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Key Points:

- Extreme weather events, while localized, but can have far reaching consequences on forests due to the interconnected wood product markets
- The effect of extreme weather events on wood product markets is mitigated through endogenous market reactions in other regions

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Unraveling the Impacts: How Extreme Weather Events Disrupt Wood Product Markets

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Abstract While extreme weather events are often localized, the potential effects on global forests can be far reaching due to the interconnected nature of forest product markets. To better understand these dynamics, this study leverages historical forest-based wind damage data in the United States and applies this information as shocks within a global forest sector outlook model. A large, localized wind event modeled as a shock to the US South creates a one-time increase of 18.7 million m³ from salvage harvest operations, equal to over 4% of national harvest. This crowds out traditional harvest activities, leading to downward pressure on prices in the short run, followed by a persistent effect that could take approximately 25 years to dissipate from markets. Average annual wind damage contributes downward pressure on roundwood prices between 1% and 4% in the United States, and this effect is distributed to other countries. The findings suggest that large, localized shocks reverberate across regions and wood product markets due to their interconnected supply chains and trade patterns, and these impacts have important temporal dynamics. Another key result is that the magnitude of these effects are offset by endogenous market reactions in other markets. In other words, unaffected regions change their harvesting patterns in order to compensate for changes in the availability of fiber, shedding light on the importance of capturing global channels as large shocks materialize in changes in market dynamics internationally. Monte Carlo simulations suggest a wide confidence band on salvage harvest rates and prices.

Plain Language Summary Extreme weather events can have significant impacts on global forests despite being localized, thanks to the interconnected nature of forest product markets. This study investigates this relationship by analyzing historical wind damage data from US forests. It finds that a major wind event in the US South led to a substantial increase in salvage harvest, equivalent to over 4% of the national harvest. This surge in harvest disrupted traditional activities, causing short-term price drops and long-lasting effects over about 25 years due to tree loss. Wind damage annually contributes to 1%–4% price decreases in US roundwood, affecting other countries too. The study emphasizes how such shocks ripple across regions and markets due to intertwined supply chains and trade patterns. It also highlights how unaffected regions adapt their harvesting to balance fiber availability, underscoring the importance of understanding global dynamics. Monte Carlo simulations reveal wide confidence bands on salvage harvest rates and prices, underlining the uncertainty surrounding these estimates.

1. Introduction

Forests play a vital role in addressing climate change by serving as a major carbon sink, providing renewable raw materials to substitute for fossil fuel-intensive products, and offering other crucial ecosystem services. However, forest disturbance associated with extreme weather events can significantly impact the forest sector. For instance, wildfires, hurricanes, drought, flooding, and other extreme events can lead to extensive damage to forest ecosystems (Sommerfeld et al., 2018), disrupting the regular supply of timber, wood, and other forest-derived products. The interconnected nature of the global forest products market means that disruptions in one region can reverberate throughout the global supply chain, affecting pricing and trade dynamics on a broader scale. Disturbances are already becoming more frequent, widespread, and/or severe in many places in the world (Patacca et al., 2023; Senf & Seidl, 2021; Sommerfeld et al., 2018). Likewise, climate change is affecting extreme weather and climate events (Leung et al., 2023), and is expected to amplify the frequency, extent, and/or severity of extreme weather events and forest disturbances in the future (Bowman et al., 2020; Costanza et al., 2023; Littell et al., 2018; Pausas & Keeley, 2021; Pureswaran et al., 2018; Seidl et al., 2017), posing additional challenges to the role of forests in combating climate change.

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Natural disturbances like wildfires, insect outbreaks, and extreme weather events can cause substantial timber losses and disrupt timber supply, final product markets, and trade flow. Large, severe wildfires have become more frequent due to accumulated fuels, climate change, and development patterns, burning millions of forested acres annually, resulting in significant economic costs (El Garroussi et al., 2024; Parks et al., 2016). Riviere et al. (2022) investigated the potential impact of climate change on wildfires in southern France, suggesting that summer burned areas could increase by up to 55% by the end of the century. This increase in wildfires could lead to modest price hikes for softwood products, potentially reaching up to 3%. Similar findings have been noted in the US (e.g., Zhai & Kuusela, 2020). In addition to wildfire, the frequency and severity of insect outbreaks—such as the mountain pine beetle epidemic—have intensified over the last decade (Audley et al., 2020). Aukema et al. (2011) estimated the value of timber losses from non-native forest insects at \$2.53 billion over a 10-year period in the Continental United States (e.g., Holmes, 1991).

There exists a small but growing literature on the effects of wind disturbance on local forest product markets. Recent studies looking at wind events note the sudden pulse of damaged timber flooding regional mills disrupts supply-demand dynamics, and depresses prices in the short term (Prestemon & Holmes, 2000). However, the wood pulse is temporary, as this excess inventory is processed, supplies can rapidly shift to scarcity within a few years after a major storm (Prestemon & Holmes, 2004). That is, the loss of standing inventory and delayed regeneration in storm-damaged areas can reduce growth and harvesting levels for decades after an extreme wind event (Chambers et al., 2007), causing persistent upward pressure on prices. Henderson et al. (2022) further confirm these dynamics during Hurricane Michael, where a reduction in standing stock in 2018 due to hurricane damage led to a decrease in removals for salvage substitution. Prices initially experienced a negative response in the hurricane year but show an upward shift post-hurricane.

Conclusions about future impacts of disturbances on markets, due to climate change, will depend on how climate change affects how disturbances change their spatial distributions, spatial extents, frequencies, severities, and durations (e.g., Dale et al., 2001). Limited research is suggestive of future shifts in these dimensions of some disturbance distributions (e.g., Abatzoglou et al., 2020; Spinoni et al., 2020). Among the possible futures for disturbances is that one or more types of disturbance becomes more frequent, larger geographically, of increased average severity or extent (e.g., Wan et al., 2019), of longer average duration, or even increasing in synchronicity (Abatzoglou et al., 2020), in which case their national and global market impacts could be felt over larger spatial and longer temporal scales than historically experienced. If such changes occur, then market impacts of larger spatial and longer temporal extent than have been observed historically. On the other hand, some research (e.g., Dale et al., 2001; Spinoni et al., 2020) indicates that climate change could reduce the severity or spatial extents of some disturbance types and that climate change's impacts could vary from downward shifts to upward shifts in such distributions, depending on planetary location and disturbance type.

The goal of this paper is to better understand how forest product markets might react to natural disturbances associated with extreme weather events. There is a specific interest in better understanding the relationships between disturbance and interconnected markets within the global forest sector. We leverage wind and hurricane damage data from the Forest Inventory Analysis program of the United States Department of Agriculture in order to measure the frequency and severity of wind damage to forest inventory in the United States. Wind is a major forest disturbance agent in many parts of the world (Gardiner, 2021; Senf & Seidl, 2021; Sommerfeld et al., 2018; Tumber-Dávila et al., 2024). Along and near the Eastern and Gulf Coasts of the United States, hurricanes and other wind events are relatively common, playing a major role in shaping forest structure and composition (Zampieri et al., 2020), and have been the focus of market shock impact analysis, as mentioned. These events therefore offer a template for the modeling reported here. We then integrate these shocks into a global forest product model to track how localized disturbances might affect wood product markets on a broader scale. We also consider a scenario in which wind damage increases, in order to shed light on possible impacts due to climate change. These changes could exacerbate national and global market impacts into larger spatial and longer temporal scales than historically experienced. In fact, increasing exposure to disturbance from hurricanes and other wind events are already being observed in North America, consistent with the expected impacts of climate change (Elsner et al., 2008; Reed et al., 2022), and is expected to continue as climate warms further (Abatzoglou et al., 2020; Balaguru et al., 2023; Spinoni et al., 2020; Wan et al., 2019).

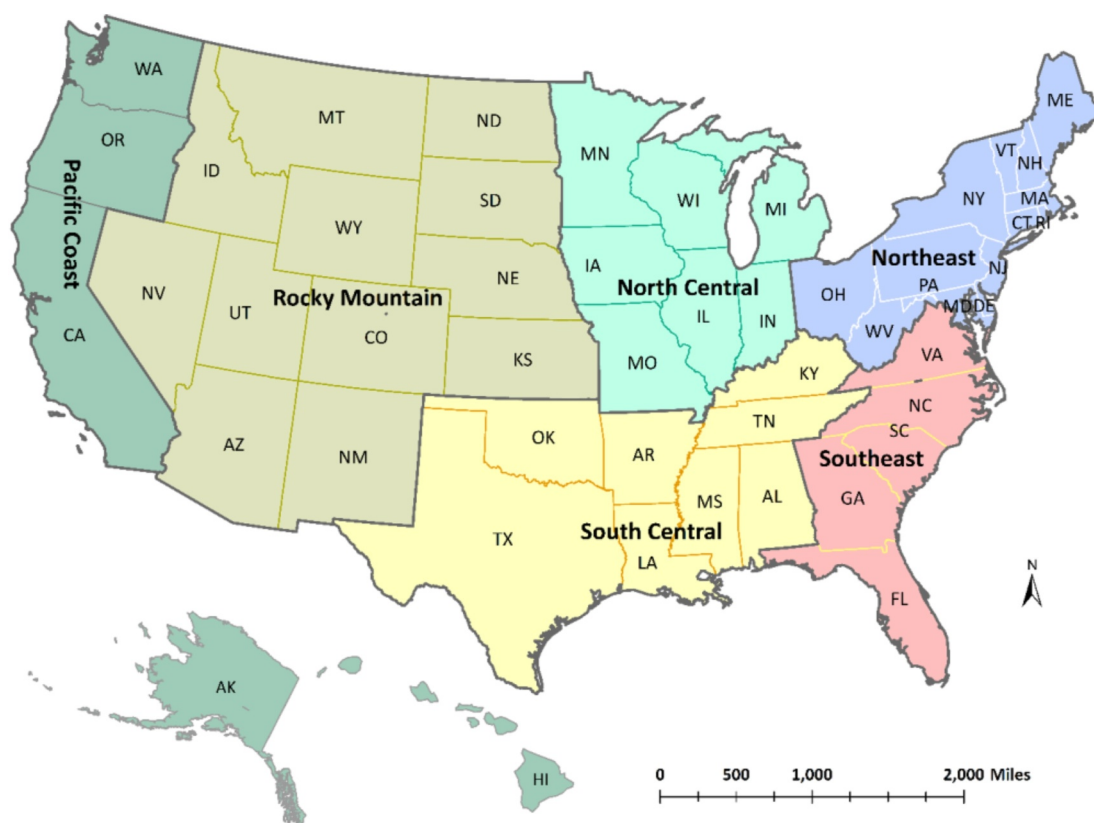


Figure 1. United States regions and subregions represented in FORUM. Note: Colors correspond to regions, and separate groups of states make up subregions within each region. We aggregated data to a combination of regions in the western U.S. and subregions in the Eastern U.S.: Pacific Coast, Rocky Mountain, North Central, Northeast, South Central, and Southeast. (Source: Nelson et al., 2020).

2. Data and Methodology

This section describes the data and methodological framework used in the analysis. The overall approach can be described in the following steps:

1. Estimate a distribution of forest inventory damaged by wind in the United States
2. Approximate potential timber salvage rates
3. Integrate inventory damage and salvage rates as shocks into a partial equilibrium model of the world's forest sector

2.1. Estimating Wind Damage to Forest Inventory in the United States

To obtain annual probabilities of wind damage on forest area, we accessed Forest Inventory and Analysis (FIA) data via the rFIA package (Stanke et al., 2020) in R statistical software (R Core Team, 2023). We used the rFIA area function with the annual estimator option to determine the annual area by US state and by species group (softwood or hardwood) that was affected by wind damage, based on the coding of disturbance code variables in FIA data (DSTRBCD1, DSTRBCD2, DSTRBCD3). To balance the geographic aggregation required in global forest sector outlook models with regional granularity necessary for spatially explicit disturbance assessment, we then aggregated to US Forest Service multi-state regions that correspond to the agency's Resources Planning Act regions and subregions (Nelson et al., 2020). Specifically, we aggregated data to 2 distinct regions in the West: Pacific Coast and Rocky Mountain, and 4 distinct subregions in the East: North Central, Northeast, South Central, and Southeast (hereafter, "regions"; Figure 1). Due to the nature of FIA data collection, not all states have observations for all years. In this case, we used states with available data in a given year as proxies for the region. We converted areas to percentage area to normalize annual area damage.

Table 1
Assumed Salvage Rates as Percent of Damaged Inventory, by Region

Region	Salvage rate (percent)		Logging Employment (NAICS 1133)
	Softwood	Hardwood	
Pacific Coast	18.8	3.8	9,731
Rocky Mountain	2.9	0.6	1,480
North Central	7.9	1.6	4,112
Northeast	7.9	1.6	4,095
South Central	25	5	12,932
Southeast	25	5	12,081

Note. Throughout the remainder of the paper, we may refer to softwood and hardwood as coniferous and non-coniferous, respectively.

With a series of regional level annual area percent damages available, we fitted gamma distributions by maximum likelihood estimation to the data for area percent damage by region and species group using the `fitdistrplus` R package (Delignette-Muller & Dutang, 2015). Gamma distribution fitting allowed us to identify extreme (tail) wind events by region and species group, based on the predicted cumulative distribution function.

The area percentages are not directly indicative of the severity of damage on standing inventory, since the wind damage code does not indicate severity. Inventory damage is needed to calculate impacts on timber supply and markets. It is therefore necessary to moderate the relationship between area damage percent and inventory damage percent. To do so, we assume a logistic relationship between area damage percentage (A) and inventory damage percentage based on the logic that the inventory damage rate (V) would have an upper limit ($V_{max} = 0.8$) and with steepness ($k = 0.8$) and midpoint parameters ($m = 1$).

$$V = \frac{V_{max}}{1 + e^{-k(A-m)}} \quad (1)$$

2.2. Adjusting Salvage Rates by Employment Constraints

For the two US South regions, the South Central and Southeast, we assume a salvage rate of damaged inventory of 25% for softwood and 5% for hardwood, consistent with Henderson et al. (2022) and with empirical salvage rate estimates (Brandeis et al., 2022). Low salvage rates are a function of mill capacity in proximity to the disturbance, higher real or perceived risk of salvaging operations, and reduced operability in post-disturbance environmental conditions (see Gordon et al., 2018). However, the US South has a higher concentration of forest industry activity compared to other regions. Therefore, the same salvage rates would not be expected for other parts of the US. We reasoned that logging labor supply short-run responsiveness would constrain the feasibility of salvage. We therefore adjusted our salvage rate assumptions for regions outside the US South by their average annual logging (NAICS 1133) employment level in 2022 (BLS, 2023) relative to the US South Central region's logging employment level, summarized in Table 1.

2.3. The FOREST Resource Outlook Model (FOROM)

The Forest Resource Outlook Model (FOROM) is a partial equilibrium model that encompasses various aspects of the global forest sector, such as forest resources, timber supply, demand for intermediate and final products, and international trade. This modeling framework allows for an examination of the impact of external shocks and changes in future socioeconomic and climatic conditions on the production, consumption, trade, and prices of raw material, intermediates, and final products. It also considers changes in forest land area and forest standing stock, positioning it well to investigate how shocks to forest inventory might manifest within the globally connected wood product market.

The current version of FOROM depicts the global wood product market by incorporating 20 interconnected products (refer to Figure 2 and Table A1) across 55 countries and regions worldwide (refer to Table A2). Additional geographic units and products may be incorporated as outlined in Nepal et al. (2021). The model tracks the relationships among wood products, which may source feedstock from diverse origins, including coniferous and non-coniferous industrial roundwood, fuelwood, or residues from sawmilling activities such as chips, particles, and residuals.

FOROM involves solving a series of interconnected static equilibrium problems linked by dynamic exogenous assumptions. In the static phase, the model optimizes economic welfare for all products across countries, adhering to the law of one price and aligning with the spatial price equilibrium framework. In this framework, disparities in prices between regions are attributed to variations in transport costs, encompassing tariffs and other non-tariff barriers.

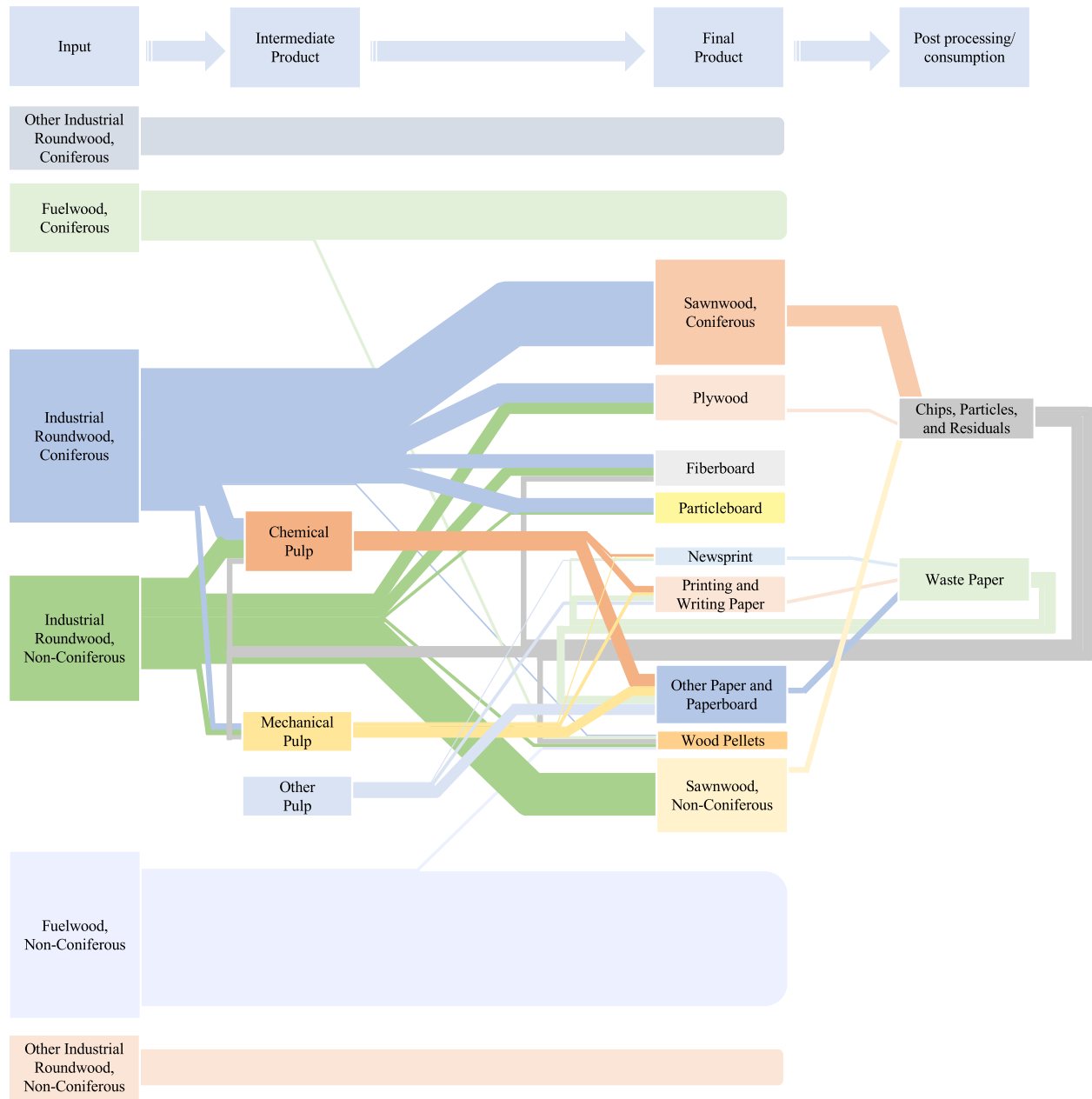


Figure 2. Forest product flow chart in FORUM.

The objective function seeks to maximize the combined consumers' and producers' surpluses, adjusted for transport costs, subject to various constraints related to material balance, resource feasibility, and equilibrium conditions.

$$W = \sum_k \left\{ \sum_j \int_0^{Q_j^k} P_j^k(Q_j^k) dQ_j^k - \sum_i \int_0^{Y_i^k} C_i^k(Y_i^k) dY_i^k - \sum_i \sum_j (t_{ij}^k + \tau_{ij}^k) x_{ij}^k \right\} \quad (2)$$

where P_j^k and Q_j^k refer to the price and quantity of wood product k consumed by region j , while C_i^k and Y_i^k refer to the manufacturing cost and production in region i . The cost of moving product k from region i to j , x_{ij}^k , is a function of the shipping and handling cost, t_{ij}^k , and the associated tariffs, τ_{ij}^k .

To satisfy material balance in any given region and product, production plus imports must equal the sum of consumption, exports, and the input of product k required in manufacturing output n , given as a_i^{kn} :

$$Y_i^k + \sum_j x_{ji}^k = Q_i^k + \sum_j x_{ij}^k + \sum_n a_i^{kn} Y_i^n \quad (3)$$

The manufacture of byproducts (i.e., sawmilling byproducts, recycled paper) are a function of primary product manufacturing, represented by:

$$Y_i^b = \sum_n \theta_i^{nb} Y_i^n \quad (4)$$

where θ_i^{nb} is the amount of byproduct $b \subseteq k$ recovered per unit of manufactured output n .

During the static phase, the model acquires equilibrium prices, quantities, and net trade levels by addressing the maximization problem within the objective function while considering diverse economic and engineering constraints. Following the determination of a solution for the current period, t , the model transitions into the dynamic phase. In this phase, the model parameters undergo updates influenced by exogenous drivers such as gross domestic product (GDP) growth, population growth, changes in productivity, and alterations in trade openness. Additionally, endogenous variables like harvest levels and standing stock levels are adjusted in readiness for the subsequent iteration cycle.

Demand is assumed to change over time through exogenous shifts to GDP per capita, $\dot{y}_t$, and translated through the growth rate of per capita GDP, $g_j^{\dot{y}_t}$, and the elasticity of demand with respect to the growth rate of per capita GDP, δ_j^k :

$$\bar{Q}_j^k = Q_j^k \left(1 + \delta_j^k g_j^{\dot{y}_t} \right) \quad (5)$$

The Food and Agricultural Organization of the United Nations (FAO, 2024) serves as the primary data source for reference prices, quantities, and trade, as outlined in Table A1. Production, import value, import quantity, export value, and export quantity data are directly extracted from the database. Consumption is computed as apparent consumption, equating to production plus imports minus exports. While prices for all 20 forest products are unavailable in the FAO database, we select unit values of imports or exports (import or export value in US\$ divided by import or export quantity) as the prices. To address apparently inconsistent data (such as negative apparent consumption and gaps between total imports and exports) and missing data for the reference year, we employ a goal programming approach. This programming method also involves recalculating input-output coefficients and manufacturing costs for each country/region. Calibrated manufacturing costs, adhering to the zero-profit assumption in each market, are determined as the price of the output minus the cost of wood and fiber input. For a more detailed explanation of the goal programming approach, refer to Johnston et al. (2021). Finally, information on forest areas and stocks is derived from the FAO's 2010 and 2015 Global Forest Resources Assessments (FAO, 2020).

The United States is disaggregated into six regions, as illustrated in Figure 1 (Nelson et al., 2020). This disaggregation is based on county-level data, utilizing information from the USDA Forest Service's Timber Product Output (TPO) program and the United States International Trade Commissions (USITC). These supplementary data sets form the basis for calculating regional shares, facilitating the reconciliation of FAO country-level data.

Shared Socio-economic Pathways, which delineate diverse scenarios of economic, social, and environmental transformations until 2100 (O'Neill et al., 2017; Riahi et al., 2017), are implemented in FORUM. This implementation involves introducing exogenous adjustments in GDP, population, technological advancements, trade openness, and preferences for bioenergy demand. This analysis primarily focuses on the “middle of the road” scenario, SSP2. Wear and Prestemon (2019a) devised a method to collectively downscale nationwide income and population projections to individual counties within the United States. We used the county projections (Wear & Prestemon, 2019b) to calibrate GDP and population projections for each region within the United States.

A detailed description of the model is available in Johnston et al. (2021).

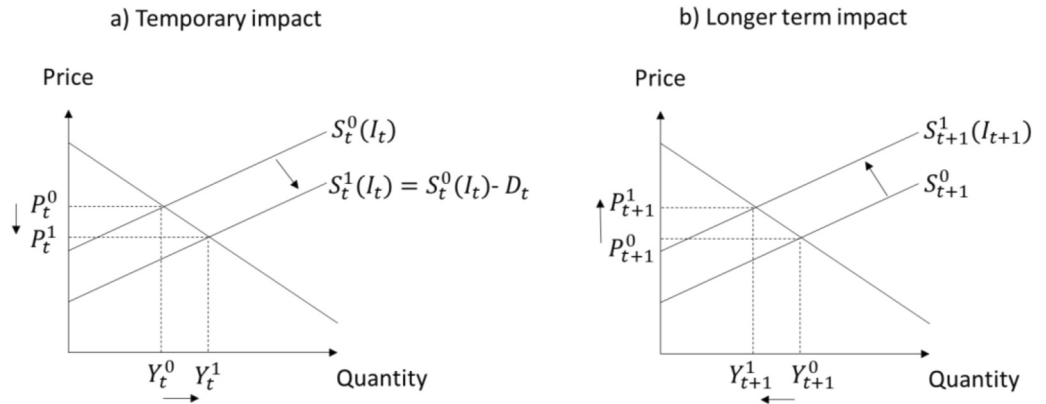


Figure 3. Stylized temporary and longer-term impacts of disturbance on removal quantities and prices.

2.4. Simulating Disturbance Shocks in FOROM

To begin, consider an illustrative disturbance shock as shown in Figure 3. Disturbance is assumed to have different impacts on forest product market prices in the short run and the longer term. Here, the temporary effects outlined in panel (a) show that forest disturbance (D) increases the additional roundwood available (Y) to meet the derived demands of manufactured products, shown here as temporarily pushing down the roundwood supply curve (S) due to the additional fiber brought about through salvage harvesting, leading to a temporary reduction in prices (P). Meanwhile, forest inventory (I) is now materially reduced, affecting the longer-term ability to produce roundwood. Panel (b) highlights that the longer-term effects of a reduction in inventory will push up the marginal cost of producing roundwood, leading to lower output and higher prices.

This process of damaged inventory and salvage harvest takes place within a more complex framework of the global forest product market within FOROM. The following highlights some of the key equations and underlying data of the FOROM model.

Forest inventory in region i evolves over time in FOROM according to the following equation:

$$I_{t+1}^i = I_t^i + G_t^i - \sum_k Y_t^{ik} \quad (6)$$

where I_{t+1}^i is the inventory in the beginning of the next period, G_t^i is the growth in inventory during the current period and subtracted is the volume removed (Y_t^i) through the production of harvested inputs h of species π during the previous.

A random shock is assumed to create a spike of mortality in the standing stock of timber in region i in period t , reducing the inventory by some established quantity prior to solving the model in period t :

$$D_t^i = I_t^i * \varphi \quad (7)$$

where D_t^i is the mortality in the standing stock, and φ is the percent of current inventory I_t^i killed by disturbance.

A share of the mortality generated by the disturbance event in region i in period t can be salvaged and serve as an input to the derived demands of manufactured wood and paper products (including solid wood energy). The salvage, to look the same as “green,” would have to be appropriately adjusted to account for the quality difference. That is, if proportion φ of inventory is killed by the disturbance, and proportion η of killed inventory is salvaged, and r is a quality adjustment factor, then the quantity of salvage would be:

$$S_t^i = I_t^i * \varphi * \eta * r \quad (8)$$

The next period's inventory is updated according to the physical standing stock growth function already embedded in FOROM. That is, while the disturbance in time t creates a pulse of additional roundwood available to

meet the derived demands of manufactured wood and paper products in time t , it reduces the available standing stock for next periods harvest. Accounting for the pulse is achieved by adjusting Equation 2 to account for the effects of the disturbance in time t :

$$I_{t+1}^i = I_t^i + G_t^i - \sum_k Y_t^{ik} - D_t^i \quad \forall k \in h \quad (9)$$

The availability of harvestable inputs (such as industrial roundwood, fuelwood, and other roundwood) is presumed to evolve over time due to external changes in forest area and forest stock:

$$\bar{Y}_t^k = Y_t^k (1 + e_i^k g_{i,t}^A + \nu_i^k g_{i,t}^I) + S_t^i \quad (10)$$

where $g_{i,t}^A$ is an exogenous change in the growth rate of forest area at time t , $g_{i,t}^I$ is an endogenously determined growth rate of forest inventory, which changes over time based on the specified nonlinear negative relationship between forest growth and stocking density, e_i^k and ν_i^k are elasticities associated with forest area and inventory, respectively, and S_t^i is the quantity of salvaged timber.

2.5. Scenarios

We consider three scenarios in this study. The first is a scenario where the US Southeast and South Central experience a one-time large disturbance shock in 2025 equal to the size of a shock in the 95th percentile of historical data—reflective of a hurricane disturbance. The purpose of this scenario is to isolate how a large, single shock manifests throughout markets, including the attendant effect of changes in forest inventory on the supply and availability of roundwood. Next, results are presented for a case of continuous repeated shocks estimated through a Monte Carlo experiment. Within this Monte Carlo experiment, we consider one case where the expected distribution of damage and salvage harvest in any given year is representative of historical averages. Next, we consider another case where these distributions shift in such a way as to elicit an increase in expected damage of 2% each year—reflecting a hypothetical world of increased average annual inventory damage, shedding light on the potential additional impacts due to climate change.

3. Results

3.1. Estimated Wind Damage and Salvage Harvesting in the US

The resulting estimated distribution of forest inventory damaged by wind in the United States is provided in Figure 4. On average, in any given year, it is expected that wind damage would result in less than 1% of inventory damage across all regions of the United States. However, the long tail of these distributions highlights the potential severity of extreme but rare wind events (e.g., hurricanes). A long tail leads to much larger shocks to forest inventory and a higher likelihood of large salvage timber pulses entering product markets in the United States than would be implied by a probability distribution (e.g., a Normal) with less positive skew.

The resulting estimated salvage volume by species grouping and region in the United States is calculated as a function of the estimated distribution of forest inventory damaged by wind (Figure 4) and the assumed regional salvage rates (Table 1)—summarized in Table 2. On average, it is estimated that the United States experiences around 12.4 and 2.5 million m^3 of softwood and hardwood salvage harvest, respectively, in any given year. Given the total harvest volume in the United States was 459 million m^3 in 2022, this equates to around 3%–4% of annual harvest. As shown in Table 2, more extreme wind events—as proxied by the 95th percentile—are estimated to lead to much larger estimated salvage harvests.

3.2. Isolated Large Disturbance in the US South

This section describes the estimated effects of an instantaneous shock to forest inventory in 2025 in the US Southeast and South Central regions equivalent in size to inventory damage in the 95th percentile of historically estimated wind damage—as presented in Table 2. This shock creates a one-time increase in harvest volume equal to 3.6 million m^3 ; there is an increase of 18.7 million m^3 from salvage harvest operations, which crowds out 15.1 million m^3 of harvest operations that would have traditionally occurred otherwise (Figure 5a). As a result of now

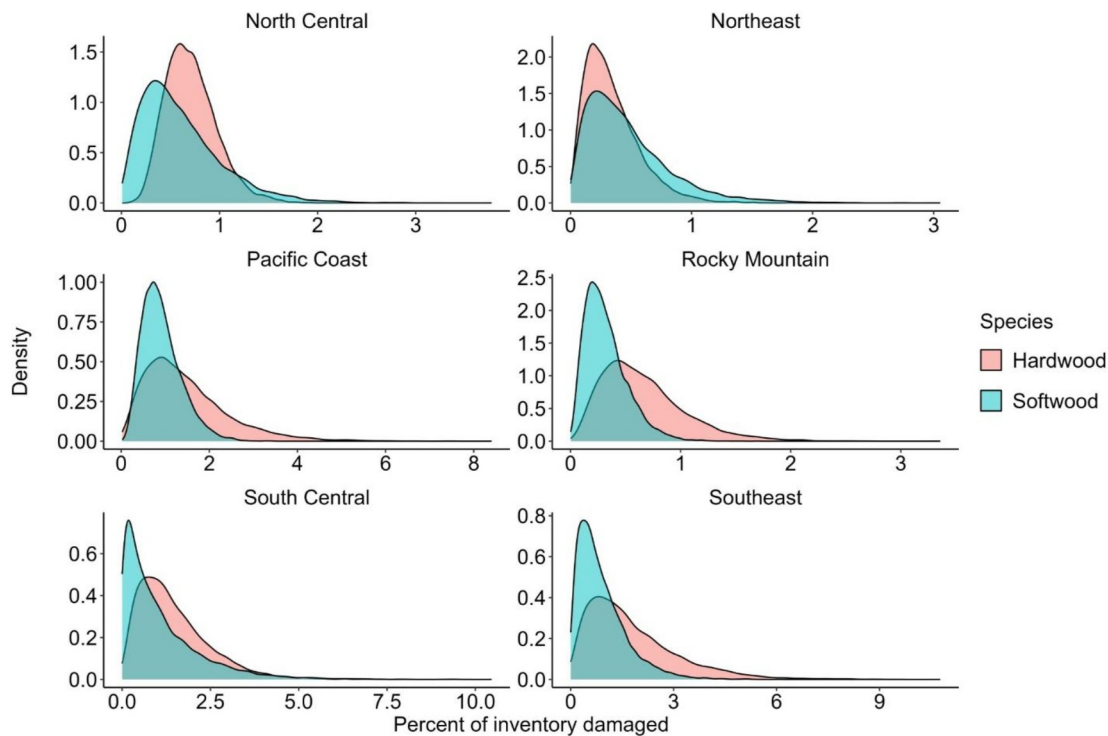


Figure 4. Estimated distribution of forest inventory damaged by wind in the United States by region and species grouping.

lower forest inventory due to killed inventory from the shock, there is a drag on US harvest volume that persists for years. After the forest regrows, harvest levels return to pre-shock baseline levels between 2045 and 2050. These results speak to the importance of investigating these types of shocks within an equilibrium framework that allows for endogenous harvest responses. The same dynamics can also be viewed in terms of change in roundwood production by type (Figure 5b), with solid bars representing production increases due to salvage harvesting, and hashed bars representing displaced production.

By construction, the shock originates in the Southeast and South Central regions of the US but has impacts that are distributed throughout the domestic market (Figure 6). The Southeast and South Central regions see an immediate increase in production due to salvage harvest operations, but a subsequent decrease in harvest volumes in years to follow due to reduced forest inventory from the killed timber (Figures 5e and 5f). While the disturbance does not directly impact other regions in this scenario, the interconnected nature of the domestic forest product industry leads to endogenous changes within those markets, offsetting some of the shock that occurred in the US South. Here, the Pacific Coast, Rocky Mountain, North Central, and Northeast all see a reduction in harvest activity in the year of the disturbance as the spike of salvaged timber from the US South displaces traditional harvest operations across the US (Figures 6a–6d). In the following years, however, there is an increase in harvest levels to offset some of the lost production from the US South that is associated with lower inventory levels.

Table 2
Estimated Mean and 95th Percentile Salvage Harvest, by Region

Region	Softwood ('000 m ³)		Hardwood ('000 m ³)	
	Mean	95th percentile	Mean	95th percentile
Pacific Coast	6,530	12,530	235	528
Rocky Mountain	473	1,011	15	32
North Central	240	555	216	361
Northeast	364	892	161	366
South Central	2,616	8,062	935	2,167
Southeast	2,197	5,620	945	2,330

The integration of markets and the law of one price hypothesis supporting the methodological framework behind the FOROM model implies the influx of timber puts broad based downward press on prices in all regions (Figure 7).

Price effects are also distributed across regions. The influx of timber from the salvage harvest in the South leads to a temporary pulse of roundwood within the United States, exerting downward pressure on prices broadly (Figure 6). In the years following the shock, tree mortality shrinks inventories in the South, putting persistent upward pressure on prices in the years to follow. This upward price pressure encourages other regions to harvest more to compensate for the restricted supply from the South, leading to higher prices

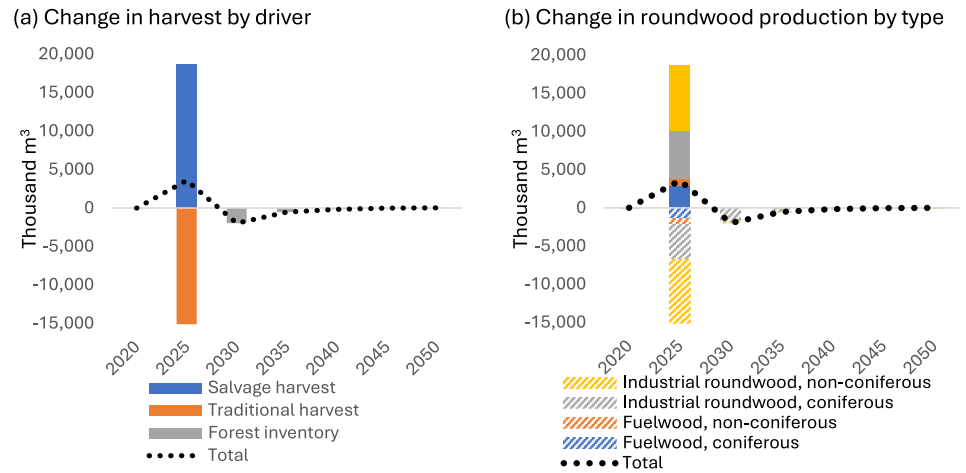


Figure 5. Change in US harvest and roundwood production from shock in the US South. Note: Solid bars in panel (b) represent production from salvage harvest. Hashed bars in panel (b) represent estimated roundwood production displaced because of disturbance. The dotted lines represent the net effects.

following the disturbance event. As the forests in the South regrow, the upward price pressure is alleviated, allowing markets to return to pre-shock price levels around 25 years after the disturbance.

The price dynamics in the roundwood markets are passed through the supply chain, and affect the production, prices, and trade of downstream wood products. To illustrate this point, consider the coniferous sawnwood market in Figure 8. Here, we see an increase in the production of coniferous sawnwood in 2025 (Figure 8a), as the pulse of coniferous roundwood due to salvage harvesting put downward pressure on roundwood prices, reducing the marginal cost of producing downstream products like sawnwood, and some of these lower costs are passed through to consumers through lower sawnwood prices (Figure 8b). In addition, this increased production of

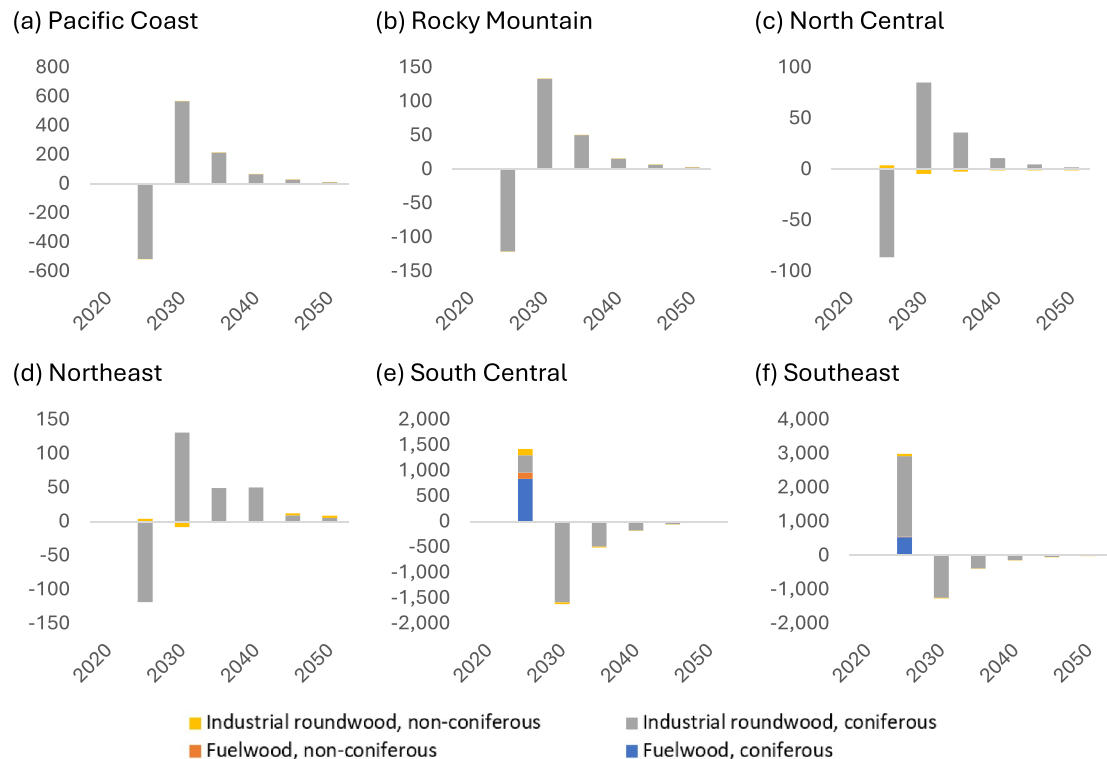


Figure 6. Estimated change in roundwood production by region, thousand cubic meters, 2025–2050.

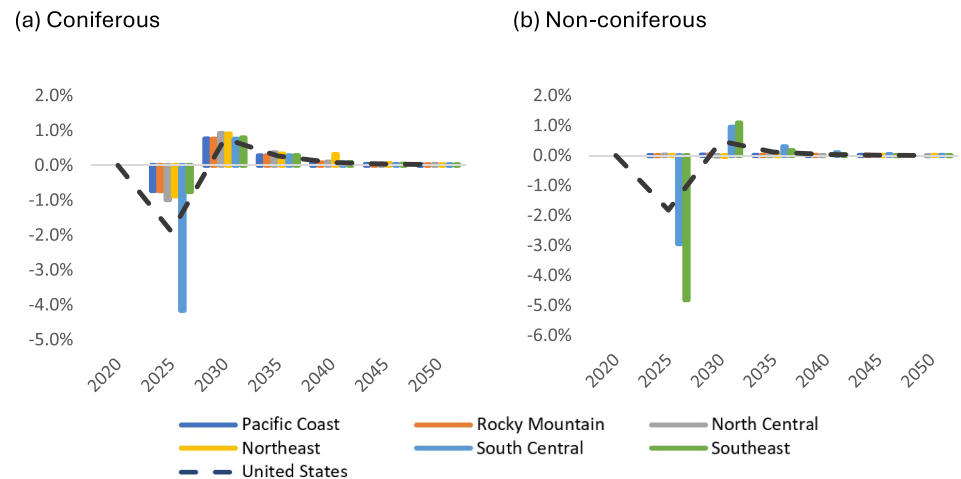


Figure 7. Change in industrial roundwood prices by region, 2020–2050.

sawnwood in 2025 implies less pressure on imports from other regions to meet domestic demands, as illustrated in Figure 7c. These dynamics are reversed in the subsequent years following the disturbance as reduced forest inventory in the South implies a shortage of roundwood and other products, pushing up the price of downstream products, and increasing the reliance on imports to meet demand.

3.3. Average Annual Impacts – A Monte Carlo Experiment

This section outlines the results associated with continuous repeated shocks estimated through a Monte Carlo experiment with 1,000 simulations. Within this section, we consider two cases. First, referred to as *current damage rates*, applies annual shocks to each region of the United States drawn from a distribution representative of historical averages. The next scenario, referred to as *increasing damage rates*, assumes the distribution of these historical shocks shift in such a way as to yield a 2% increase in wind damage each year.

The average annual expected salvage harvest volume in the United States is projected to be between 15 and 17 million m³ assuming wind damage frequency and intensity remains at recent historical averages (Figure 9a). The total harvest volume in the United States was 459 million m³ in 2022, which equates to around 3.5% of annual harvests. Even using current damage rates, rising salvage volumes are partially explained by a growing inventory, which puts a greater volume of timber at risk of damage. Figure 8b highlights the impact of the 2% increasing damage rate assumption on salvage volume.

Salvage volume estimates are a function of inventory volume, the distribution of inventory damage (as shown in Figure 1), and the assumed salvage rates (as shown in Table 1). The sum of the mean salvage volume estimates

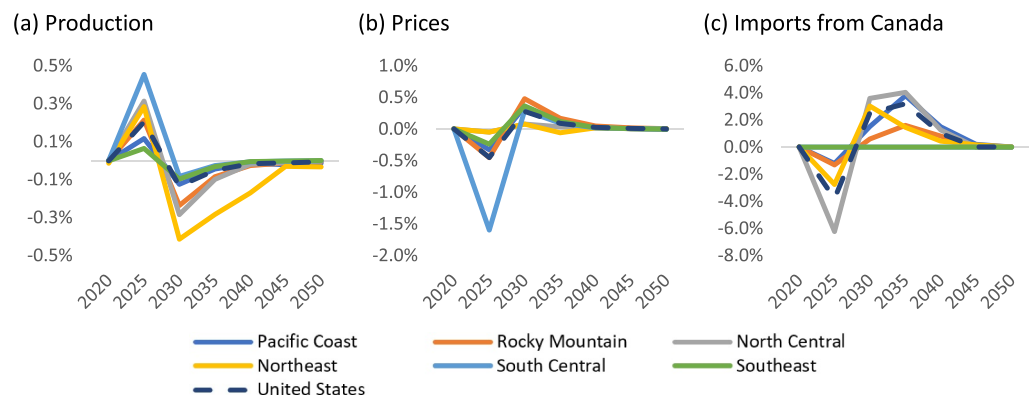


Figure 8. Change in US coniferous sawnwood market dynamics by region, 2020–2050.

Table 3
Estimated Mean Salvage Volumes From Monte Carlo Simulations, by US Region

Region	Current damage rates		Increasing damage rates	
	‘000 m ³ (standard deviation)		‘000 m ³ (standard deviation)	
	2025	2050	2025	2050
Pacific Coast	7,003 (±3,694)	8,071 (±4,011)	6,978 (±3,709)	12,266 (±4,415)
Rocky Mountain	440 (±262)	507 (±280)	449 (±286)	844 (±350)
North Central	437 (±162)	557 (±244)	475 (±150)	820 (±210)
Northeast	571 (±276)	585 (±284)	486 (±246)	899 (±426)
South Central	3,373 (±3,303)	4,329 (±3,323)	3,530 (±1,822)	5,142 (±2775)
Southeast	2983 (±1,392)	3,682 (±2121)	3,155 (±1,549)	5,965 (±2840)

shown in Table 3 and the regional salvage volume dynamics depicted in Figures B1 and B2 are consistent with the aggregated values in displayed in Figure 9.

Recall from the previous section on isolated events, the immediate impact of wind damage is a large pulse of roundwood in the market, putting upward pressure on total harvest volume. Following the event, killed inventory implies a subsequent lower growing stock of trees, increasing the marginal cost of production, putting downward pressure on harvests. These two dynamics compete against each other when we have repeated shocks, but the simulations suggest the upward pressure on total production from salvage operations out-competes the downward pressure from reduced inventory (Figure 10a). This dominance of the salvage pulse is even larger under a scenario of increasing damage rates (Figure 10b).

What cannot be seen from changes in aggregated national numbers is important regional dynamics in harvest volumes. For one, some regions experience only small changes in harvest volumes despite meaningful wind disturbance and salvage harvest activities. Such interregional production dampening occurs because all regions are simultaneously experiencing wind damage in this scenario; the increase in salvage harvest in some regions may crowd out traditional harvest activities that would otherwise have occurred. In fact, the large confidence intervals on the regional change in harvest volumes in Table 4 suggest the crowding out effect could be strong enough to lead to a decline in harvest volumes in certain regions, in reaction to large shocks in other regions. For more information on regional harvest volume dynamics, refer to Figures B2 and B3.

Consistently, the impact of surplus fiber brought about through salvage harvesting puts downward pressure on prices, overriding any potential upward pressure created through killed inventory and a higher marginal cost of production (See Figures 11 and 12). The profiles begin at zero and grow overtime for 20 years because the baseline calibration of the model does not incorporate any disturbance or salvage harvest. So the competing effects of surplus fiber at the time of disturbance, and subsequent inventory effects, must take time to play out before reaching a steady state. In other words, the impact on prices at around 2040 and beyond is what can be expected to be priced into the market from current wind average annual damage. Of course, the effects on prices will be larger, and may never reach a steady state in a scenario of increasing wind damage driven (Figure 12).

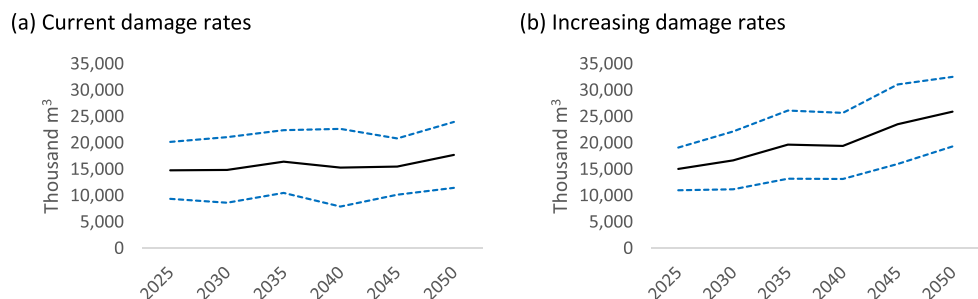


Figure 9. Estimated total US salvage volume, thousand cubic meters, 2025–2050. Note: dashed lines represent 95% confidence interval based on Monte Carlo simulations.

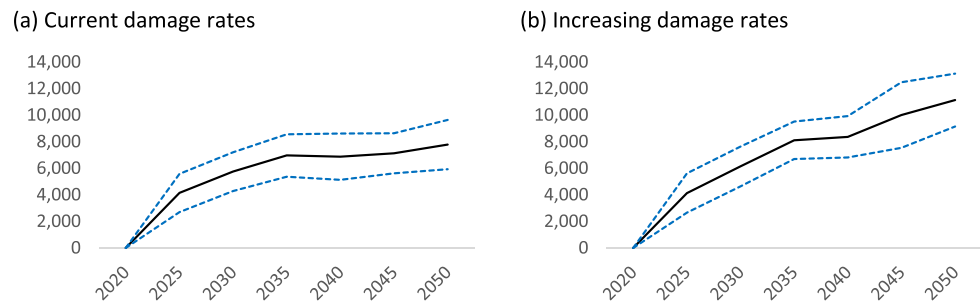


Figure 10. Estimated change in total US harvest volume, thousand cubic meters, 2025–2050. Note: dashed lines represent 95% confidence interval based on Monte Carlo simulations.

Another consequence of increased harvest activity due to disturbance in the United States is less reliance on imports to meet domestic demand. Focusing again on coniferous markets, Figure 13 shows the projected changes in imports of coniferous sawnwood from Canada into the United States. Increased production of industrial roundwood in the United States supported by salvage harvest operations from wind disturbance puts downward pressure on industrial roundwood prices. Some of these savings are passed along to sawnwood producers, decreasing their marginal cost of production, leading to higher output, putting less pressure on imports to meet domestic demand. Consistently, this trade effect is more significant under a scenario of increasing damage rates—Figure 13b.

4. Discussion

Results suggest that salvage harvesting of wind damaged forests contributed to around 3%–4% of total annual harvest volume in the United States in any given year. Large, localized wind damage events like hurricanes lead to large amounts of killed inventory and influx of salvaged timber, displacing traditional harvest activities. Consistent with previous studies (e.g., Prestemon & Holmes, 2000, 2004), this leads to downward pressure on prices in the short run, but tree mortality leads to persistent upward pressure on prices. Estimates from this study support the findings of Henderson et al. (2022), where it could take approximately 25 years for the shock to fully dissipate from markets as forest inventories reestablish to pre-shock levels.

The results of this study suggest that evaluating the impacts of disturbances on the forest products market requires a multi-product, global perspective. The more comprehensive view offered in this paper enabled the identification of several channels that work endogenously across markets in order to smooth localized disturbance shocks. For one, a disturbance in one region leads to surplus fiber and longer-term inventory changes that affect prices in the zone of impact, but the magnitudes of these effects are offset by endogenous market reactions and spatiotemporal shock transmission to other markets to compensate for changes in the availability of fiber. The study also sheds light on the importance of capturing global channels, as large shocks materialize as changes in market dynamics internationally. We demonstrated that a dominant channel for achieving market equilibria following these shocks is in the processed product market, not simply the roundwood market. There is a growing literature assessing

Table 4
Estimated Mean Change in Harvest Volumes From Monte Carlo Simulations, by US Region

Region	Current damage rates		Increasing damage rates	
	‘000 m ³ (standard deviation)		‘000 m ³ (standard deviation)	
	2025	2050	2025	2050
Pacific Coast	3,590 (±2074)	5,997 (±2293)	3,591 (±2076)	8,991 (±2797)
Rocky Mountain	78 (±177)	158 (±206)	84 (±164)	277 (±209)
North Central	26 (±96)	98 (±141)	63 (±106)	139 (±145)
Northeast	79 (±145)	25 (±110)	48 (±143)	87 (±138)
South Central	221 (±648)	932 (±1,478)	267 (±464)	669 (±1,378)
Southeast	147 (±859)	574 (±1,268)	84 (±888)	973 (±1,478)

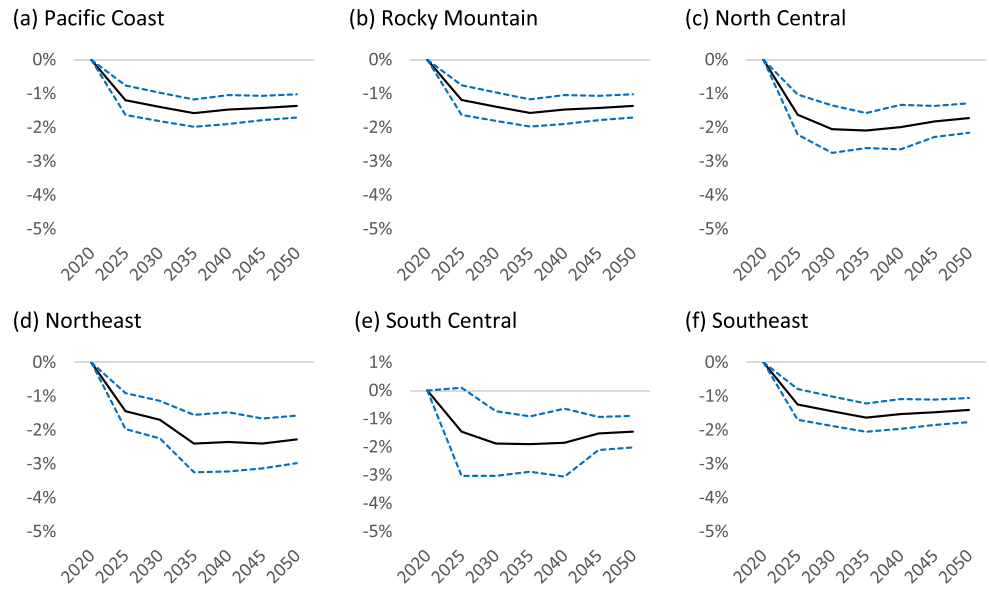


Figure 11. Estimated change in roundwood prices by US region under current damage rates, percent, 2025–2050. Note: dashed lines represent 95% confidence interval based on Monte Carlo simulations.

many of the economic impacts of these sorts of shocks in the forest sector (see Montagné-Huck & Brunette, 2018), and much of their market economic focus is on roundwood (e.g., Henderson et al., 2022; Holmes, 1991; Prestemon & Holmes, 2004) or in the valuation of post-shock policies (Caurila et al., 2015; Costa & Ibanez, 2005). More uniquely, our analysis showcases the importance of arbitrage forces mediated through derived product markets, which emphasizes an advantage of using a multiproduct forest sector model in characterizing the scope of impacts more completely.

An important implication of this work is that shocks to forest inventory through localized disturbances can lead to broader changes not just in forest product markets but also to forest management decisions. Since forests are crucial in providing a variety of ecosystem services, including carbon sequestration, biodiversity, water regulation, and livelihood support for millions of people worldwide, characterizing the overall impact of localized

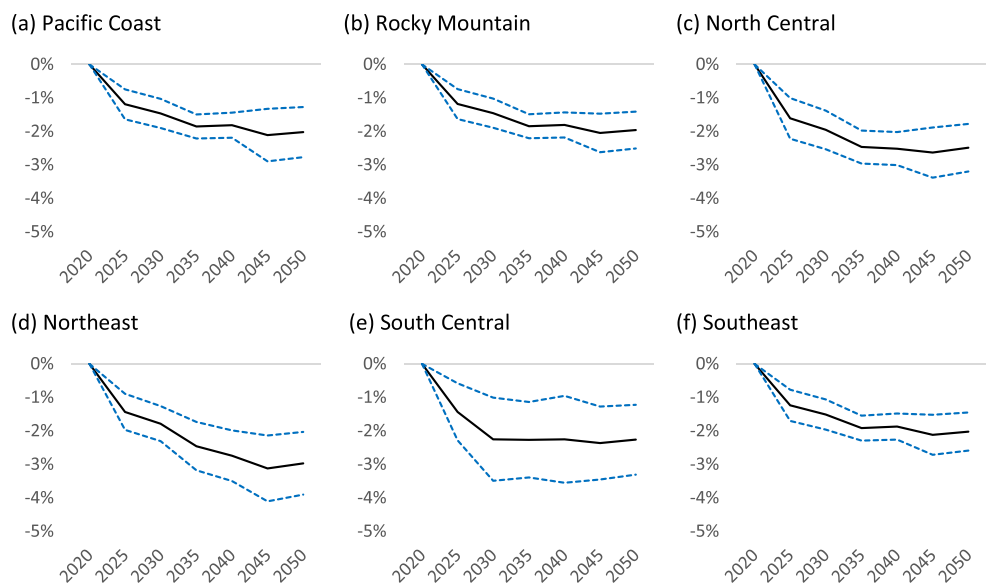


Figure 12. Estimated change in roundwood prices by US region under increasing damage rates, percent, 2025–2050. Note: dashed lines represent 95% confidence interval based on Monte Carlo simulations.

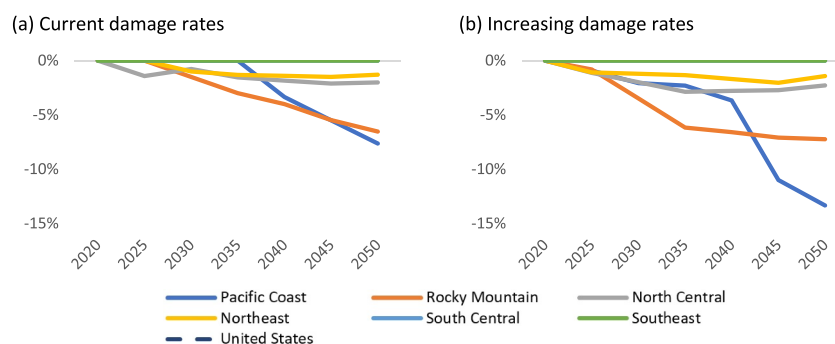


Figure 13. Estimated change in coniferous sawnwood imports from Canada to the US by US region, 2025–2050.

weather events would entail a multipronged analytical effort. For example, the modeling approach described here could be applied to assessing the effects of such large-scale disturbances on national and global forest carbon flux.

Another implication of this work is the potential effect of forest disturbance on softwood lumber tariff collections by the United States government. The ongoing softwood lumber dispute between Canada and the United States (e.g., Zhang, 2007) is in a stage with significant tariffs imposed on imports from Canada into the United States (Johnston & Parajuli, 2017). Findings from this work suggest surplus fiber in the United States from salvage operations puts downward pressure on imports of downstream products from Canada to meet domestic demand. This effect on international product flows would lead to a reduction in tariff revenue by the United States.

While outside the scope of this analysis, other climate-related extreme weather events, including wildfire, can have significant impacts on the forest products market and forest ecosystem (Riviere et al., 2022). An opportunity for future work would be to investigate wildfire-related shocks in more detail within a similar global framework of interconnected wood products. Such analyses would recognize how different disturbance regimes create distinctive effects on markets due to differences in their damage distributions, frequencies, and rates of salvage.

Further outside the scope of this analysis is an assessment of projected changes in the severity and frequency of wind events due to climate change. This study adopted a simplified approach of investigating a scenario of increase in damage rates over time to give a broad sense of the impacts because, to our knowledge, detailed projections of future increases in hurricane and other wind events for the U.S. do not exist, and even the relative magnitudes of future increases are highly uncertain. If such projections are developed in the future, connecting this modeling structure to them to model regional climate impacts would enrich our findings. Furthermore, the full set of climate impacts to forests will also include impacts to inventory growth through CO₂ fertilization. Additionally, the strongest tropical cyclones destroy housing through storm surge flooding and wind (Pistrika & Jonkman, 2010), boosting forest product demand for rebuilding, a dynamic that is likely to become more frequent or severe due to sea-level rise (e.g., Nepal et al., 2022), but was not modeled in this analysis. These aspects of disturbance effects on the forest sector have been left for future work.

It is important to note the results of this analysis contains a reasonable amount of uncertainty, both in terms of the empirical functions used to estimate historical wind disturbance damages, but also in terms of the forest sector outlook model. The deployment of Monte Carlo simulations aims to put this uncertainty in context and highlight that, in some instances, the confidence bounds are large.

Appendix A: Supplementary Information of the FOrEst Resource Outlook Model (FOROM)

This section outlines the wood product category and region definitions used in the current version of FOROM for this study.

Table A1
Wood Product Categories Represented in FOROM

Name	Description	Units
Industrial roundwood	Sawlogs and veneer logs; pulpwood, round and split; and other industrial Roundwood.	m ³
Fuelwood	Roundwood that will be used as fuel for purposes such as cooking, heating or power production.	m ³
Other roundwood	Industrial roundwood (wood in the rough) other than sawlogs, veneer logs and/or pulpwood.	m ³
Sawnwood	Wood that has been produced from both domestic and imported roundwood, either by sawing lengthways or by a profile-chipping process and that exceeds 6 mm in Thickness.	m ³
Plywood	A panel consisting of an assembly of veneer sheets bonded together with the direction of the grain in alternate plies generally at right angles. Thin sheets of wood of uniform thickness, not exceeding 6 mm, rotary cut (i.e. peeled), sliced or sawn.	m ³
Particleboard	A panel manufactured from small pieces of wood or other ligno-cellulosic materials (e.g. chips, flakes, splinters, strands, shreds, shives, etc.) bonded together by the use of an organic binder together with one or more of the following agents: heat, pressure, humidity, a catalyst, etc. The particle board category is an aggregate category. It includes oriented strandboard (OSB), medium density particle board (MDP), waferboard and Flaxboard.	m ³
Fiberboard	A panel manufactured from fibers of wood or other ligno-cellulosic materials with the primary bond deriving from the felting of the fibers and their inherent adhesive properties (although bonding materials and/or additives may be added in the manufacturing process). It includes fiberboard panels that are flat-pressed and molded fiberboard products. In JQ1 and JQ2, it is an aggregate comprising hardboard, medium/high density fiberboard (MDF/HDF) and other fiberboard.	m ³
Mechanical pulp	Wood pulp obtained by grinding or milling pulpwood or residues into fibers, or through refining chips or Particles.	t
Chemical pulp	Wood pulp obtained by subjecting pulpwood, wood chips, particles or residues to a series of chemical treatments. It includes sulfate (kraft) wood pulp; soda wood pulp and sulfite Wood pulp.	t
Other pulp	Pulp manufactured from recovered paper or from fibrous vegetable materials other than wood and used for the manufacture of paper, paperboard and fiberboard.	t
Newsprint	Paper mainly used for printing newspapers. It is made largely from mechanical pulp and/or recovered paper, with or without a small amount Of filler.	t
Printing and writing paper	Paper, except newsprint, suitable for printing and business purposes, writing, sketching, drawing, etc. Made from a variety of pulp blends and with various finishes.	t
Other paper and paperboard	Other papers and boards for industrial and special purposes.	t
Wood pellets	Agglomerates produced either directly by compression or by the addition of a binder in a proportion not exceeding 3% By weight.	t
Chips, particles, and residuals	Wood that has been reduced to small pieces and is suitable for pulping, for particle board and/or fiberboard production, for use as a fuel, or for other purposes.	m ³
Waste paper	Waste and scraps of paper or paperboard that have been collected for re-use or trade.	t

Note. Adapted from FAO definitions. <http://www.fao.org/forestry/34572-0902b3c041384fd87f2451da2bb9237.pdf>.

Table A2
Countries and Regions Represented in FORUM in the Current Study

Africa	Asia	Europe	Central America	North America	Oceania	South America	World
Nigeria	China	Austria	Rest of Central America	Canada	Australia	Argentina	Rest of World
South Arica	India	Belarus		Mexico	New Zealand	Brazil	
Rest of Africa	Indonesia	Belgium		United States	Rest of Oceania	Chile	
	Japan	Estonia		North Central		Uruguay	
	Malaysia	Finland		Northeast		Rest of South America	
	Myanmar	France		Pacific Coast			
	Russian Federation	Germany		Rocky Mountain			
	Thailand	Latvia		South Central			
	Turkey	Norway		Southeast			
	Viet Nam	Poland		Rest of North America			
	Rest of Asia	Portugal					
		Romania					
		Russian Federation					
		Slovakia					
		Spain					
		Sweden					
		Ukraine					
		United Kingdom					
		Rest of Europe					

Appendix B: Additional Output

This section provides additional outputs to supplement the results presented in the main body of the paper.

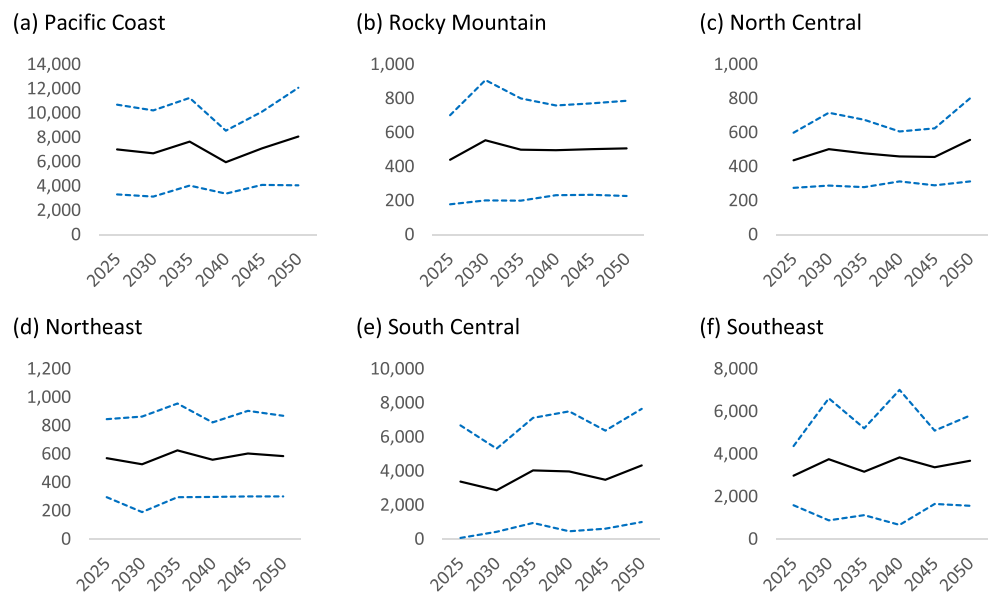


Figure B1. Estimated salvage volume by US region under current damage rates, thousand cubic meters, 2025–2050. Note: dashed lines represent 95% confidence interval based on Monte Carlo simulations.

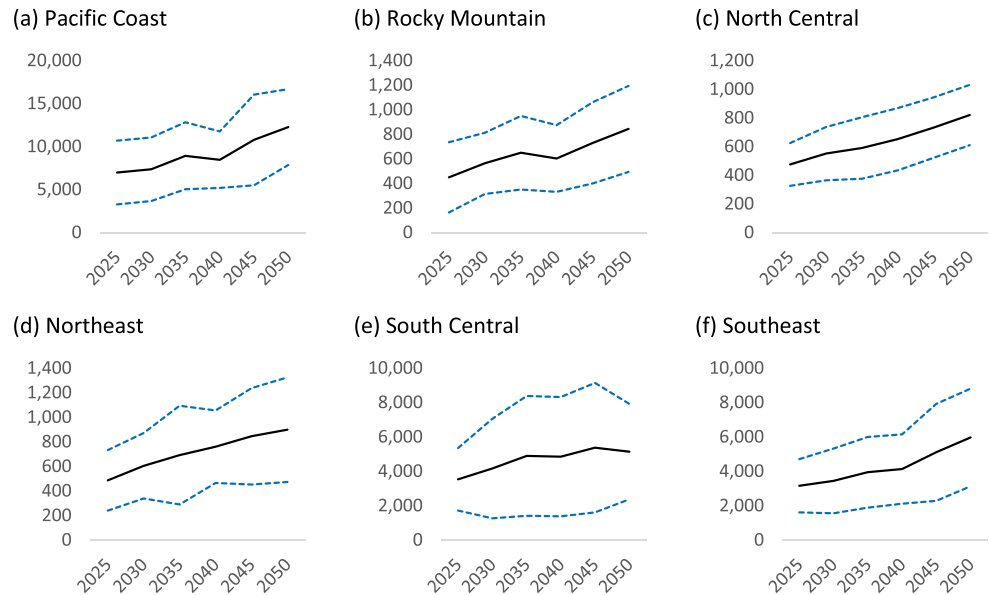


Figure B2. Estimated salvage volume by US region under increasing damage rates, thousand cubic meters, 2025–2050. Note: dashed lines represent 95% confidence interval based on Monte Carlo simulations.

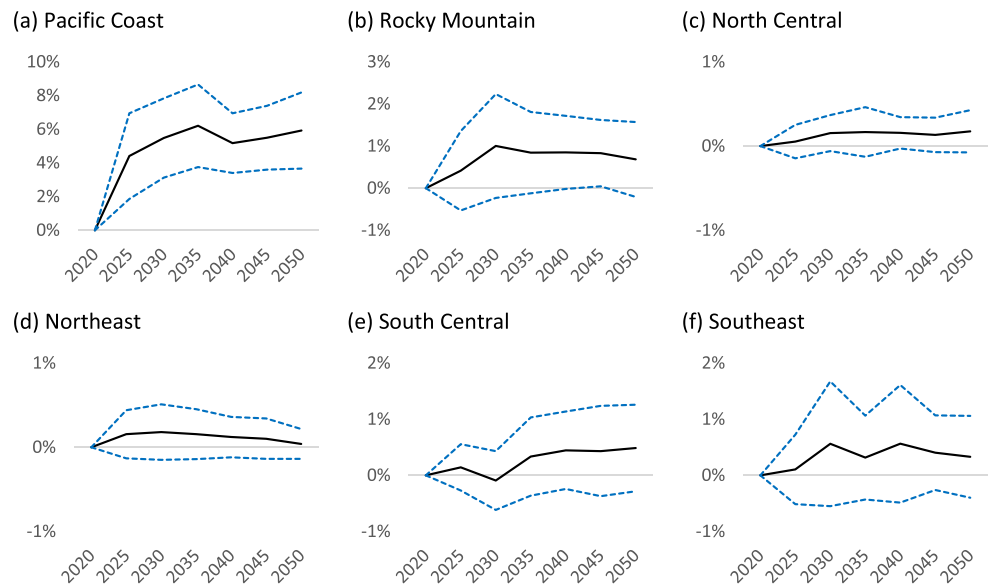


Figure B3. Estimated change in harvest volume by US region under current damage rates, 2025–2050. Note: dashed lines represent 95% confidence interval based on Monte Carlo simulations.

Figure B4

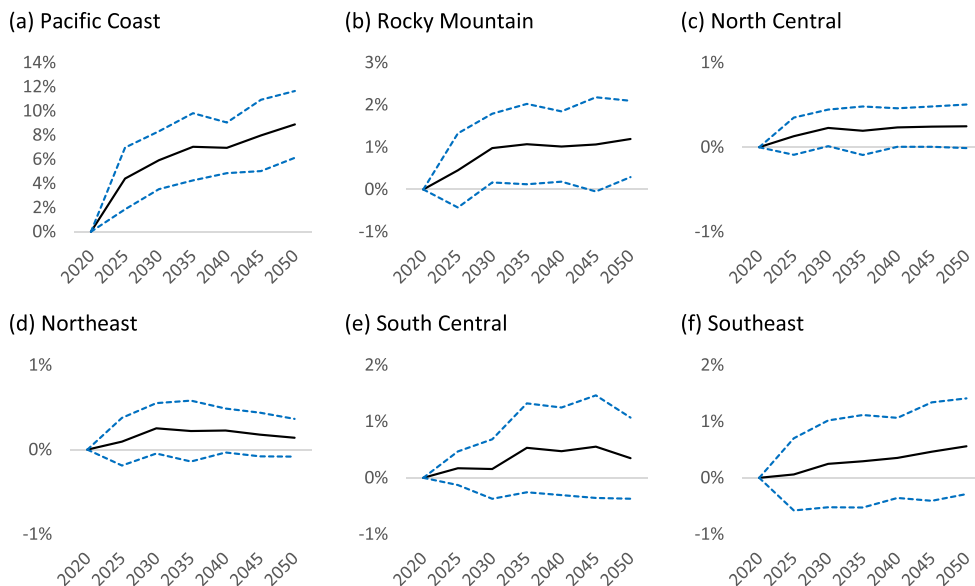


Figure B4. Estimated change in harvest volume by US region under increasing damage rates, 2025–2050. Note: dashed lines represent 95% confidence interval based on Monte Carlo simulations.

Table B1

Table B1								
Estimated Mean Change in Production of Non-Coniferous Industrial Roundwood From Monte Carlo Simulations								
Region Country	2020 '000 m ³	Deviation from baseline						
		Current estimate damage rates						+2%/yr
		2025	2030	2035	2040	2045	2050	2050
North America	140,076	0.1%	0.2%	0.2%	0.2%	0.1%	0.1%	0.2%
United States	112,101	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.3%
Canada	27,290	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Africa	61,355	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Asia	420,227	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Central America	3,729	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Europe	91,236	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
South America	148,257	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Oceania	19,846	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
World	892,593	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table B2

Table B2 <i>Estimated Mean Change in Production of Coniferous Sawnwood From Monte Carlo Simulations</i>								
Region Country	2020 '000 m ³	Deviation from baseline						
		Current estimate damage rates						+2%/yr
		2025	2030	2035	2040	2045	2050	2050
North America	105,275	0.1%	0.2%	0.2%	0.2%	0.3%	0.3%	0.3%
<i>United States</i>	56,821	0.2%	0.5%	0.5%	0.5%	0.7%	0.7%	0.9%
<i>Canada</i>	46,387	−0.2%	−0.2%	−0.3%	−0.3%	−0.3%	−0.4%	−0.5%
Africa	3,082	1.7%	1.4%	1.6%	1.4%	1.3%	1.5%	2.3%
Asia	94,015	0.1%	0.0%	0.1%	0.1%	0.0%	0.0%	0.1%
Central America	470	2.8%	2.5%	2.8%	2.5%	2.4%	2.9%	4.5%
Europe	101,115	−0.1%	−0.1%	−0.1%	−0.1%	−0.2%	−0.2%	−0.2%
South America	18,920	−0.1%	−0.1%	−0.1%	−0.2%	−0.2%	−0.2%	−0.2%
Oceania	8,475	0.4%	0.3%	0.3%	0.2%	0.2%	0.2%	0.4%
World	331,372	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%

Table B3

Table B3 <i>Estimated Mean Change in Production of Non-Coniferous Sawnwood From Monte Carlo Simulations</i>								
Region Country	2020 '000 m ³	Deviation from baseline						
		Current estimate damage rates						+2%/yr
		2025	2030	2035	2040	2045	2050	2050
North America	25,833	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.1%
<i>United States</i>	23,469	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.1%
<i>Canada</i>	2,124	0.0%	0.0%	0.0%	0.0%	−0.1%	0.0%	0.1%
Africa	6,577	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Asia	93,377	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Central America	866	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Europe	13,051	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
South America	11,915	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Oceania	1,016	−0.1%	−0.1%	−0.1%	0.0%	0.0%	0.0%	0.0%
World	156,018	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table B4

Table B4 <i>Estimated Mean Change in Production of Wood Pellets From Monte Carlo Simulations</i>								
Region Country	2020 '000 m ³	Deviation from baseline						
		Current estimate damage rates						+2%/yr
		2025	2030	2035	2040	2045	2050	2050
North America	11,496	0.1%	0.1%	0.1%	0.1%	0.8%	0.8%	1.1%
United States	9,191	0.1%	0.2%	0.2%	0.2%	1.2%	1.2%	1.7%
Canada	2,293	−0.1%	−0.1%	−0.1%	−0.3%	−1.1%	−0.9%	−1.4%
Africa	55	0.4%	0.3%	0.4%	0.3%	−0.8%	−0.5%	−0.6%
Asia	4,234	0.0%	0.2%	0.2%	0.2%	−0.5%	−0.4%	−0.6%
Central America	47	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Europe	24,218	0.0%	0.0%	0.0%	0.1%	−0.2%	−0.2%	−0.3%
South America	182	0.1%	−0.2%	−0.2%	−0.1%	−0.9%	−0.9%	−1.3%
Oceania	316	0.1%	0.1%	0.2%	−0.1%	−0.6%	−0.5%	−0.7%
World	40,589	0.0%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%

Table B5

Table B5 <i>Gamma Distribution Fits by Region and Species Group</i>					
Region	Species group	Shape		Rate	
		Estimate	Std. Error	Estimate	Std. Error
Pacific Coast	Softwood	4.178104	1.305128	457.9181	151.9967
	Hardwood	2.421879	0.780273	165.7052	59.30433
Rocky Mountain	Softwood	2.747222	0.918312	848.7479	311.2387
	Hardwood	3.045937	1.294554	464.1137	214.4314
South Central	Softwood	0.892703	0.229432	84.09528	28.48799
	Hardwood	2.030079	0.544751	139.7738	42.51747
Northeast	Softwood	1.86507	0.574772	396.6846	140.1179
	Hardwood	2.286679	0.631396	675.4598	208.4817
North Central	Softwood	2.126996	0.597872	346.544	109.7962
	Hardwood	7.368092	2.173081	1,032.723	315.1973
Southeast	Softwood	1.599793	0.431514	178.4239	56.40347
	Hardwood	1.762904	0.478779	99.77753	31.30245

Table B6

Table B6 Area Damage Rates by Region and Species Group for Cumulative Distribution Probabilities				
Region	Species group	p0.5	p0.95	p0.975
North Central	Softwood	0.0052	0.0143	0.0167
	Hardwood	0.0068	0.0119	0.0131
Northeast	Softwood	0.0039	0.0114	0.0135
	Hardwood	0.0029	0.0077	0.0090
Pacific Coast	Softwood	0.0084	0.0175	0.0197
	Hardwood	0.0127	0.0327	0.0379
Rocky Mountain	Softwood	0.0029	0.0070	0.0080
	Hardwood	0.0059	0.0137	0.0157
South Central	Softwood	0.0070	0.0331	0.0411
	Hardwood	0.0122	0.0343	0.0402
Southeast	Softwood	0.0072	0.0229	0.0272
	Hardwood	0.0145	0.0436	0.0517

Data Availability Statement

Wind damage information used to calibrate wind damage to forest inventory are available from the FIA data via the rFIA package (Stanke et al., 2020) in R statistical software (R Core Team, 2023). Salvage rate adjustments were based on relative logging employment levels in 2022, based on NAICS 1133 from the United States Bureau of Labor Statistics (BLS, 2023). The Forest Resource Outlook Model (FOROM) is a model that encompasses various aspects of the global forest sector, such as forest resources, timber supply, demand for intermediate and final products, and international trade. A detailed description of the model is available in Johnston et al. (2021). The model and its source code will be preserved in a GIT repository at https://github.com/cjohnston5/FOROM/tree/main/FOROM_GIT. The model and data supporting this research are available at Johnston (2024) with restrictions related to third party proprietary data. Access to the data is made available for academic purposes only, through request to the corresponding author. The Food and Agricultural Organization of the United Nations (FAO, 2024) serves as the main data source for FOROM. Information on forest areas and stocks is derived from the Food and Agricultural Organization's Global Forest Resources Assessments (FAO, 2020). The United States is disaggregated into six regions, utilizing information from the United States Department of Agriculture's Forest Service's Timber Product Output program (TPO, 2024), and the USITC available through their open data platform (USITC, 2024). GDP and population serve as the main driving forces behind projections in FOROM, calibrated to the Shared Socioeconomic Pathway data (IIASA, 2024). We used the county projections (Wear & Pre-stemon, 2019b) to calibrate GDP and population projections for each region within the United States.

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References

- Abatzoglou, J. T., Juang, C. S., Williams, A. P., Kolden, C. A., & Westerling, A. L. (2020). Increasing synchronous fire danger in forests of the western United States. *Geophysical Research Letters*, 48(2), e2020GL091377. <https://doi.org/10.1029/2020GL091377>
- Audley, J. P., Fetting, C. J., Munson, A. S., Runyon, J. B., Mortenson, L. A., Steed, B. E., et al. (2020). Impacts of mountain pine beetle outbreaks on lodgepole pine forests in the Intermountain West, US, 2004–2019. *Forest Ecology and Management*, 475, 118403. <https://doi.org/10.1016/j.foreco.2020.118403>
- Aukema, J. E., Leung, B., Kovacs, K., Chivers, C., Britton, K. O., Englin, J., et al. (2011). Economic impacts of non-native forest insects in the continental United States. *PLoS One*, 6(9), e24587. <https://doi.org/10.1371/journal.pone.0024587>
- Balaguru, K., Xu, W., Chang, C. C., Leung, L. R., Judi, D. R., Hagos, S. M., et al. (2023). Increased U.S. coastal hurricane risk under climate change. *Science Advances*, 9(14). <https://doi.org/10.1126/sciadv.adf0259>
- Bowman, D. M. J. S., Kolden, C. A., Abatzoglou, J. T., Johnston, F. H., van der Werf, G. R., & Flannigan, M. (2020). Vegetation fires in the anthropocene. *Nature Reviews Earth & Environment*, 1(10), 500–515. <https://doi.org/10.1038/s43017-020-0085-3>
- Brandeis, T., Turner, J., Castro, A. B., Brown, M., & Lambert, S. (2022). Assessing forest resource damage following natural disasters using national forest inventory plots: A case study of Hurricane Michael. <https://doi.org/10.2737/SRS-RP-65>

- Caurla, S., Garcia, S., & Niedzwiedz, A. (2015). Store or export? An economic evaluation of financial compensation to forest sector after windstorm. The case of hurricane Klaus. *Forest Policy and Economics*, 61, 30–38. <https://doi.org/10.1016/j.forpol.2015.06.005>
- Chambers, J. Q., Fisher, J. I., Zeng, H., Chapman, E. L., Baker, D. B., & Hurr, G. C. (2007). Hurricane Katrina's carbon footprint on US Gulf Coast forests. *Science*, 318(5853), 1107. <https://doi.org/10.1126/science.1148913>
- Costa, S., & Ibanez, L. (2005). Can wood storage be profitable? French experience after the windstorms in 1999. *Journal of Forest Economics*, 11(3), 161–176. <https://doi.org/10.1016/j.jfe.2005.08.001>
- Costanza, J. K., Koch, F. H., & Reeves, M. C. (2023). Future exposure of forest ecosystems to multi-year drought in the United States. *Ecosphere*, 14(c4525). <https://doi.org/10.1002/ecs2.4525>
- Dale, V. H., Joyce, L. A., McNulty, S., Nielson, R. P., Ayres, M. P., Flannigan, M. D., et al. (2001). Climate change and forest disturbances. *BioScience*, 51(9), 723–734. [https://doi.org/10.1641/0006-3568\(2001\)051\[0723:ccafd\]2.0.co;2](https://doi.org/10.1641/0006-3568(2001)051[0723:ccafd]2.0.co;2)
- Delignette-Muller, M. L., & Dutang, C. (2015). fitdistrplus: An R package for fitting distributions. *Journal of Statistical Software*, 64(4). <https://doi.org/10.18637/jss.v064.i04>
- El Garroussi, S., Di Giuseppe, F., Barnard, C., & Wetterhall, F. (2024). Europe faces up to tenfold increase in extreme fires in a warming climate. *npj Climate and Atmospheric Science*, 7(1), 30. <https://doi.org/10.1038/s41612-024-00575-8>
- Elsner, J. B., Kossin, J. P., & Jagger, T. H. (2008). The increasing intensity of the strongest tropical cyclones. *Nature*, 455(7209), 92–95. <https://doi.org/10.1038/nature07234>
- Food and Agricultural Organization of the United Nations. (FAO). (2024). Forestry production and trade [Dataset]. <http://www.fao.org/faostat/en/#data/>
- Food and Agriculture Organization of the United Nations. (FAO). (2020). Global forest resources assessment 2020 [Dataset]. *Global Forest Resources Assessment 2020*. <http://www.fao.org>
- Gardiner, B. (2021). Wind damage to forests and trees: A review with an emphasis on planted and managed forests. *Journal of Forest Research*, 26(4), 248–266. <https://doi.org/10.1080/13416979.2021.1940665>
- Gordon, J. S., Auel, J. B., Blair-Agyeman, N., Montague, I. B., & Shmuly, R. (2018). Infrastructure enhancement to support value-added bioproduct recovery. *Natural Resources*, 9(4), 129–149. <https://doi.org/10.4236/nr.2018.94009>
- Henderson, J. D., Abt, R. C., Abt, K. L., Baker, J., & Sheffield, R. (2022). Impacts of hurricanes on forest markets and economic welfare: The case of hurricane Michael. *Forest Policy and Economics*, 140, 102735. <https://doi.org/10.1016/j.forpol.2022.102735>
- Holmes, T. P. (1991). Price and welfare effects of catastrophic forest damage from southern pine beetle epidemics. *Forest Science*, 37(2), 500–516. <https://doi.org/10.1093/forestscience/37.2.500>
- International Institute for Applied Systems Analysis. (2024). Shared socioeconomic pathways scenario database (SSP) [Dataset]. <https://iiasa.ac.at/models-tools-data/ssp>
- Johnston, C. M. T. (2024). FOROM disturbance model [Software]. <https://doi.org/10.5281/zenodo.12521328>
- Johnston, C. M. T., Guo, J., & Prestemon, J. P. (2021). The FForest Resource Outlook Model (FOROM): A technical document supporting the forest service 2020 RPA assessment. USDA Forest Service General. Technical Report SRS-254. Asheville, NC, 2021.
- Johnston, C. M. T., & Parajuli, R. (2017). What's next in the U.S.-Canada softwood lumber dispute? An economic analysis of restrictive trade policy measures. *Forest Policy and Economics*, 85(1), 135–146. <https://doi.org/10.1016/j.forpol.2017.09.011>
- Leung, L. R., Terando, A., Joseph, R., Tselioudis, G., Bruhwiler, L. M., Cook, B., et al. (2023). Ch. 3. Earth systems processes. In A. R. Crimmins, C. W. Avery, D. R. Easterling, K. E. Kunkel, B. C. Stewart, & T. K. Maycock (Eds.), *Fifth national climate assessment*. U.S. Global Change Research Program. <https://doi.org/10.7930/NCA5.2023.CH3>
- Littell, J. S., McKenzie, D., Wan, H. Y., & Cushman, S. A. (2018). Climate change and future wildfire in the western United States: An ecological approach to nonstationarity. *Earth's Future*, 6(8), 1097–1111. <https://doi.org/10.1029/2018ef000878>
- Montagné-Huck, C., & Brunette, M. (2018). Economic analysis of natural forest disturbances: A century of research. *Journal of Forest Economics*, 32, 42–71. <https://doi.org/10.1016/j.jfe.2018.03.002>
- Nelson, M. D., Riitters, K. H., Coulston, J. W., Domke, G. M., Greenfield, E. J., Langner, L. L., et al. (2020). Defining the United States land base. USDA Forest Service Gen. Tech. Rep. NRS-191. (p. 70). <https://doi.org/10.2737/NRS-GTR-191>
- Nepal, P., Johnston, C. M. T., & Ganguly, I. (2021). Effects on global forests and wood product markets of increased demand for Mass timber. *Sustainability*, 13(24), 13943. <https://doi.org/10.3390/su132413943>
- Nepal, P., Prestemon, J. P., Joyce, L. A., & Skog, K. E. (2022). Global forest products markets and forest sector carbon impacts of projected sea level rise. *Global Environmental Change*, 77, 102611. <https://doi.org/10.1016/j.gloenvcha.2022.102611>
- O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., et al. (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change*, 42, 169–180. <https://doi.org/10.1016/j.gloenvcha.2015.01.004>
- Parks, S. A., Miller, C., Abatzoglou, J. T., Holsinger, L. M., Parisien, M. A., & Dobrowski, S. Z. (2016). How will climate change affect wildland fire severity in the western US? *Environmental Research Letters*, 11(3), 035002. <https://doi.org/10.1088/1748-9326/11/3/035002>
- Patacca, M., Lindner, M., Lucas-Borja, M. E., Cordonnier, T., Fidej, G., Gardiner, B., et al. (2023). Significant increase in natural disturbance impacts on European forests since 1950. *Global Change Biology*, 29(5), 1359–1376. <https://doi.org/10.1111/gcb.16531>
- Pausas, J. G., & Keeley, J. E. (2021). Wildfires and global change. *Frontiers in Ecology and the Environment*, 19(7), 387–395. <https://doi.org/10.1002/fec.2359>
- Pistrika, A. K., & Jonkman, S. N. (2010). Damage to residential buildings due to flooding of New Orleans after hurricane Katrina. *Natural Hazards*, 54(2), 413–434. <https://doi.org/10.1007/s11069-009-9476-y>
- Prestemon, J. P., & Holmes, T. P. (2000). Timber price dynamics following a natural catastrophe. *American Journal of Agricultural Economics*, 82(1), 145–160. <https://doi.org/10.1111/0002-9092.00012>
- Prestemon, J. P., & Holmes, T. P. (2004). Market dynamics and optimal timber salvage after a natural catastrophe. *Forest Science*, 50(4), 495–511. <https://doi.org/10.1093/forestscience/50.4.495>
- Pureswaran, D. S., Roques, A., & Battisti, A. (2018). Forest insects and climate change. *Current Forestry Reports*, 4(2), 35–50. <https://doi.org/10.1007/s40725-018-0075-6>
- R Core Team. (2023). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. Retrieved from <https://www.R-project.org/>
- Reed, K. A., Wehner, M. F., & Zarzycki, C. M. (2022). Attribution of 2020 hurricane season extreme rainfall to human-induced climate change. *Nature Communications*, 13(1), 1905. <https://doi.org/10.1038/s41467-022-29379-1>
- Riahi, K., Van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., et al. (2017). The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, 42, 153–168. <https://doi.org/10.1016/j.gloenvcha.2016.05.009>

- Riviere, M., Pimont, F., Delacote, P., Cauria, S., Ruffault, J., Lobianco, A., et al. (2022). A bioeconomic projection of climate-induced wildfire risk in the forest sector. *Earth's Future*, 10(4), e2021EF002433. <https://doi.org/10.1029/2021ef002433>
- Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., et al. (2017). Forest disturbances under climate change. *Nature Climate Change*, 7(6), 395–402. <https://doi.org/10.1038/nclimate3303>
- Senf, C., & Seidl, R. (2021). Storm and fire disturbances in Europe: Distribution and trends. *Global Change Biology*, 27(15), 3605–3619. <https://doi.org/10.1111/gcb.15679>
- Sommerfeld, A., Senf, C., Buma, B., D'Amato, A. W., Després, T., Díaz-Hormazábal, I., et al. (2018). Patterns and drivers of recent disturbances across the temperate forest biome. *Nature Communications*, 9(1), 4355. <https://doi.org/10.1038/s41467-018-06788-9>
- Spinoni, J., Formetta, G., Mentaschi, L., Forzieri, G., & Feyen, L. (2020). Global warming and windstorm impacts in the EU. European Commission Joint Research Center Technical Report JRC PESETA IV project-Task 13.
- Stanke, H., Finley, A. O., Weed, A. S., Walters, B. F., & Domke, G. M. (2020). rFIA: An R package for estimation of forest attributes with the US Forest Inventory and Analysis database. *Environmental Modelling & Software*, 127, 104664. <https://doi.org/10.1016/j.envsoft.2020.104664>
- Tumber-Dávila, S. J., Lucey, T., Boose, E. R., Laflour, D., León-Sáenz, A., Wilson, B. T., et al. (2024). Hurricanes pose a substantial risk to New England forest carbon stocks. *Global Change Biology*, 30(4), e17259. <https://doi.org/10.1111/gcb.17259>
- U.S. Bureau of Labor Statistics (BLS). (2023). Quarterly census of employment and wages [Dataset]. *QCEW Data Files: U.S. Bureau of Labor Statistics*. <https://www.bls.gov/cew/downloadable-data-files.htm>
- U.S. Department of Agriculture's Forest Service's Timber Product Output (TPO). (2024). Timber products output (TPO) interactive reporting tool [Dataset]. <https://www.fs.usda.gov/research/products/dataandtools/tools/timber-products-output-tpo-interactive-reporting-tool>
- U.S. International Trade Commission (USITC). (2024). DataWeb [Dataset]. <https://dataweb.usitc.gov/>
- Wan, H. Y., Cushman, S. A., & Ganey, J. L. (2019). Recent and projected future wildfire trends across the ranges of three spotted owl subspecies under climate change. *Frontiers in Ecology and Evolution*, 7, Article 37. <https://doi.org/10.3389/fevo.2019.00037>
- Wear, D. N., & Prestemon, J. P. (2019a). Spatiotemporal downscaling of global population and income scenarios for the United States. *PLoS One*, 14(7), e0219242. <https://doi.org/10.1371/journal.pone.0219242>
- Wear, D. N., & Prestemon, J. P. (2019b). *Socioeconomic data for forest service 2020 RPA assessment*. Forest Service Research Data Archive. <https://doi.org/10.2737/RDS-2019-0041>
- Zampieri, N. E., Pau, S., & Okamoto, D. K. (2020). The impact of Hurricane Michael on longleaf pine habitats in Florida. *Scientific Reports*, 10(1), 8483. <https://doi.org/10.1038/s41598-020-65436-9>
- Zhai, J., & Kuusela, O. P. (2020). Estimating price dynamics in the aftermath of forest disturbances: The biscuit fire in southwest Oregon. *Forest Science*, 66(5), 556–567. <https://doi.org/10.1093/forsci/fxaa004>
- Zhang, D. (2007). *The softwood lumber war: Politics, economics, and the long U.S.-Canadian trade dispute*. Routledge. <https://doi.org/10.4324/9781936331581>