

3.1.3. Feedstock cost

Analysis of the unit cost of lumber production revealed cost variability across the three NFs. The total unit cost was lowest in Malheur (\$233.38 m^{-3}) and highest in Umatilla (\$283.82 m^{-3}), with Wallowa–-Whitman exhibiting an intermediate cost (\$265.53 m^{-3}) (Table 6). This cost differential was almost entirely governed by the stump-to-mill logistics, as the lumber production cost component remained fixed at \$120.22 m^{-3} across all forests. The most influential component of the stump-to-mill cost was off-road transportation, whose share of the total cost varied widely from 27% in Malheur to 38% in Umatilla. The high percentage in Umatilla underscores the logistical challenges posed by its

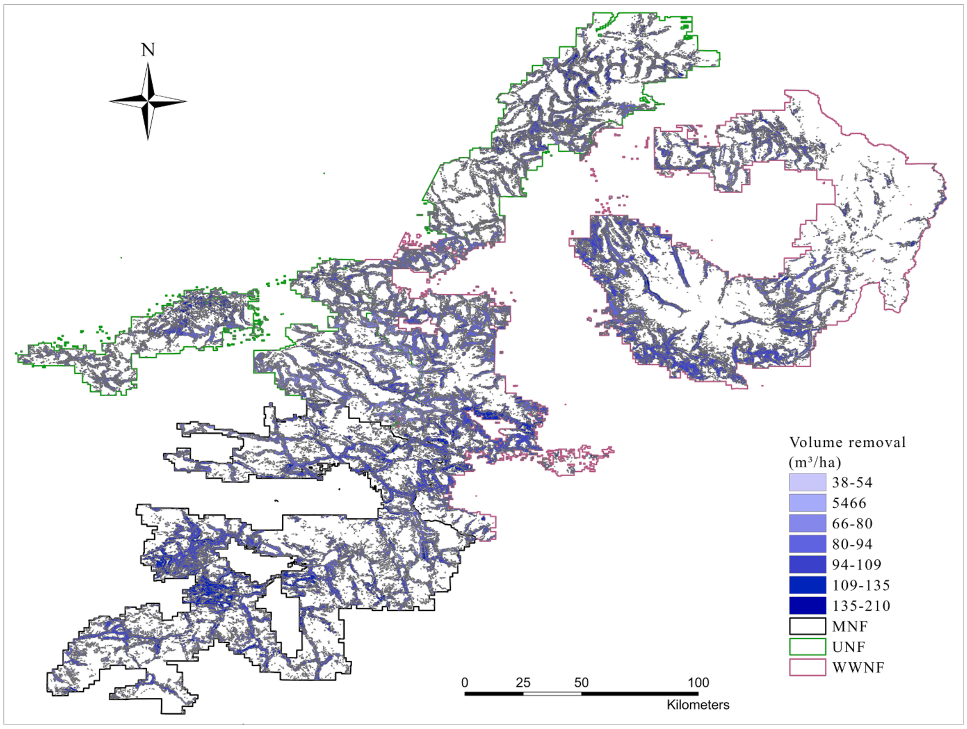

Fig. 3. Spatial distribution of Potential Treatment Units (PTUs) across the study area with their associated merchantable volume removal rates (m^3/ha).

Table 6
Unit costs ($ m^{-3}) of lumber production from Potential Treatment Units (PTUs) by national forest (Malheur (MNF), Umatilla (UNF), and Wallowa–Whitman (WWNF)) across scheduling scenarios. The total unit cost includes all stump-to-mill logistical expenses and a fixed lumber processing cost. The stump to mill costs differ among the three different scenarios in a same NF because the PTUs were randomly selected and these costs represent the average estimated from these selected PTUs.

	Costs		Overall treatment	Basecase20	Accelerated10	Extended30
MNF	Stump to mill	Felling	8.04	7.92	8.30	8.05
		Offroad	63.31	59.63	61.68	51.85
		Treatment	5.37	5.50	5.49	5.48
		Processing	25.14	25.11	25.19	25.06
		Haul	11.30	12.35	11.95	11.19
	Lumber processing		120.22	120.22	120.22	120.22
	Total cost		233.38	230.73	232.83	221.85
UNF	Stump to mill	Felling	8.85	9.02	9.17	8.97
		Offroad	108.07	110.09	114.70	98.04
		Treatment	5.45	5.69	5.45	5.53
		Processing	25.44	25.36	25.33	25.52
		Haul	15.79	15.06	16.70	17.57
	Lumber processing		120.22	120.22	120.22	120.22
	Total cost		283.82	285.44	291.57	275.85
WWNF	Stump to mill	Felling	8.87	8.66	8.77	9.36
		Offroad	92.13	86.05	94.28	87.33
		Treatment	5.52	5.75	5.71	5.83
		Processing	25.46	25.41	25.51	25.65
		Haul	13.33	11.77	12.56	12.28
	Lumber processing		120.22	120.22	120.22	120.22
	Total cost		265.53	257.86	267.05	260.67

rugged terrain, resulting in an off-road cost component that was over 70% greater than that observed in Malheur. Among all cost components, lumber processing consistently represented the largest single cost component, accounting for between 42% and 51% of the total unit cost across the forests. The remaining, smaller cost components felling, treatment, processing, and hauling were relatively stable and collectively accounted for approximately 12% to 16% of the total cost.

3.1.4. *Treatment scheduling*

The random selection of PTUs for the first-year treatments across all scheduling scenarios resulted in a wide distribution of PTUs across the study area. Due to the inherent differences in total treatment area, the merchantable volume outputs varied widely across the scheduling scenarios (Table 5). The *accelerated10* scenario treated the largest area, totaling 68,897 ha and yielding the highest merchantable volume output of 6.4 million m^3. This volume was significantly higher than the *basecase20* scenario, which treated a total of 34,540 ha and generated 3.2 million m^3, and the *extended30* scenario, which treated 22,856 ha and generated 2.1 million m^3.

For small-diameter sections, volume outputs exhibited similar trends across all treatment schedules. Across scenarios, small-diameter PP and LP volumes totaled 311 thousand m^3 under the *basecase20* scenario, 606 thousand m³ under *accelerated10*, and 206 thousand m³ under *extended30*. In all scenarios, PP remained the dominant contributor to small-diameter sectional volume (Table 5).

Unit costs exhibited only modest variation among the three scheduling scenarios, primarily impacting the variable stump-to-mill components (Table 6). The results indicate that the total cost of restoration is relatively inelastic to the specific scheduling scenario chosen, with total unit costs generally fluctuating by no more than 5% from the overall average treatment cost within any given forest.

3.2. Lumber and mass timber production

Assuming a 56% lumber recovery rate, the total lumber production potential derived from merchantable volume outputs across the three NFs was different for different scenarios for the first year (Table 7). For *basecase20*, the potential lumber volume from the small-diameter sectional PP and LP volumes was estimated at 174 thousand m³. The *accelerated10* scenario yielded the highest first-year production of lumber, totaling 339 thousand m³ from the three NFs. The *extended30* scenario produced the lowest first-year volumes, totaling 115 thousand m³.

Under the *accelerated10* scenario, total MT production volume across the study area in the first year was estimated at 288 thousand m³, while 148 thousand m³ under *basecase20* and 98 thousand m³ under the *extended30* scenario. The unit cost associated with mass timber production showed variation among the three NFs but followed a consistent pattern across all scheduling scenarios. The Malheur NF consistently exhibited the lowest unit production costs, ranging from \$493 m^{-3} (*extended30*) to \$515 m^{-3} (*accelerated10*). In contrast, the Umatilla NF consistently showed the highest production costs, ranging from \$585 m^{-3} (*extended30*) to \$616 m^{-3} (*accelerated10*).

3.3. Economic impact assessment

Under the *basecase20* scenario, using the small-diameter PP sections from Malheur NF to produce mass timber results in a total of 119 jobs (86 direct, 17 indirect, and 16 induced), whereas for Umatilla and Wallowa–Whitman NF it was 42 (28 direct, 7 indirect, and 7 induced) and 69 (48 direct, 11 indirect, and 10 induced) respectively (Table 8). The total labor income for Malheur was \$8.4 million whereas for Umatilla and Wallowa–Whitman NF it was \$3.3 million and \$5.2 million, respectively. The total output from mass timber production using small dimension PP was \$36.6, \$14.3, and \$22.5 million respectively for Malheur, Umatilla, and Wallowa–Whitman NF. Using LP results in comparatively smaller economic impacts with 34 jobs and \$5.2 million as total outputs in Malheur whereas it was 36 jobs and \$7.8 million total output for Umatilla and 65 jobs and \$18.8 million total output for Wallowa–Whitman NF.

The *accelerated10* scenario delivered the highest impacts for all the forests. Using PP for mass timber production results in 232 jobs (180 direct, 27 indirect, and 25 induced) in Malheur, 115 (86 direct, 15 indirect, and 14 induced) in Umatilla and 125 (86 direct, 20 indirect, and 19 induced) in Wallowa–Whitman NF. The labor income was \$13.1, \$7.5, and \$9.9 millions, respectively for Malheur, Umatilla, and Wallowa–Whitman NF. The total output was \$57.1 million for Malheur, \$32.5 million for Umatilla, and \$43.1 million for Wallowa–Whitman NF. Use of LP for mass timber production has slightly smaller economic impacts for Malheur (65 jobs and \$17.5 million total output) and Umatilla (41 jobs and \$14 million total output) whereas for Wallowa–Whitman it was slightly higher (128 jobs and \$45.8 million total output) than that of using PP.

The *extended30* scenario yielded the lowest impacts, with a total of 109 jobs from Malheur, 35 from Umatilla and 38 from Wallowa–Whitman NF for using PP whereas using LP the total jobs created were 30, 36, and 63 for Malheur, Umatilla, and Wallowa–Whitman NF, respectively. The total outputs for using PP were \$24.2 million (Malheur), \$6.6 million (Umatilla), and \$10.9 million (Wallowa–Whitman) whereas for LP it was \$2.1 million for Malheur, \$8.6 million for Umatilla, and \$16 million for Wallowa–Whitman NF.

Regarding the Social Accounting Matrix (SAM), the employment multipliers ranged from 1.38 in Malheur to 1.50 in Umatilla, indicating that each direct job in mass timber production supports 0.38 – 0.50 additional jobs regionally. Labor income multipliers were 1.49 across all forests, generating \$0.49 in additional income per dollar of direct labor income. Total value-added multipliers (1.44) and total output multipliers (1.31) were consistent across all forests, adding \$0.44 and \$0.31, respectively, per dollar of direct activity. The SAM employment multipliers (ranging from 1.38 to 1.50) are structurally derived from the same IMPLAN region and modified Sector 127 and are therefore applied consistently across all three national forests. The small numerical variation in reported multipliers across forests reflects differences in the direct employment tier activated by each forest's production volume (e.g., 28, 48, 86, or 180 direct jobs), rather than differences in the underlying regional economic structure. Absolute differences in employment outcomes across forests are attributable to these differences in direct employment base, not to variation in multiplier values. These findings underscore mass timber’s potential role in enhancing regional employment and economic activity while supporting wildfire resilience.

The first-year employee compensation tax contributions for *basecase20* from mass timber production from PP was \$331.9 thousand federal and \$8.5 thousand state for Malheur NF whereas it increased to \$518.3 thousand federal and \$13.2 thousand state for *accelerated10* and decreased to \$219.8 thousand for federal and \$5.6 thousand state for *extended30* scenario. The household tax was highest for *accelerated10* scenario (\$240.9 thousand federal and \$132.8 thousand state). The tax contribution for LP for Malheur NF was comparatively lower than the tax contribution from PP for all three scenarios.

For Umatilla NF, the tax contributions from mass timber production from PP are comparatively lower than Malheur NF for all scenarios such as federal employee compensation tax for *basecase20* is \$130.1

Table 7
First-year lumber and mass timber (MT) production volume (in 1,000 m³) and unit production cost (\$ m^{-3}) of mass timber from small-diameter sections (10–23 cm) by national forest (Malheur (MNF), Umatilla (UNF), and Wallowa–Whitman (WWNF)) and scheduling scenario. Product volumes are categorized by species: Ponderosa pine (PP) and Lodgepole pine (LP).

Scenarios		MNF			UNF			WWNF		
		Lumber volume	MT volume	Unit cost	Lumber volume	MT volume	Unit cost	Lumber volume	MT volume	Unit cost
Basecase20	PP	64.44	54.77	510.29	21.35	18.15	604.03	36.84	31.31	548.88
	LP	9.08	7.72		11.60	9.86		30.79	26.17	
	Total	73.51	62.49		32.95	28.01		67.63	57.48	
Accelerated10	PP	99.81	84.84	514.51	47.35	40.24	616.30	68.25	58.01	567.26
	LP	30.54	25.96		20.39	17.33		72.56	61.68	
	Total	130.35	110.79		67.73	57.57		140.81	119.69	
Extended30	PP	44.22	37.59	492.55	10.14	8.62	584.86	17.64	15.00	554.49
	LP	3.90	3.32		13.27	11.28		26.00	22.10	
	Total	48.13	40.91		23.41	19.90		43.64	37.10	

Table 8
Estimated first-year economic impacts of mass timber production from small-diameter sections (10–23 cm) by species (Ponderosa pine (PP), Lodgepole pine (LP)) and national forest (Malheur (MNF), Umatilla (UNF), and Wallowa–Whitman (WWNF)) across treatment scheduling scenarios. Results detail employment (number of jobs), labor income (LI), total value added (TVA), and total output (TO), with all monetary values reported in $ million.

Scenarios		Activity	Direct			Indirect			Induced			Total Impacts		
			MNF	UNF	WWNF	MNF	UNF	WWNF	MNF	UNF	WWNF	MNF	UNF	WWNF
Basecase20	PP	Employment	86	28	48	17	7	11	16	7	10	119	42	69
		LI	5.7	2.2	3.5	1.7	0.7	1.0	1.1	0.4	0.7	8.4	3.3	5.2
		TVA	10.5	4.1	6.5	2.7	1.1	1.7	2.0	0.8	1.2	15.2	6.0	9.3
		TO	28.0	11.0	17.2	5.7	2.2	3.5	3.0	1.2	1.8	36.6	14.3	22.5
	LP	Employment	28	28	48	3	4	9	3	4	8	34	36	65
		LI	0.8	1.2	2.9	0.2	0.4	0.9	0.2	0.2	0.6	1.2	1.8	4.3
		TVA	1.5	2.2	5.4	0.4	0.6	1.4	0.3	0.4	1.0	2.1	3.2	7.8
		TO	3.9	6.0	14.4	0.8	1.2	2.9	0.4	0.6	1.5	5.2	7.8	18.8
Accelerated10	PP	Employment	180	86	86	27	15	20	25	14	19	232	115	125
		LI	8.8	5.0	6.7	2.6	1.5	2.0	1.7	1.0	1.3	13.1	7.5	9.9
		TVA	16.4	9.3	12.4	4.2	2.4	3.2	3.1	1.7	2.3	23.7	13.5	17.9
		TO	43.7	24.8	32.9	8.8	5.0	6.7	4.7	2.6	3.5	57.1	32.5	43.1
	LP	Employment	48	28	86	9	7	22	8	6	20	65	41	128
		LI	2.7	2.2	7.1	0.8	0.6	2.1	0.5	0.4	1.3	4.0	3.2	10.5
		TVA	5.0	4.0	13.2	1.3	1.0	3.4	0.9	0.8	2.5	7.3	5.8	19.0
		TO	13.4	10.7	35.0	2.7	2.2	7.1	1.4	1.1	3.7	17.5	14.0	45.8
Extended30	PP	Employment	86	28	28	12	4	5	11	3	5	109	35	38
		LI	3.7	1.0	1.7	1.1	0.3	0.5	0.7	0.2	0.3	5.6	1.5	2.5
		TVA	7.0	1.9	3.1	1.8	0.5	0.8	1.3	0.4	0.6	10.1	2.7	4.5
		TO	18.5	5.0	8.3	3.7	1.0	1.7	2.0	0.5	0.9	24.2	6.6	10.9
	LP	Employment	28	28	48	1	4	8	1	4	7	30	36	63
		LI	0.3	1.3	2.5	0.1	0.4	0.7	0.1	0.3	0.5	0.5	2.0	3.7
		TVA	0.6	2.5	4.6	0.2	0.6	1.2	0.1	0.5	0.9	0.9	3.6	6.7
		TO	1.6	6.6	12.3	0.3	1.3	2.5	0.2	0.7	1.3	2.1	8.6	16.0

Table 9
Estimated first-year tax contributions (in $ thousand) from mass timber production across treatment scheduling scenarios. Contributions are presented separately by national forest (Malheur (MNF), Umatilla (UNF), and Wallowa–Whitman (WWNF)) and species (Ponderosa pine (PP), Lodgepole pine (LP), and other softwoods (OS)).

	Scenarios		Employee compensation		Proprietor income		Taxes on production & imports		Household income		Corporations	
			Federal	State	Federal	State	Federal	State	Federal	State	Federal	State
MNF	*Basecase20*	PP	331.9	8.5	11.2	-	10.1	62.9	154.3	85.0	73.6	26.9
		LP	46.8	1.2	1.6	-	1.4	8.9	21.7	12.0	10.4	3.8
	Accelerated10	PP	518.3	13.2	17.6	-	15.8	98.2	240.9	132.8	115.0	42.0
		LP	158.6	4.0	5.4	-	4.8	30.0	73.7	40.6	35.2	12.8
	Extended30	PP	219.8	5.6	7.4	-	6.7	41.6	102.2	56.3	48.8	17.8
		LP	19.4	0.5	0.7	-	0.6	3.7	9.0	5.0	4.3	1.6
UNF	*Basecase20*	PP	130.1	3.3	4.4	-	4.0	24.7	60.5	33.3	28.9	10.5
		LP	70.7	1.8	2.4	-	2.2	13.4	32.9	18.1	15.7	5.7
	Accelerated10	PP	294.5	7.5	10.0	-	9.0	55.8	136.9	75.5	65.3	23.9
		LP	126.8	3.2	4.3	-	3.9	24.0	58.9	32.5	28.1	10.3
	Extended30	PP	59.9	1.5	2.0	-	1.8	11.3	27.8	15.3	13.3	4.9
		LP	78.3	2.0	2.7	-	2.4	14.8	36.4	20.1	17.4	6.3
WWNF	*Basecase20*	PP	204.1	5.2	6.9	-	6.2	38.7	94.9	52.3	45.3	16.5
		LP	170.6	4.3	5.8	-	5.2	32.3	79.3	43.7	37.8	13.8
	Accelerated10	PP	390.7	10.0	13.2	-	11.9	74.0	181.6	100.1	86.7	31.6
		LP	415.4	10.6	14.1	-	12.6	78.7	193.1	106.4	92.2	33.6
	Extended30	PP	98.7	2.5	3.3	-	3.0	18.7	45.9	25.3	21.9	8.0
		LP	145.5	3.7	4.9	-	4.4	27.6	67.6	37.3	32.3	11.8

thousand, *accelerated10* is $294.5 thousand and *extended30* is $59.9 thousand. The PP has the highest tax contribution except in *extended30* scenario where LP dominates the tax contribution in Umatilla NF.

For Wallowa–Whitman NF, the tax contribution for mass timber production using LP were higher for *accelerated10* and *extended30* scenario whereas the PP dominated the *basecase20* scenario a shown in Table 9. The corporate taxes were highest in *accelerated10* scenario with $86.7 thousand federal and $31.6 thousand state for PP and $92.2 thousand federal and $33.6 thousand state for LP.

4. Discussions

The escalating wildfire crisis in the western US necessitates landscape-level fuel reduction and restoration treatments to mitigate wildfire risks and enhance ecological resilience, particularly within fire-prone dry, mixed conifer forests. However, the financial burden of these treatments remains a substantial obstacle to widespread implementation. This study examines the potential economic impact of new mass timber manufacturing technology designed to utilize the small-diameter portion (between 10 and 23 cm) of PP and LP species in the Blue Mountain region of eastern Oregon. We assumed that emerging processing technology capable of efficiently converting small-diameter pine logs into mass timber-grade dimension lumber will become commercially viable. If this assumption is realized, our analysis suggests that such technology could create a new market for low-value, underutilized restoration materials, thereby substantially improving the economic viability of landscape-level fuel reduction and restoration treatments.

Building on high-resolution raster data from TreeMap 2022 (Houtman et al., 2025) and PODs (Dunn et al., 2020), our study prioritized treatments across the Malheur, Umatilla, and Wallowa–Whitman

NFs, using a spatially explicit approach that compared current vegetation status against desirable future conditions (DFCs). The resulting volume of small-diameter softwood, obtained from these treatments, then served as the core input for IMPLAN input-output modeling. This model quantified the direct, indirect, and induced economic impacts generated by processing the small-diameter feedstock into lumber-based mass timber (Clouse, 2023; Henderson et al., 2017).

Our study estimated that a significant portion of the landscape, approximately 69% of the forested area across the three NFs, exceeds the DFC threshold. After considering operational feasibility, about 31% of the forested land was aggregated into potential treatment units (PTUs). This widespread need for fuel reduction and restoration treatments indicates a significant departure from desired fire-resilient conditions. This extensive departure reflects the legacy of fire exclusion, which has resulted in heavy fuel accumulation in historically fire-adapted forests (Hessburg et al., 2005). Past timber-harvest patterns and altered disturbance regimes that have further contributed to denser and more homogeneous stand structures (Koontz et al., 2020; Peterson et al., 2005). Our findings align with previous regional research. Haugo et al., (2015) found that 40% of all coniferous forests across Oregon and Washington required changes in current forest structure, corroborating the extensive scale of structure departure we observed. Accordingly, Hessburg et al. (2016) emphasized that large-scale interventions, such as managed wildfire, prescribed burning, and variable-density thinning, are critical for enhancing forest resilience, reducing wildfire risk, and restoring historical landscape heterogeneity in eastern Oregon.

Our treatment scheduling scenarios indicate that approximately 34,500 ha were scheduled for annual treatment across the three NFs under the base case scenario. This estimate aligns well with the treatment implementation pace over the past decade, which averaged 38,305 ha of annual fuel reduction treatments between 2010 and 2019 (Neil, 2024). One of the three National Forests under study (Malheur NF) has been identified as a priority “wildfire crisis landscape” (USDA Forest Service, 2022). Across all three NFs, a substantial gap exists between identified fuel treatment needs and implementation, with only a fraction of high-priority areas treated in recent decades (Neil, 2024; Prichard et al., 2021). This persistent shortfall underscores the urgent need to accelerate and strategically prioritize fuel management while balancing treatment costs and revenue from timber sale. For instance, Belavenutti et al., (2023) demonstrated that strategically sequencing fuel treatment projects within a linear fuel-break network in the Umatilla NF can substantially enhance hazard-reduction efficiency while balancing treatment costs and merchantable timber recovery. Our accelerated treatment scheduling scenario extends this concept by increasing treatment rates to rapidly reduce hazardous fuels while addressing financial balance through increased timber output.

Despite clear ecological imperatives, scaling forest restoration often faces substantial financial barriers. For example, Belavenutti et al. (2022) reported restoration costs of up to $8,000 ha^{-1}. High costs are frequently driven by challenging logistics. Keefe et al., (2014) found that transportation expenses can represent roughly one-third of total costs, while Loeffler et al., (2010) highlighted that limited revenue from small-diameter timber further constrains economic feasibility. Our study found even higher restoration costs, averaging approximately $13,000 ha^{-1}. Offroad transportation costs ranged from $63 m^{-3} to $108 m^{-3}, primarily reflecting topographic and logistical constraints. Steeper terrain, such as in the Umatilla NF, requires more expensive harvesting methods like cable yarding systems, contributing to elevated costs.

Additionally, the shrinking milling infrastructure in eastern Oregon limits options for utilizing small-diameter material, leaving much biomass onsite or burned (Hartsough et al., 2008; Kuusela et al., 2019). This lack of markets and processing infrastructure reduces economic feasibility and discourages private investment, leaving many restoration projects reliant on public subsidies and limiting both the scale and continuity of restoration (Hjerpe and Mottek-Lucas, 2018; Porter and Longcor, 2020). While previous work suggests that integrating high-cost fuel treatment areas with revenue-generating operations in productive stands can improve the overall financial viability of restoration projects (Belavenutti et al., 2022), our approach focused on developing new value-added products and markets for restoration materials to eventually offset these high implementation costs of restoration projects. We explored the potential for a new market for small-diameter sectional volume, currently underutilized, through lumber-based mass timber products. While this market is not yet established and future revenues remain uncertain, it could significantly improve the economic viability of restoration projects. Increased revenue from this material would not only offset implementation costs, but also enable the treatment of more extensive areas, consistent with the conceptual approach suggested by Belavenutti et al. (2022).

The most dominant species in the Blue Mountain region, including Ponderosa pine and lodgepole pine, along with other softwood species, such as Douglas fir, western juniper, white fir, grand fir, and subalpine fir, could provide feedstock for lumber-based mass timber production. Ponderosa pine, which has been widely studied for CLT applications, has demonstrated suitability for structural use in residential and light-commercial construction (Jahedi et al., 2024; USDA Forest Service, 2023). By extension, more structurally robust species such as Douglas fir and western larch could also be effectively processed into mass timber. This potential allows a larger fraction of small-diameter material to contribute to both restoration and mass timber production.

Our study estimated that the annual total small-diameter volume from PP and LP species reaches 606 thousand m^3 under the accelerated scenario from three NFs. This volume translates into about 288 thousand m^3 of mass timber production per year, which is sufficient to meet the projected PNW demand of 182 thousand m^3 by 2030 (Anderson et al., 2025). Although challenges related to small-wood and species-specific properties and high capital costs remain (Bremner et al., 2025; Laguarda and Espinoza, 2015), the combination of advanced processing and manufacturing technologies, alongside supportive market incentives, holds the potential to establish a mass timber economy based on small-diameter restoration materials.

The IMPLAN analysis demonstrated that the utilization of the small-diameter softwood feedstock for mass timber could provide notable economic and employment benefits. Under the *basecase20* scenario, first-year treatments generated about 365 jobs and contributed $105 million in total output from utilizing small-diameter sections of both PP and LP species across the three NFs. These economic outcomes can be further specified by tree species and region. For example, a medium sized mass timber industry producing 31.31 thousand m^3 of mass timber annually, utilizing small diameter PP from the Wallowa–Whitman NF, could generate 69 jobs and contribute $22.5 million to the Oregon’s economy. These findings align with similar research, such as Haynes et al. (2019), who reported comparable economic outcomes following the establishment of a medium-sized CLT manufacturing facility in Minnesota, resulting in $16.8 million in total output and the creation of 82 jobs. Our *basecase20* Wallowa–Whitman PP scenario yields slightly higher output ($22.5 million) with fewer total jobs (69). This apparent paradox is explained by three methodological differences: (1) Haynes et al. used a shock value closer to market sales price, whereas our shock is based on production cost—a deliberate conservative choice that affects the output-to-employment ratio; (2) the two studies use different IMPLAN regions with structurally different employment multipliers; and (3) the direct employment tier activated differs slightly between studies. Despite these differences, the two estimates are broadly consistent in order of magnitude, lending confidence to the plausibility of our results.

The SAM multipliers estimated in our impact analysis reveal that for every dollar directly spent on mass timber production using small-diameter wood, an additional 31 cents of economic output is generated through indirect and induced effects in the broader economy. This result aligns with findings from a recent study of the Wisconsin mass timber industry, which reported SAM multiplier of 1.61, indicating that every dollar of direct output supports 61 cents in total economic activity due to ripple effects across sectors (Thapa et al., 2025b). These economic ripple effects reflect strong interlinkages among key sectors, with major indirect and induced job creation occurring in logging, sawmilling, and transportation industries across I-84 corridor. The robust connections between these sectors underscore the broad-based economic benefits of developing mass timber manufacturing facilities, extending beyond direct production to support rural and regional economies through supply chain and labor market impacts.

In addition, our estimated unit mass timber production costs from small-diameter wood in the Blue Mountains ranged from $492 to $616 m^3 in the study region. Although these production costs do not include typical business-related costs (e.g., stumpage values, fixed costs, overhead, profits, risks, product quality) and may thus be underestimates, they are substantially lower than current market prices for CLT ($1483–$1554 m^3) (Atkins et al., 2023). This suggests that establishing a mass timber market for small-diameter restoration wood holds the potential for significant revenue generation, fundamentally improving the financial viability of fuel reduction and restoration treatments.

To make the economic viability argument more explicit, we present the following producer surplus calculation. Prevailing CLT market prices range from $1483 to $1554 m^{-3} (Atkins et al., 2023). Our estimated unit production costs across scenarios and forests range from $492.55 m^{-3} (Malheur, *extended30*) to $616.30 m^{-3} (Umatilla, *accelerated10*). The resulting gross producer surplus, defined here as the difference between market price and estimated production cost, therefore ranges from approximately $867 m^{-3} to $1,062 m^{-3}. This substantial margin must cover the cost components excluded from our analysis: stumpage costs, fixed facility capital costs, overhead and administrative expenses, profit and return on investment, and market risk associated with price volatility. The existence of this margin suggests meaningful economic headroom for a commercially viable operation. For example, if stumpage, fixed costs, and overhead together represent $400–$600 m^{-3}, a conservative estimate consistent with Pacific Northwest timber industry benchmarks, a net profit margin of $250–$650 m^{-3} would remain. Across the *basecase20* total mass timber production volume of 148,000 m^3, this translates to potential annual revenues of $37–$96 million above our cost-floor estimate, with corresponding implications for offsetting restoration treatment costs.

This study has several limitations that should be acknowledged, primarily concerning data uncertainty, methodological simplifications, and the assumptions inherent in the economic model. Volume estimates derived from allometric equations, TreeMap 2022, and tree sections may be uncertain without ground validation due to site-specific variation and limitations in remote sensing and data imputation. Our quantification of tree removal based solely on basal area per hectare and desired conditions may oversimplify spatial heterogeneity. Input data, including topography, road networks, rivers, and hydrological features, may contain errors and biases compounded by integrating multiple disparate data sources. Methodologically, the PTUs were defined arbitrarily and may not be fully implementable on the ground. Similarly, our cost analysis used a simplified categorization of sites for harvesting method selection that may not entirely reflect site-specific ground and vegetation conditions. Cost inputs drawn from external sources spanned multiple years (2017–2024) and were not formally deflated to a common price year; while our dominant cost components are contemporaneous with our 2023 IMPLAN base year and the older inputs inform relative expenditure shares rather than absolute cost levels, which are comparatively robust to price-level drift, we acknowledge this as a source of residual uncertainty not fully captured by our existing sensitivity analyses. This landscape-level approach may mask local variability and critical interactions between treatment units.

The IMPLAN economic model also introduces several inherent limitations. The model assumes a static economy, potentially overlooking future market dynamics, supply chain constraints, and infrastructure impacts. Our analysis also assumed that existing sawmills could accommodate all harvested sawtimber materials, whereas the construction of new or additional processing mills could alter the final economic outcomes. Finally, a key limitation in the planning phase is that the treatment scheduling did not explicitly prioritize fire risk. Instead, PTUs were randomly selected. While this approach addresses unbiased harvesting and transportation cost estimation and provides a measure of long-term average feedstock volume, it may not reflect the optimal risk reduction strategy from an ecological or fire mitigation perspective.

A further source of uncertainty concerns the lumber recovery factor. We applied a 56% recovery rate following Wagner et al. (2009), which is calibrated to conventional inland Northwest softwood sawtimber involving larger-diameter logs. For small-diameter pine logs (10–23 cm), recovery rates in the literature range from approximately 40% to 55%, depending on log size, taper, knot frequency, and the degree of sawing method optimization for small-diameter material (Fredriksson et al., 2015; USDA Forest Service, 2023). We conducted a sensitivity analysis at 40% and 60% recovery rates, treating 56% as the base case. Because mass timber volume is derived proportionally from the sectional log volume via the recovery rate, all monetary outputs scale in direct proportion. Employment, however, is assigned through discrete facility-size tiers and is therefore evaluated explicitly at each recovery rate. Under the *basecase20* scenario for Ponderosa pine, total economic output for the Malheur, Umatilla, and Wallowa–Whitman NFs shifts from $36.6, $14.3, and $22.5 million (base case) to $26.1, $10.1, and $16.1 million respectively at 40% recovery, and to $39.1, $15.2, and $24.2 million at 60% recovery. Employment is unchanged across both recovery scenarios for Ponderosa pine in all three forests, since none of the scaled volumes cross a tier boundary. For Lodgepole pine, monetary outputs follow the same proportional pattern. The exception in employment occurs at Wallowa–Whitman NF, where the base-case mass timber volume of 26,170 m^3 falls to 18,700 m^3 at 40% recovery, crossing the 20,000 m^3 tier boundary and reducing total employment from 65 to 38 jobs; at 60% recovery the volume remains within the original tier and employment is unchanged at 65 jobs. The results are qualitatively consistent across the *accelerated10* and *extended30* scenarios and across all three national forests, confirming that the core findings are robust to the full range of recovery rate assumptions tested. Future research using empirical recovery data from small-diameter pine processing trials would substantially reduce this source of uncertainty.

The assumed 50% lumber input share (Anderson et al., 2020), used to derive the unit mass timber production cost, is a single-point estimate from a 2020 industry survey. We conducted a sensitivity analysis at lumber input shares of 40% and 60%, adjusting the remaining input coefficients in the spending pattern (Table 4) proportionally to maintain the 100% total. Because physical mass timber volumes are held constant, all facility-size tier assignments and employment levels are identical across all three scenarios. Only monetary outputs are scaled with the unit production cost through the SAM multipliers. Under the *basecase20* scenario for Ponderosa pine, total economic output for Malheur, Umatilla, and Wallowa–Whitman NFs shifts from $36.6, $14.3, and $22.5 million (base case) to $44.8, $17.6, and $27.8 million respectively at a 40% lumber share, and to $31.0, $12.0, and $19.0 million at a 60% share, a range of approximately +23% to −16% relative to the base case. Labor income and total value added follow the same proportional pattern. Employment remains unchanged at 119, 42, and 69 jobs respectively across all lumber share scenarios. Results are consistent in direction and magnitude for Lodgepole pine and across the *accelerated10* and *extended30* scheduling scenarios, confirming that the main finding is robust to plausible variation in this assumption.

5. Conclusions

This study demonstrates that integrating spatially explicit forest restoration with mass timber production in the Blue Mountain region provides a robust strategy for enhancing wildfire resilience while yielding significant economic benefits. Utilizing high-resolution

TreeMap 2022 data and PODs, this study prioritized restoration treatments across the Malheur, Umatilla, and Wallowa–Whitman National Forests, identifying about one-third of forest area for fire resilience interventions. The analysis confirms that the utilization of small-diameter wood for mass timber production can improve the economic viability of fuel reduction and restoration treatments through the development of a new value-added product market. Economic impact assessments using the IMPLAN model reveal substantial regional benefits, with significant job creation and contribution to the regional economy. These findings align with prior research emphasizing the ecological and economic advantages of utilizing low-value biomass feedstock for innovative forest products. Despite methodological and data limitations, this study offers a framework for sustainable forest management that simultaneously supports resilient forests and rural economic development in fire-prone regions. Future research should integrate dynamic fire behavior models for enhanced restoration strategy, incorporate more site-specific and ground-validated data sources for better representation of the current and future desired conditions, and integrate other potential innovative forest products to further highlight the importance of achieving both ecological and economic benefits simultaneously.

CRediT authorship contribution statement

Naresh Khanal: Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Woodam Chung:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **John Hogland:** Data curation, Methodology, Supervision, Validation, Writing – review & editing. **Yong Chen:** Methodology, Supervision, Validation, Writing – review & editing. **Andres Susaeta:** Methodology, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the Economic Development Administration, U.S. Department of Commerce [grant #07-79-07914]. The statements, findings, conclusions, and recommendations are those of the authors and do not necessarily reflect the views of the Economic Development Administration or the U.S. Department of Commerce. The authors thank Nils Christoffersen and Mark Webb for their valuable insights and support during the development of this study.

Data availability

Data will be made available on request.

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