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Growth in Economic Losses Due to Forest Disturbances in the Eastern United States

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Abstract

Climate change projections suggest growth in the rate and intensity of forest disturbances such as wildfire and hurricanes. This study compares observed forest mortality and infers economic losses associated with forest disturbance events in eight ecoregions of the eastern United States for the first two decades of the twenty-first century. For each ecoregion, we estimate disturbance rates and their impacts on tree mortality and timber values based on multiple remeasurements of forest inventory plots for two decadal periods ending in 2015 (“period 1”) and 2024 (“period 2”). Using an excess mortality approach, we attribute mortality to either normal stand development or disturbance events in these two periods. We then estimate the losses that would be anticipated in period 2 based on period 1 disturbance patterns and compare them with realized losses. Area disturbed and forest mortality increased between the two periods and in all ecoregions; major drivers were hurricanes in the southeast and insects in the northeast. Total losses from disturbances in the eastern United States grew from \$30.8 billion per year in period 1 to \$49.5 billion per year in period 2, with substantial variation across ecoregions. In period 2, about 40 percent of disturbance-related losses (~\$20 billion per year) were unanticipated based on period 1 disturbance regimes applied to exposed resources. Area disturbance rates and biomass mortality rates are poor proxies for timber value losses that depend on the species/size mix of timber.

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1. Introduction

Climate change is expected to alter the area, pattern, and intensity of forest disturbance events, including wildfire, wind, insect outbreaks, and disease infestations, with potentially compounding effects for forest owners and society at large (Dudney et al. 2025; Seidl et al. 2017). Among direct impacts is the provision of timber benefits from managed forests. Forest investments are based on the anticipated accumulation of forest biomass over long periods and are subject to market risk as well as risk that disturbance events will alter biomass accumulation and expected returns. Investors can incorporate expectations regarding disturbance losses in their planning, but decisions can be efficient only if risk processes are known and stable. Unanticipated climate-driven shifts in disturbance risk could alter biophysical and financial outcomes in ways that define real losses for landowners and investors. Using forest inventory and price data, we estimate how forest disturbance rates and associated economic losses have changed between two decadal periods ending in 2015 (“period 1”) and 2024 (“period 2”) and estimate the portion of economic losses that were unanticipated.

Our study focuses on forest disturbances in eight ecoregions of the eastern United States, where timber values are relatively high but forest conditions, disturbances, and management are highly varied (Coulston et al. 2023; Oswalt et al. 2019). For each ecoregion, we compare disturbance rates on an area basis and resulting changes in tree mortality and timber values using multiple remeasurements of forest inventory plots. Measurements of forest mortality and forest value dynamics are conducted at a very fine scale (tree species for individual forest plots) and then aggregated to provide estimates of biophysical and economic impacts for broad ecosystems. We first isolate the tree mortality associated with disturbances from background mortality, a fundamental and ongoing demographic process in the development of forest stands (e.g., Pretzsch 2009). Defining the effects of disturbance on mortality requires modeling expected background mortality to isolate excess mortality, similar to human demographic models applied to disease epidemics.

Disturbance-related mortality can alter forest composition (Seidl et al. 2017; Senf et al. 2020), timber product distribution (Brecka, Shahi, and Chen 2018; Březina, Michal, and Hlaváčková 2024; Johnston et al. 2024; Zhai and Ning 2022), and carbon offsets (Badgley et al. 2022; Kurz et al. 2008; Siebel-McKenna, Johnston, and van Kooten 2020).¹ We note that some disturbances can actually increase timber value if they selectively remove unmarketable species. Here, we address how excess mortality from disturbances alter forest composition and associated timber values to develop our estimates of economic losses.

Previous studies of the economic impacts of disturbances focus on specific episodic events, with several studies addressing the economic implications of hurricanes (Henderson et al. 2022; Johnston et al. 2024; Sun 2016), large-scale insect outbreaks (Asada et al. 2023; Pye et al. 2011), and wildfire events (Prestemon et al. 2006; Zhai

1 For example, increasing rates of disturbances and mortality have raised concerns about the capitalization of buffer pools in carbon offset markets (Badgley et al. 2022).

and Kuusela 2020). Many studies focus on price dynamics in local markets (Zhai and Ning 2022). In contrast, we address all observed disturbance types between inventory measurements and estimate their impact on mortality and implied values of standing forests. Unlike studies that use normative optimal harvest choice models as the basis for valuing forest inventories (e.g., Wang and Lewis 2024), we estimate forward-looking timber forest values based on observed harvest choices and standing inventories organized by species and product classes and species/product prices.²

We expect that landowners can efficiently mitigate known and stable disturbance risk using a variety of techniques, including alternative silvicultural practices to alter species and forest development (Jactel et al. 2009), portfolio diversification to spread risk (Busby, Binkley, and Chudy 2020), and adjusting asset pricing formulae to account for expected losses (Yao and Mei 2015). Real economic losses accrue to disturbance effects that exceed those predicted by historical disturbance regimes. We estimated expected losses for period 2 based on beginning period inventories (exposed assets) and disturbance rates and losses from period 1. The difference between realized losses and these expected losses defines unanticipated losses.

Results provide novel estimates of the economic losses associated with all forest disturbances for each ecoregion and highlight how disturbance rates, disturbance-related mortality, and economic losses have grown across all ecoregions between periods. Unanticipated economic losses are shown to be substantial, accounting for about 40 percent of disturbance-related losses (~\$20 billion per year). We discuss the limitations of our approach, especially for interpreting change between two periods. Disturbance events may be episodic at broad scales and interact with long-run trends in climate variables. We contemplate extensions of our models, for example to address carbon offset reversal risk and carbon buffer pool strategies (Badgley et al. 2022).

2. Methods

We use remeasured plots from the full US Forest Service Forest Inventory and Analysis (FIA) inventory of the eastern United States to evaluate forest disturbances and resulting mortality (Miles et al. 2001). Based on a rotating panel design, these plots are remeasured on a regular basis, with an average remeasurement period of six to seven years in the eastern United States. Tree-level observations are used to define current conditions at the species level and allow for estimation of biomass change related to tree mortality and timber harvesting. Remeasurements of standing inventory define net change in tree biomass, mortality, and harvesting between measurements. Inventory crews record whether a plot shows evidence of one of several disturbance events. We also use records of other tree and plot-level conditions, including ownership type, tree diameters, and slope. Because the FIA inventory is based on an area frame, plot

2 The optimal rotation approach based on Faustman, Hartman, and Reed (Hartman 1976; Reed 1984) is contraindicated in much of the eastern United States because a large share of harvests removes only a portion of standing stocks from multi-species stands, implying a different management approach. See Wear and Coulston (2025) for more discussion.

estimates expanded by area expansion factors define population estimates for each of the studied regions. All measurements are constructed for two decadal periods, one that concludes in 2015 and the other that concludes in 2024.

2.1. Background versus Excess Mortality

The ordinary course of forest development involves tree mortality as the number of trees declines while a stand accumulates biomass (Pretzsch 2009). Tree survival functions have been modeled as (decreasing) functions of tree height, diameter at breast height, and stand basal area, all of which are increasing functions of stand age (Bugmann et al. 2019). We posit that background forest mortality measured as biomass per unit area is a function of 1) the developmental state of the forest proxied by average forest age and biomass density, 2) management approaches proxied by ownership group (commercial, family forest, or public), and 3) species assemblages (hardwood or softwood) and other biophysical conditions, proxied by ecoregion. We also examine the possibility that background mortality has shifted between early- and late-period measurements.

We model background mortality as follows:

$$\text{mortality}_{\text{back}} = f(\text{age}, I_b, \text{soft}, D_{\text{owner}}, D_t, D_{\text{planted}}, D_{\text{ecoregion}}), \quad (1)$$

where age is the average plot age; I_b is the biomass volume at the beginning of the remeasurement period; and D variables are dummy variables for owner (family, commercial, or public), time period (1 or 2), planted (yes or no), and ecoregion (eight regions defined in Section 3). We estimate these equations using a linear regression model applied only to the panel of undisturbed plot observations.

To estimate excess mortality, we subtract the predicted values from the background mortality model (equation 1) from observed mortality for all plots experiencing a disturbance. Results are summarized to the ecoregion-level based on the area frame design of the forest inventory.

2.2. Timber Value Impacts

The effect of forest mortality on the economic value of forests depends on the distribution of tree mortality across species and size classes. Some species—for example, black walnut (*Juglans nigra*)—have high price premiums; trees that are large enough to provide sawtimber products are much more valuable than small-diameter timber suitable for pulpwood or bioenergy uses. Based on methods detailed in Wear and Coulston (2025), we use measures of the plot's individual trees to assign species-specific and product-class components to the standing inventory and to harvest removals and species/product prices to assign value to standing inventory

and harvests. We define the observed value of each plot as the sum of the value of the ending inventory plus all revenues generated from harvests over the remeasurement period:

$$\text{value} = \sum_{sp=1}^n \sum_{k=1}^2 p_{sp,k} I_{sp,k} * (1 + d)^{-\text{remp}} + \sum_{sp=1}^n \sum_{k=1}^2 p_{sp,k} R_{sp,k} * (1 + d)^{-\text{remp}/2}, \quad (2)$$

where $p_{sp,k}$, $I_{sp,k}$ and $R_{sp,k}$ are prices, inventory, and harvest removals, respectively, all indexed by species code (sp) and by product class (k , either sawtimber or nonsawtimber/pulpwood). We discount the ending inventory value using a discount rate ($d=0.05$) and the remeasurement period (remp). We value harvests at the midpoint of the remeasurement period ($\text{remp}/2$). In effect, we anticipate a forest investor evaluating a forest stand as a part of a closed-end fund, where returns are defined by revenues over the fund's duration (the remeasurement period), plus the "salvage" value at its conclusion. "Value" in equation 2 is a reasonable approximation of the timber-based asset price based on realized harvest and inventory changes.

As with biophysical mortality, we estimate the expected value of an undisturbed stand (value_u) based on equation 2, using a linear regression model applied to the panel of undisturbed plot observations as follows:

$$\text{value}_u = f(\text{remp}, \text{age}, vI_b, \text{soft}, D_{\text{owner}}, D_t, D_{\text{planted}}, D_{\text{ecoregion}}), \quad (3)$$

where most variables are defined as in equation 1. Additionally, vI_b is defined as $\sum_{sp=1}^n \sum_{k=1}^2 p_{sp,k} I_{b,sp,k}$, where b indicates inventory at the beginning of the remeasurement period. Predictions from the estimated equation 3 can be viewed as expectations regarding forest value from the beginning of the remeasurement period.

To estimate value loss related to disturbances, we subtract the predicted values based on the undisturbed value model (equation 3) from observed values for all plots experiencing a disturbance:

$$\widehat{\text{loss}} = \left[\text{value}_d - \widehat{\text{value}}_u \right]. \quad (4)$$

Losses related to disturbance reflect not only losses due to changes in the standing inventory at the end of the remeasurement period but also changes in harvest revenues that include both foregone harvests and salvage harvesting.

To evaluate anticipated versus unanticipated mortality, we estimate linear regression model based on equation 3 but applied to the panel of disturbed plot observations as follows:

$$\text{value}_d = f(\text{remp}, \text{age}, vI_b, \text{soft}, D_{\text{owner}}, D_t, D_{\text{planted}}, D_{\text{ecoregion}}), \quad (5)$$

where variables are as defined for equation 3. To estimate anticipated losses from disturbance at the beginning of period 2, we use beginning inventory values for period

2 and equations 3 and 5 to assign $\widehat{\text{value}}_u$ and $\widehat{\text{value}}_d$, respectively, but with $D_t=1$. We define the expected frequency of disturbance $fr_{ecoregion}$ for each region as the portion of forest area experiencing a disturbance in period 1. Expected losses for each plot is then defined as:

$$E(\text{loss}[t = 2]) = [\widehat{\text{value}}_d - \widehat{\text{value}}_u] * fr_{ecoregion}. \quad (6)$$

Subtracting estimated loss in period 2 (equation 4) from expected loss (equation 6) defines the unanticipated losses to forest investors due to changes in the disturbance regime between periods.

3. Study Region and Data

Each FIA plot is assigned to an ecological province based on the National Hierarchical Framework for Ecological Units (Cleland et al. 2007), and we report results for eight of these provinces, as shown in Figure A1. These include all the provinces east of the Great Plains (roughly east of the 100th meridian) except for two. We exclude the Prairie Parklands Temperate and Prairie Parklands Subtropical that are adjacent to the biome boundary between grasslands and forests because of their low forest biomass density and high variability. Figure A1 shows three provinces that comprise Southeastern forest types in shades of green (Outer Coastal Plain, Southeastern Mixed Forest, and Mississippi Riverine) and five that comprise Northeastern types in shades of purple (Northeastern Mixed Forest, Laurentian, Eastern Broadleaf, Midwest Broadleaf, and Central Interior Broadleaf).

From each plot's tree table, we generate records by individual species for each plot, including beginning and ending growing stock inventory, harvest removals, and mortality. All inventory values are estimated as cubic feet for sawtimber and non-sawtimber components. Removals and mortality are recorded as volume per year, and cumulative totals for the remeasurement period require multiplying by the remeasurement period. We link each species record to a price table from Wear and Coulston (2025) that defines prices by species and product class (sawtimber/non-sawtimber) and allows for estimating the terms in equations 2 and 3. We then aggregate volume and value measures to define total volumes and values for each plot by condition observation ($n=271,227$ remeasured plots, with $n=132,684$ for $time=1$ and $n=138,543$ for $time=2$). Plot by condition tables provide records of other explanatory variables for our analysis, including age, ecoregion, and stand origin. The share of softwood (softshare) is defined as the portion of volume that is coniferous based on individual species codes.

Plot records indicate evidence of a disturbance and the type of disturbance. A disturbance is recorded and categorized for the plot/condition only if "mortality or damage to 25 percent of the trees in the condition" occurs (Woudenberg et al.

2010). We summarize these categories to classify disturbance types as the following: insects, disease, fire, weather, and all other.³ Where more than one disturbance category is recorded (e.g., fire and insects), we use only the first disturbance code on the list. Because fire disturbance records do not exclude fire associated with prescribed burning, an especially common occurrence in the southeast, we record a fire disturbance only when “crown fire damage” is indicated and exclude “ground fire damage” when it occurs alone. While this removes prescribed fire activities from the list of disturbances, the result may somewhat underestimate wildfire impacts.

Given FIA’s rotating panel design, our estimates can be viewed as a mid-point average of effects. For example, our 2015 period includes the most recent remeasurements of all plots in 2015 and, given a six-year remeasurement interval, would include remeasurements beginning in 2003 (midpoint circa 2009).

4. Results

The annual rate of disturbance events (panels (A) and (B) of Figure A2) varies by ecoregion and by time period. In period 1 the area of forest disturbance ranges from 1.5 to 4.8 percent per year, with rates in the northern ecoregions (2.6–4.8 percent per year) higher than rates in southern regions (1.5–2.5 percent per year). In period 2, annual rates are higher in all ecoregions (ranging from 1.8 to 6.6 percent year).

Rates of forest mortality (mortality/beginning inventory) are substantially lower and less variable than aerial disturbance rates (panels (C) and (D) of Figure A2). In period 1, rates range between 0.85 and 1.44 percent per year. In period 2, rates range from 0.96 to 1.44 percent per year, representing somewhat of an increase between period 1 and period 2 for five of the eight ecoregions.

To decompose mortality rates, we first estimate the expected mortality equation for all undisturbed plots (equation 1, Table A1). Except for two dummy variables, all coefficients are significant at $p=0.05$. One exception is the insignificant coefficient on the time dummy, indicating no significant difference in background mortality rates between the two periods. The other insignificant coefficient is for the Midwest Broadleaf ecoregion, indicating no significant difference between the intercept for this region and the base case ecoregion (Central Interior Broadleaf). Mortality is positively related to age and biomass density at the beginning of the remeasurement period. Coefficient estimates for ownership dummy variables indicate that the mortality for private ownerships (commercial and family) is significantly lower than for public ownership. Planted forests have significantly lower mortality than do naturally regenerated forests.

Using predictions from equation 1, we decompose mortality rates into components for background mortality and excess mortality due to disturbance events (Figure A3). Overall, total mortality rates average 1.08 percent per year across all ecoregions.

3 “All other” includes various types of animal damage; geological disturbances, such as landslides; human-caused damage not related to harvesting, thinning, or other such timber treatments; and unknown causes.

Background mortality accounts for 81 percent and excess mortality accounts for 19 percent of total mortality, with large variation across ecoregions. Excess mortality rates range from 0.05 percent per year to 0.51 percent per year in period 1 and from 0.13 percent per year to 0.52 percent per year in period 2, when rates for all ecoregions are higher. In the North, the Midwest Broadleaf ecoregion has the highest rate of excess mortality (0.51 percent and 0.52 percent per year for periods 1 and 2, respectively). In the South, the Outer Coastal Plain is the ecoregion with the highest excess mortality rates (0.23 percent and 0.32 percent per year for periods 1 and 2, respectively).

The estimation of the background forest value model (equation 3) indicates that, as expected, forest value is positively related to stand age, beginning inventory values, remeasurement period, and the share of softwood volume (Table A2). The average value of planted stands is significantly greater than the average value of naturally regenerated forests. Values are also greater on private lands than on public lands. Four of the seven coefficients for ecoregion dummies are significant.

Using predictions from equation 3, we compare expected values with measured values for plots experiencing a disturbance event to attribute value changes to disturbances. The impact of disturbance on timber values ranged from 0.7 to 1.9 percent year in period 1 and increased to 0.7–3.1 percent per year in period 2 (Figure A4). The ranking of excess value change is comparable to the ranking for excess mortality, but the levels are about an order of magnitude larger. In the North, the Midwest Broadleaf ecoregion has the highest rate of excess value loss (1.9 and 3.1 percent per year for periods 1 and 2, respectively). In the South, the Outer Coastal Plain is the ecoregion with the highest excess value loss rates (1.7 and 2.4 percent per year for periods 1 and 2, respectively).

We expand excess value loss estimates for each plot to define total value losses by region and disturbance class (Figure A5). Total timber value losses from disturbances in the eastern United States totaled \$30.8 billion per year in period 1 and \$49.5 billion per year in period 2. Losses on the Outer Coastal Plain of the southeast account for a majority of losses in the East (60 percent in period 1 and 54 percent in period 2). Fire disturbances on the Outer Coastal Plain alone account for 38 percent and 22 percent of all losses in periods 1 and 2, respectively. The 61 percent increase in value loss between periods 1 and 2 is largely accounted for by increases in damage associated with weather in the Outer Coastal Plain (mainly hurricanes), and by increased insect damage in the northern ecoregions. Fire damages are relatively stable between the periods. The increase in weather-driven losses in the Outer Coastal Plain accounts for 25 percent of the difference in damages between the periods for the entire eastern United States.

We apply the disturbance regime models for period 1 to the beginning inventory values for period 2 to estimate expected value losses over the remeasurement period (equations 5 and 6) and the amount of unanticipated losses by region (Figure A6). Of the \$49.5 billion per year of disturbance losses in period 2, \$20 billion (40 percent) was unanticipated by the previous disturbance regime. Anticipated and unanticipated losses are greatest in the Outer Coastal Plain, where unanticipated losses amount to \$10.3 billion per year—52 percent of the total unanticipated losses for the eastern United States.

5. Discussion

Our results indicate that the area of forest disturbances is a poor indicator of expected mortality and value losses. Damage associated with disturbances is determined by the mechanism and the intensity of the disturbance combined with the amount and value of exposed resources. For example, insects and diseases target species-specific hosts and hurricane damages are scaled by the intensity of storms. At the plot scale, the average mortality experienced during a disturbance event is between 15 and 20 percent of beginning inventory values, and very few events kill more than half the standing biomass (Figure S1 in Supporting Material).

Across ecoregions, background mortality rates have been relatively constant across time periods and regions (0.8–1 percent per year). Stable background mortality is consistent with no broadscale shifts in growth due to changes in environmental conditions, for example due to drought or warming. In effect, we accept the null hypothesis of no discernible shift in background mortality (based on estimates of equation 1 in Table A1). After accounting for background mortality, the remaining excess mortality due to disturbances is generally less than 0.5 percent per year with considerable variation across ecoregions and between periods 1 and 2. Estimation of the mortality equation for disturbed plots (Table A1) indicates that, after accounting for the attributes of each plot (in effect, differences in exposure), we reject the null and find that mortality rates have increased between periods 1 and 2. This finding is consistent with the hypothesis that disturbance impacts have increased over time due to exogenous factors, such as climate change, rather than endogenous changes in forest conditions.

Disturbance related mortality may or may not translate into economic damage. In some cases, we could even expect disturbance mortality to increase the value of the stand—for example, an insect pest might kill an undesirable species and allow for greater growth of a high-value species. The economic loss from disturbance depends on how mortality is distributed across the species and products components of the standing inventory but also on forgone revenues from expected harvests. Value losses in the Outer Coastal Plain clearly demonstrate this relationship. The anticipated rate of value loss in period 1 in Outer Coastal Plain forests (2.2 percent per year) is only slightly larger than the average loss rate across all regions (2.0 percent per year). However, much larger loss values accrue to higher rates of harvesting in this ecoregion (\$18.7 billion out of \$30.8 billion per year in period 1 and \$26.5 billion out of \$49.5 billion per year in period 2).

Because the anticipated risks of disturbances are readily incorporated into management plans, for example through adjustments to asset prices and spatial risk spreading, unanticipated losses associated with changes in the disturbance regime might define the best measure of realized losses in timber revenue streams. One approach to endogenizing risk is to discount the prices offered for forest land to reflect

anticipated disturbances.⁴ We use our estimates of realized and expected losses to estimate optimal land price reductions for a risk neutral landowner (Figure S2). At the beginning of period 2, discounts for anticipated disturbances range from 2.5 percent in the Southeast Mixed Forest to 14.5 percent in the Laurentian ecoregion. Thus, a risk adjusted forest value based on period 1 disturbance regime is 2.5–14.5 percent less than the expected value for an undisturbed stand. In all ecoregions except Laurentian, price adjustments based on realized losses in period 2 are substantially higher (ranging from 6.1 to 25.8 percent), with the largest differences in the Midwest Broadleaf ecoregion, followed by the Outer Coastal Plain and Lower Mississippi.

6. Conclusions

Effective investing in timber production requires understanding and accounting for hazard risk and expected mortality. A deep literature on the role of risk and uncertainty in timber management includes risk-adjusted optimal rotation models (e.g., Reed 1984) for harvest timing and real option models for entry/exit decisions (e.g., Mei, Wear, and Henderson 2019). These and other management/investment models rely on knowledge of disturbance risk and impacts that have heretofore been limited. To address this knowledge deficit, we introduce novel results regarding the attribution of mortality to natural stand progression or background mortality and to disturbance events or excess mortality. Our approach also allows for a definition of risk of timber losses in dollar terms in addition to commonly applied biophysical measures. Our results indicate that rates of biophysical loss are not proximal to rates of economic loss. Instead, the latter depends on the species/size of killed trees and the temporal proximity of the plot to expected harvesting and regional markets.

While results vary across regions in important ways, they can be summarized as follows: the average area of forests exposed to disturbances is about 3 percent per year, total mortality of tree biomass is about 1.1 percent per year, and excess mortality associated with disturbance events is about 0.25 percent per year. That is, about 23 percent of observed mortality in forests is associated with disturbances. However, because mortality affects returns to both harvesting and growing stock, disturbances result in value losses of about 2.0 percent per year.

Because investors can incorporate expected mortality and hazard risk in valuation of forest land and risk mitigation—for example, through adaptive silviculture or spatial portfolio diversification—known risk/mortality rates can be endogenized in their decision calculus. Losses are most consequential when they arise from unexpected increases in disturbance rates. Our results indicate that value losses substantially increased between periods 1 and 2 and that 40 percent of period 2 losses were unanticipated by the disturbance patterns observed in period 1.

4 Because we estimate value impacts at the ecoregion level, this amounts to modeling returns/losses for a portfolio of forest holdings diversified to reflect regional conditions and treating the portfolio as a closed-end fund—i.e., with realized returns in the form of harvests and sales of assets at the conclusion of the fund's duration.

Climate change is expected to alter weather patterns in ways that could amplify disturbance regimes over time (Costanza et al. 2023; Dudley et al. 2025; Seidl et al. 2017), and our analysis has documented increased disturbance rates and damages in the first quarter of the twenty-first century in the eastern United States.

While we cannot directly attribute disturbance growth to climate change, we demonstrate consequential and unanticipated growth in disturbance impacts between the decades ending in 2015 and 2024, resulting in important damages for the timber sector. Damage increases are especially large for insect epidemics in the northern regions and weather (mainly hurricane) damage in the southern regions. Increases in disturbances and losses over these two periods should not be viewed as a measure of trend. While some aspects of disturbance regimes may be directly tied to climate projections, future disturbance regimes will be influenced by several interacting biological and physical factors—including the introduction of new nonnative pests and spread of existing pests, changes in weather events driven by climate—as well as evolving forest conditions. For example, insect and disease epidemics can recede after host species are removed from the inventory. Accounting for the interaction of episodic (e.g., insects) and secular trends (e.g., climate) in the projection of disturbance regimes remains a challenge for researchers.

References

- Asada, Raphael, Elias Hurmekoski, Annechien Dirkje Hoebe, Marco Patacca, Tobias Stern, and Anne Toppinen. 2023. "Resilient Forest-Based Value Chains? Econometric Analysis of Roundwood Prices in Five European Countries in the Era of Natural Disturbances." *Forest Policy and Economics* 153: 102975. doi:10.1016/j.forpol.2023.102975.
- Badgley, Grayson, Freya Chay, Oriana S. Chegwiddden, Joseph J. Hamman, Jeremy Freeman, and Danny Cullenward. 2022. "California's Forest Carbon Offsets Buffer Pool Is Severely Undercapitalized." *Frontiers in Forests and Global Change* 5. doi:10.3389/ffgc.2022.930426.
- Brecka, Aaron F. J., Chander Shahi, and Han Y. H. Chen. 2018. "Climate Change Impacts on Boreal Forest Timber Supply." *Forest Policy and Economics* 92: 11–21. doi:10.1016/j.forpol.2018.03.010.
- Březina, David, Jakub Michal, and Petra Hlaváčková. 2024. "The Impact of Natural Disturbances on the Central European Timber Market—An Analytical Study." *Forests* 15 (4): 592. doi:10.3390/f15040592.
- Bugmann, Harald, Rupert Seidl, Florian Hartig, Friedrich Bohn, Josef Brůna, Maxime Cailleret, Louis François, Jens Heinke, Alexandra-Jane Henrot, Thomas Hickler, Lisa Hülsmann, Andreas Huth, Ingrid Jacquemin, Chris Kollas, Petra Lasch-Born, Manfred J. Lexer, Ján Merganič, Katarína Merganičová, Tobias Mette, Brian R. Miranda, Daniel Nadal-Sala, Werner Rammer, Anja Rammig, Björn Reineking, Edna Roedig, Santi Sabaté, Jörg Steinkamp, Felicitas Suckow, Giorgio Vacchiano, Jan Wild, Chonggang Xu, and Christopher P. O. Reyer. 2019. "Tree Mortality Submodels Drive Simulated Long-term Forest Dynamics: Assessing 15 Models from the Stand to Global Scale." *Ecosphere* 10 (2): e02616. doi:10.1002/ecs2.2616.
- Busby, Gwenlyn M., Clark S. Binkley, and Rafal P. Chudy. 2020. "Constructing Optimal Global Timberland Investment Portfolios." *Forest Policy and Economics* 111: 102083. doi:10.1016/j.forpol.2019.102083.
- Costanza, Jennifer K., Frank H. Koch, Matt Reeves, Kevin M. Potter, Karen Schleeweis, Kurt Riitters, Sarah M. Anderson, Evan B. Brooks, John W. Coulston, Linda A. Joyce, Prakash Nepal, Benjamin Poulter, Jeffrey P. Prestemon, J. Morgan Varner, and David M. Walker. 2023. "Disturbances to Forests and Rangelands." In *Future of America's Forest and Rangelands: Forest Service 2020 Resources Planning Act Assessment*. Gen. Tech. Rep. WO-102. Washington, DC: US Department of Agriculture, Forest Service. doi:10.2737/WO-GTR-102-Chap5.
- Coulston, John W., Evan B. Brooks, Brett J. Butler, Jennifer K. Costanza, David M. Walker, Grant M. Domke, Jesse Caputo, Marla Markowski-Lindsay, Emma M. Sass, Brian F. Walters, and Jinggang Guo. 2023. "Forest Resources." In *Future of America's Forest and Rangelands: Forest Service 2020 Resources Planning Act Assessment*. Gen. Tech. Rep. WO-102. Washington, DC: US Department of Agriculture, Forest Service. doi:10.2737/WO-GTR-102-Chap6.
- Dudney, Joan, Julie Edwards, Brian J. Harvey, and Rupert Seidl. 2025. "Climate Change Effects on Interacting Disturbances in Forest Ecosystems." *Annual Review of Ecology, Evolution, and Systematics* 56: 393–420. doi:10.1146/annurev-ecolsys-102723-052437.
- Hartman, R. 1976. "The Harvest Decision When the Standing Forest Has Value." *Economic Inquiry* 14 (1): 52–58. doi:10.1111/j.1465-7295.1976.tb00377.x.

- Henderson, Jesse D., Robert C. Abt, Karen L. Abt, Justin Baker, and Ray Sheffield. 2022. "Impacts of Hurricanes on Forest Markets and Economic Welfare: The Case of Hurricane Michael." *Forest Policy and Economics* 140:102735. doi:10.1016/j.forpol.2022.102735.
- Jactel, Hervé, Bruce C. Nicoll, Manuela Branco, José Ramon Gonzalez-Olabarria, Wojciech Grodzki, Bo Långström, Francisco Moreira, Sigrid Netherer, Christophe Orazio, Dominique Piou, Helena Santos, Mart Jan Schelhaas, Karl Tojic, and Floor Vodde. 2009. "The Influences of Forest Stand Management on Biotic and Abiotic Risks of Damage." *Annals of Forest Science* 66 (7): 701–701. doi:10.1051/forest/2009054.
- Johnston, Craig M. T., Jesse D. Henderson, Jinggang Guo, Jeffrey P. Prestemon, and Jennifer Costanza. 2024. "Unraveling the Impacts: How Extreme Weather Events Disrupt Wood Product Markets." *Earth's Future* 12 (9). doi:10.1029/2024EF004742.
- Kurz, Werner A., Graham Stinson, Gregory J. Rampley, Caren C. Dymond, and Eric T. Neilson. 2008. "Risk of Natural Disturbances Makes Future Contribution of Canada's Forests to the Global Carbon Cycle Highly Uncertain." *Proceedings of the National Academy of Sciences* 105 (5): 1551–55. doi:10.1073/pnas.0708133105.
- Mei, Bin, David N. Wear, and Jesse D. Henderson. 2019. "Timberland Investment under Both Financial and Biophysical Risk." *Land Economics* 95 (2): 279–91. doi:10.3368/le.95.2.279.
- Miles, Patrick D., Gary J. Brand, Carol L. Alerich, Larry F. Bednar, Sharon W. Woudenberg, Joseph F. Glover, and Edward N. Ezell. 2001. *The Forest Inventory and Analysis Database Description and Users Manual Version 1.0. General Technical Report NC-218*. St. Paul, MN: US Department of Agriculture, Forest Service, North Central Research Station. doi:10.2737/NC-GTR-218.
- Oswalt, Sonja N., W. Brad Smith, Patrick D. Miles, and Scott A. Pugh. 2019. *Forest Resources of the United States, 2017*. US Department of Agriculture, Forest Service. doi:10.2737/wogtr-97.
- Prestemon, Jeffrey P., David N. Wear, Fred J. Stewart, and Thomas P. Holmes. 2006. "Wildfire, Timber Salvage, and the Economics of Expediency." *Forest Policy and Economics* 8 (3): 312–22. doi:10.1016/j.forpol.2004.07.003.
- Pretzsch, Hans. 2009. "Forest Dynamics, Growth, and Yield." In *Forest Dynamics, Growth and Yield: From Measurement to Model*, edited by H. Pretzsch. Berlin, Heidelberg: Springer, 1–39.
- Pye, John M., Thomas P. Holmes, Jeffrey P. Prestemon, and David N. Wear. 2011. Economic Impacts of the Southern Pine Beetle. *Southern Pine Beetle II*, edited by Robert N. Coulson and Kier D. Klepzig. Gen. Tech. Rep. SRS-140. Asheville, NC: US Department of Agriculture Forest Service, Southern Research Station, 213–222. <https://www.fs.usda.gov/treearch/pubs/39071>.
- Reed, William J. 1984. "The Effects of the Risk of Fire on the Optimal Rotation of a Forest." *Journal of Environmental Economics and Management* 11 (2): 180–90. doi:10.1016/0095-0696(84)90016-0.
- Seidl, Rupert, Dominik Thom, Markus Kautz, Dario Martin-Benito, Mikko Peltoniemi, Giorgio Vacchiano, Jan Wild, Davide Ascoli, Michal Petr, Juha Honkaniemi, Manfred J. Lexer, Volodymyr Trotsiuk, Paola Mairota, Miroslav Svoboda, Marek Fabrika, Thomas A. Nagel, and Christopher P. O. Reyer. 2017. "Forest Disturbances under Climate Change." *Nature Climate Change* 7: 395–402. doi:10.1038/nclimate3303.
- Senf, Cornelius, Allan Buras, Christian S. Zang, Anja Rammig, and Rupert Seidl. 2020. Excess Forest Mortality Is Consistently Linked to Drought across Europe." *Nature Communications* 11 (1): 6200. doi:10.1038/s41467-020-19924-1.

- Siebel-McKenna, Alexandra, Craig M. T. Johnston, and G. Cornelis van Kooten. 2020. "Knock on Wood: Managing Forests for Carbon in the Presence of Natural Disturbance Risk." *Spatial Economic Analysis* 15 (3): 299–310. doi:10.1080/17421772.2019.1701700.
- Sun, Changyou. 2016. "Timber Market Recovery after a Hurricane." *Forest Science* 62 (6): 600–612. doi:10.5849/forsci.15-123.
- Wang, Yuhan, and David J. Lewis. 2024. "Wildfires and Climate Change Have Lowered the Economic Value of Western US Forests by Altering Risk Expectations." *Journal of Environmental Economics and Management* 123:102894. doi:10.1016/j.jeem.2023.102894.
- Wear, David N., and John W. Coulston. 2025. "A Comparative Analysis of Timber Harvesting, Timber Supply, and Tree Planting across Ownerships and Regions of the United States." *Forest Policy and Economics* 178: 103542. doi:10.1016/j.forpol.2025.103542.
- Woudenberg, Sharon, Barbara Conkling, Barbara O'Connell, Elizabeth Burrill, Jeffery Turner, and Karen Waddell. 2010. *The Forest Inventory and Analysis Database: Database Description and Users Manual Version 4.0 for Phase 2*. Gen. Tech. Rep. RMRS-GTR-245. Fort Collins, CO: US Department of Agriculture, Forest Service, Rocky Mountain Research Station. doi:10.2737/RMRS-GTR-245.
- Yao, Wenjing, and Bin Mei. 2015. "Assessing Forestry-Related Assets with the Intertemporal Capital Asset Pricing Model." *Forest Policy and Economics* 50: 192–99. doi:10.1016/j.forpol.2014.06.006.
- Zhai, Jun, and Olli-Pekka Kuusela. 2020. "Estimating Price Dynamics in the Aftermath of Forest Disturbances: The Biscuit Fire in Southwest Oregon." *Forest Science* 66 (5): 556–67. doi:10.1093/forsci/fxaa004.
- Zhai, Jun, and Zhuo Ning. 2022. "Models for the Economic Impacts of Forest Disturbances: A Systematic Review." *Land* 11 (9): 1608. doi:10.3390/land11091608.

A1. Tables

Table A1. Coefficient Estimates for Mortality on Forest Plots

Variable	Undisturbed plots			Disturbed plots		
	Estimate	Standard error	P value	Estimate	Standard error	P value
(Intercept)	11,699.61	1,498.071	0.0000	58,721.52	7,335.196	0.0000
Age	69.58	12.91265	0.0000	-141.59	60.90845	0.0201
I_b	0.01	4.77E-05	0.0000	0.02	0.000199	0.0000
Softshare	-2,359.62	619.4339	0.0001	3,676.02	3,011.995	0.2223*
owner: Family	-3,546.98	758.1643	0.0000	-2,0745.16	3,329.904	0.0000
owner: Commercial	-5,404.17	916.8992	0.0000	-15,768.49	4,148.771	0.0001
time: 2	-247.35	579.4074	0.6695*	-10,063.86	2,813.463	0.0003
origin: Planted	-9,663.59	960.7072	0.0000	-15,614.57	5,042.451	0.0020
ecoregion: Eastern broadleaf	-8,128.71	1,294.579	0.0000	-30,804.40	5,291.893	0.0000
ecoregion: Lower mississippi riverine	9,212.21	1,960.338	0.0000	32,980.28	10,378.55	0.0015
ecoregion: Laurentian	-9,420.42	1,307.357	0.0000	2,279.47	5,967.968	0.7025*
ecoregion: Midwest broadleaf	-1,687.47	1,649.43	0.3063*	35,903.02	6,093.83	0.0000
ecoregion: Northeastern	-3,570.53	1,411.736	0.0114	-20,861.56	6,186.155	0.0007
ecoregion: Outer coastal plain	-3,494.88	1,265.184	0.0057	46,855.13	5,756.876	0.0000
ecoregion: Southeast mixed forest	-2,866.27	1,225.019	0.0193	36,751.47	6,042.961	0.0000
disturbance: Insect	—	—	—	-50,019.00	4,309.958	0.0000
disturbance: Disease	—	—	—	-90,547.78	5,092.255	0.0000
disturbance: Fire	—	—	—	72,118.20	5,275.833	0.0000
disturbance: Weather	—	—	—	-40,062.21	3,892.329	0.0000

Note: Separate equations are estimated for disturbed and undisturbed plots. An * indicates that the coefficient is not significant at the 5 percent level. Bases for dummy variables include: ownership=public, ecoregion=Central Interior Broadleaf, disturbance type=insect, time=1, origin=natural regeneration. Adjusted R² for undisturbed plots.

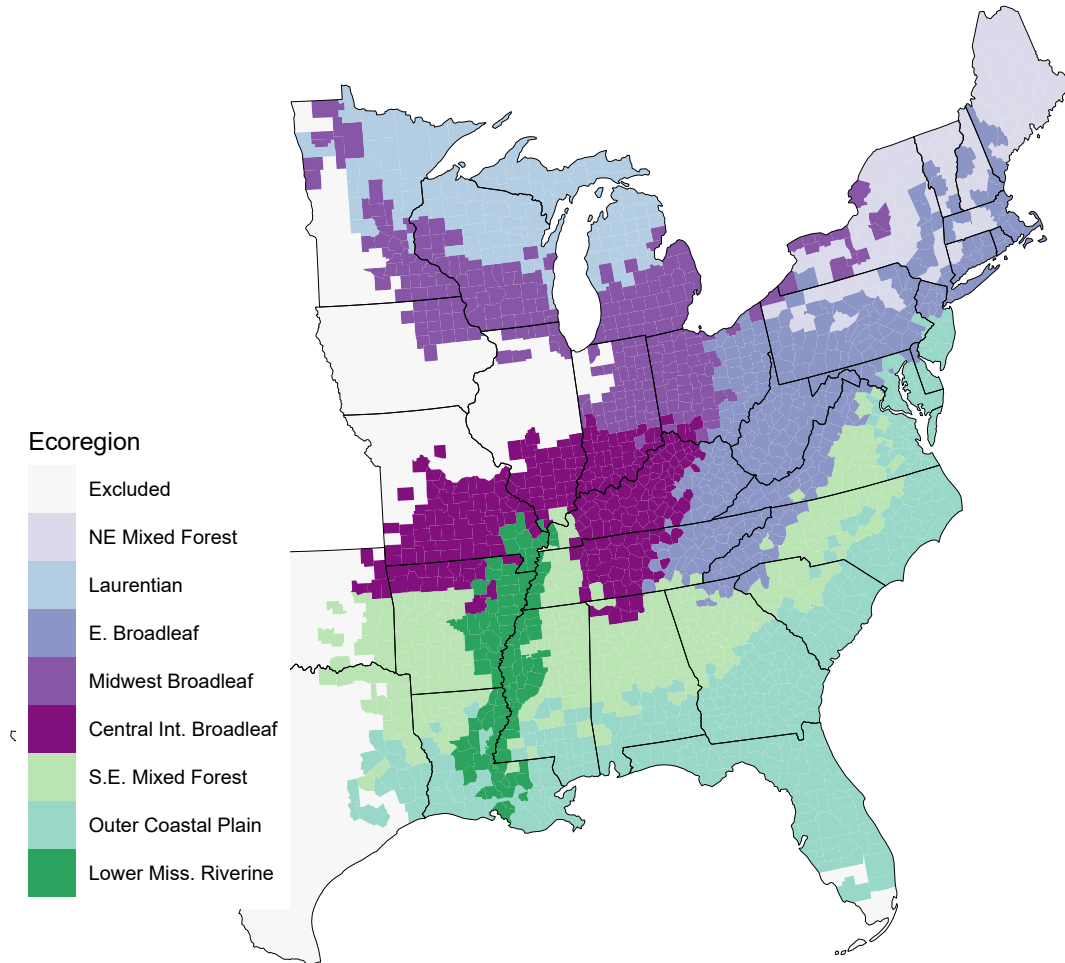
Table A2. Coefficient Estimates for the Value of Forest Plots (Equation 3)

Variable	Undisturbed plots			Disturbed plots		
	Estimate	Standard error	P value	Estimate	Standard error	P value
(Intercept)	-10,387.13	714.6112	0.0000	-6,729.87	462.8286	0.0000
Remper	1,459.74	82.2155	0.0000	632.9934	52.74313	0.0000
Age	16.15	4.955936	0.0011	21.86061	3.052606	0.0000
$v _b$	1.26	0.001595	0.0000	1.093056	0.004219	0.0000
Softshare	3,902.18	262.4999	0.0000	753.861	207.7781	0.0003
owner: Family	1,432.55	249.3179	0.0000	2,285.98	151.4529	0.0000
owner: Commercial	8,357.88	313.4699	0.0000	3,090.543	198.5327	0.0000
time: 2	-914.39	205.6071	0.0000	724.4129	140.6628	0.0000
origin: Planted	3,048.78	350.0616	0.0000	3,647.089	251.7608	0.0000
ecoregion: Eastern broadleaf	-1,075.81	380.9771	0.0047	503.9294	218.46	0.0211
ecoregion: Lower mississippi riverine	-597.82	659.018	0.3643*	1,851.385	506.0604	0.0003
ecoregion: Laurentian	739.18	442.2053	0.0946*	628.5669	305.7955	0.0398
ecoregion: Midwest broadleaf	328.67	518.5712	0.5262*	3,549.174	251.4998	0.0000
ecoregion: Northeastern	-2,234.77	485.248	0.0000	404.3788	289.3932	0.1623*
ecoregion: Outer coastal plain	5,414.59	421.9941	0.0000	1,492.401	286.0255	0.0000
ecoregion: Southeast mixed forest	736.98	381.8117	0.0536*	2,613.235	273.5652	0.0000
disturbance: Insect	—	—	—	-1,042.63	182.2308	0.0000
disturbance: Disease	—	—	—	-1,299.84	228.502	0.0000
disturbance: Fire	—	—	—	455.2729	244.1962	0.0623*
disturbance: Weather	—	—	—	-2,652.44	261.589	0.0000

Note: Separate equations are estimated for disturbed and undisturbed plots. An * indicates that the coefficient is not significant at the 5 percent level. Bases for dummy variables include: ownership=public, ecoregion=Central Interior Broadleaf, disturbance type=insect, time=1, origin=natural regeneration. Adjusted R² for undisturbed plots.

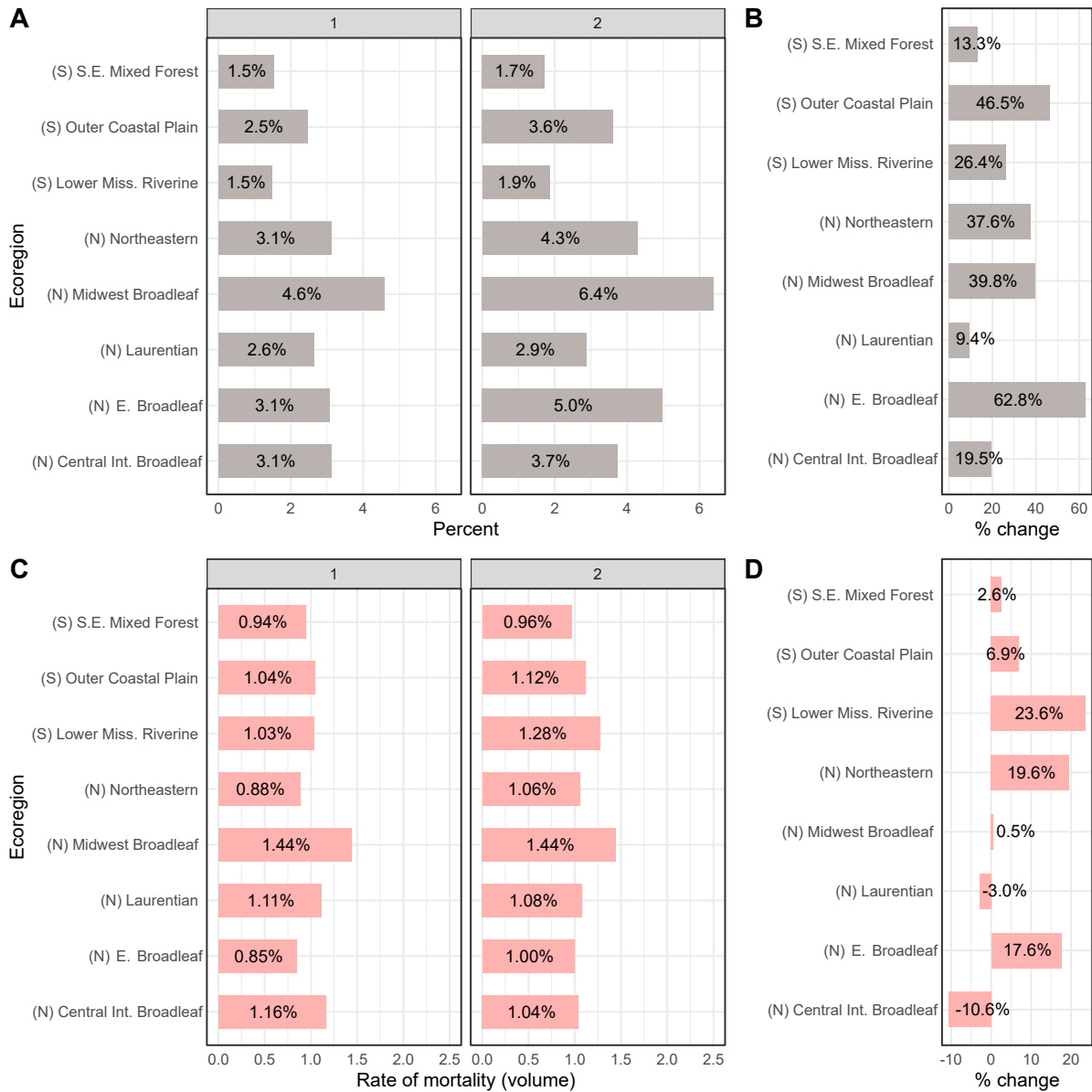
A2. Figures

Figure A1. Eight Ecoregions in the Eastern United States Evaluated in This Study



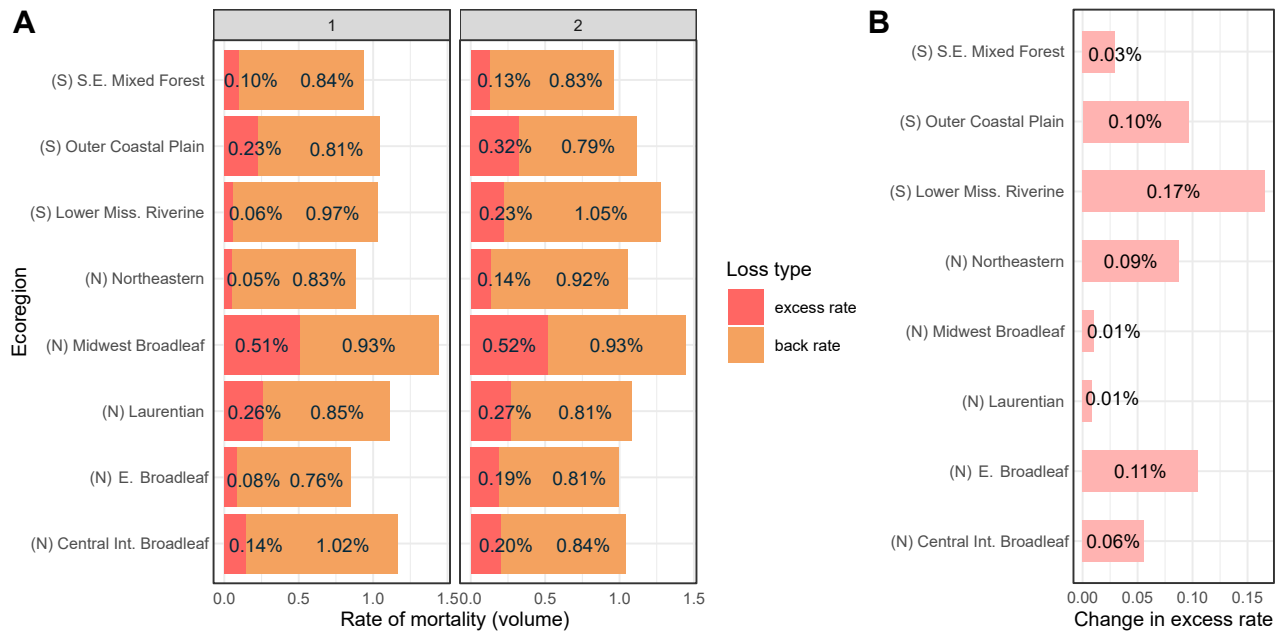
Note: Counties are assigned to ecoregions to the largest area of classification, based on assignment of detailed ecoregion to the Forest Inventory and Analysis inventory plots. SE = Southeast, E = Eastern, Miss. = Mississippi, Int. = Interior.

Figure A2. (A) Annual Rate of Area Exposed to a Forest Disturbance Event by Ecoregion, (B) Percent Change in Rates Between Time Periods, (C) Annual Rate of Tree Mortality by Ecoregion, and (D) Percent Change in Rates Between Time Periods



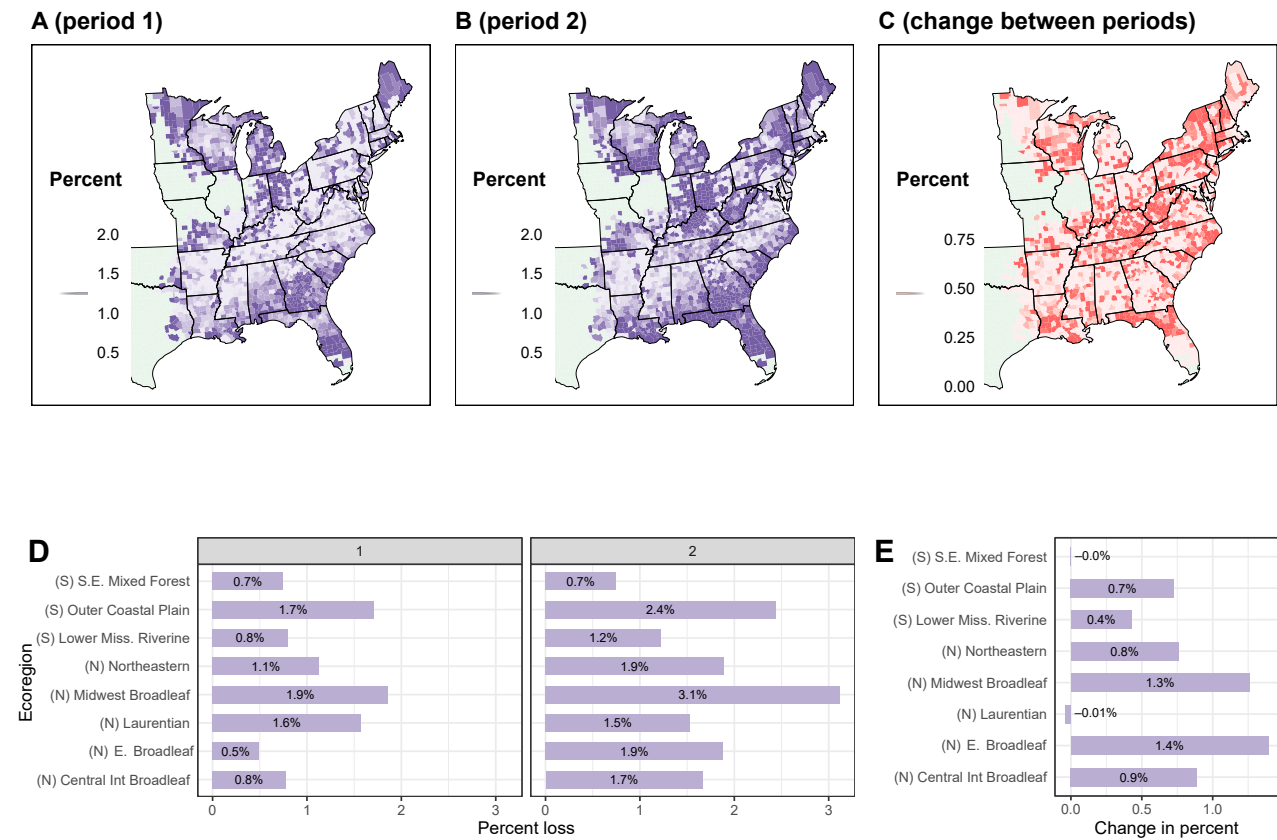
Note: Panels (A) and (C) display the differences between time periods 1 and 2. Panel (C) rate of mortality is measured in mortality per beginning inventory in cubic feet. SE = Southeast, E = Eastern, Miss. = Mississippi, Int. = Interior.

Figure A3. (A) Mortality Rates Decomposed Into Background Mortality Associated with Forest Development and (B) Excess Mortality Associated with Disturbance Events



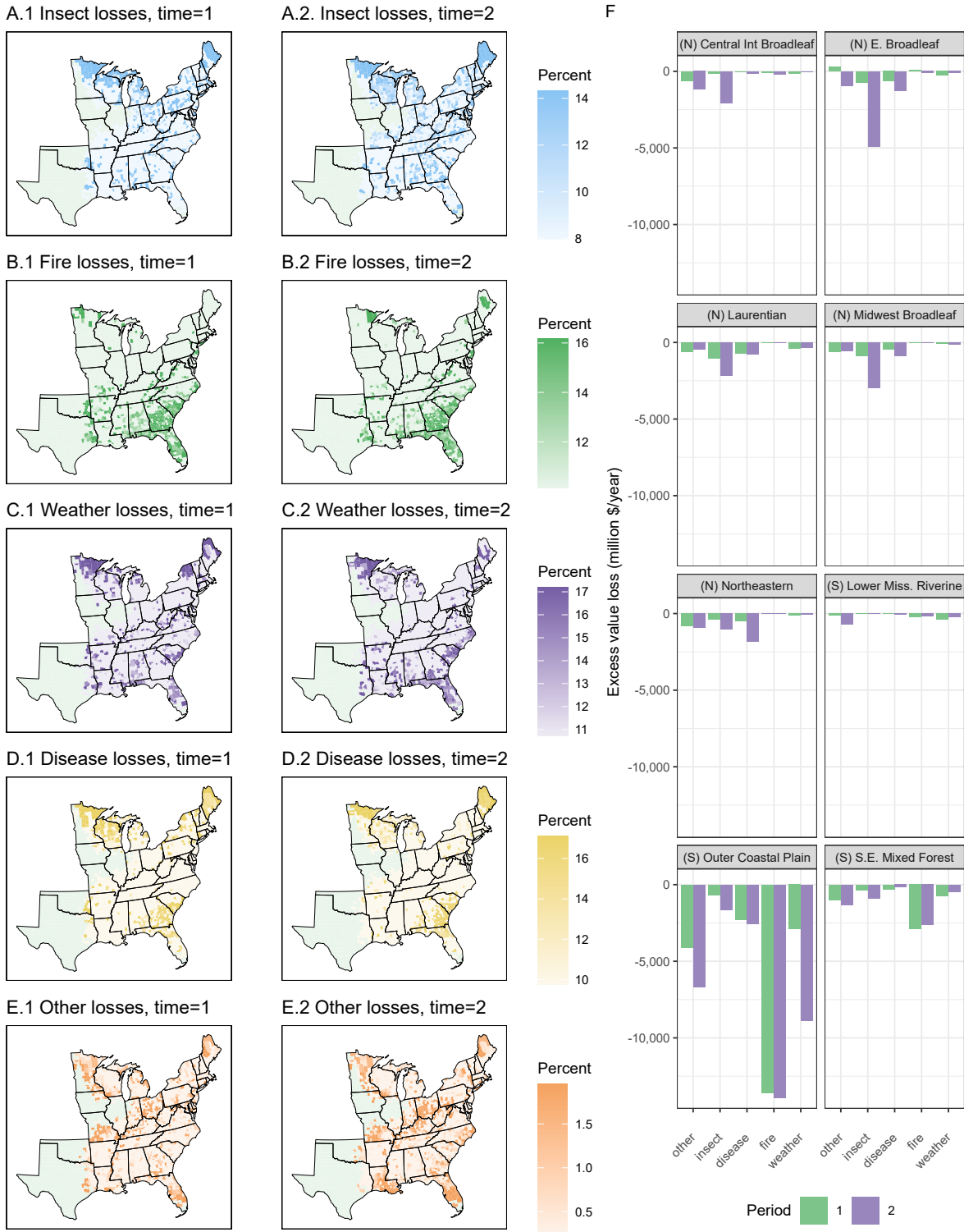
Note: Mortality rates are measured by annual mortality per beginning inventory in cubic feet. SE = Southeast, E = Eastern, Miss. = Mississippi, Int. = Interior.

Figure A4. Annual Rates of Excess Value Loss Due to Disturbance Events by Region and Period



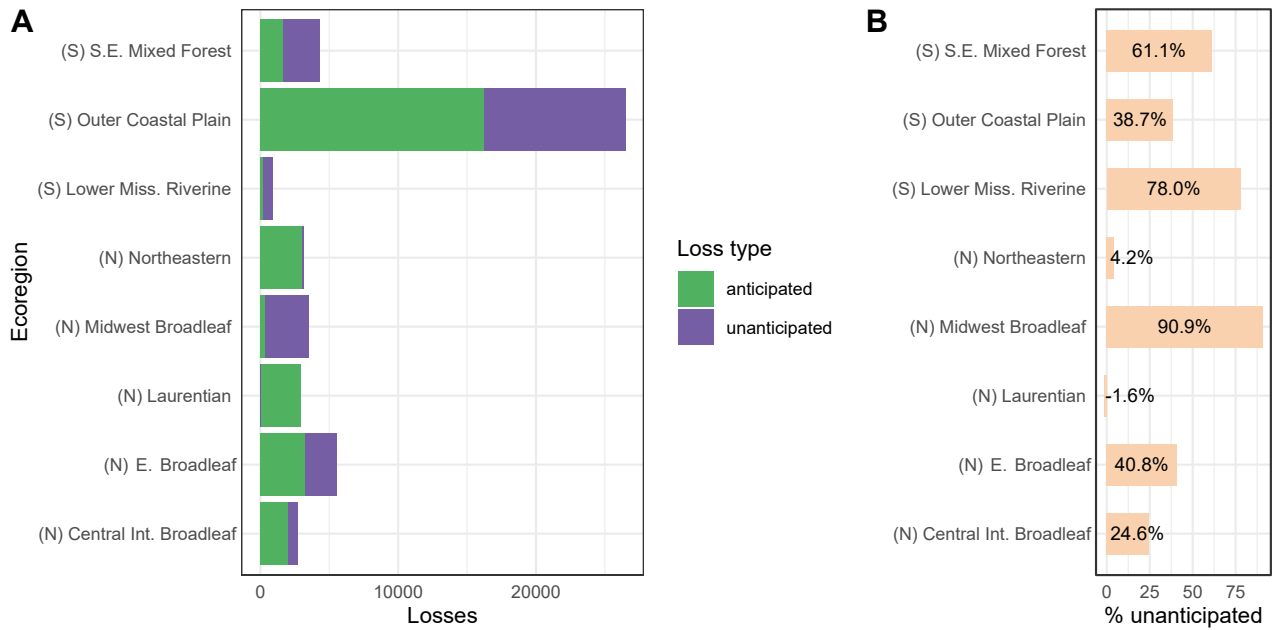
Panels display the following: (A) loss rate by county in time period 1, (B) loss rate by county in time period 2, (C) difference in loss rates between time periods, (D) loss rate by ecoregion and time period, and (E) absolute change in loss rate by ecoregion between time periods. SE = Southeast, E = Eastern, Miss. = Mississippi, Int. = Interior.

Figure A5. (A) to (E) Percent Annual Excess Value Losses Mapped to Counties by Disturbance Categories and Time Period and (F) Total Losses (Million Dollars) by Ecoregion, Disturbance Type, and Time Period



Note: Disturbance categories are categorized in panels (A) to (E) as so: A=insect, B=fire, C=weather, D=disease, and E=other. Time=1 and 2 in panels (A) to (E). SE = Southeast, E = Eastern, Miss. = Mississippi, Int. = Interior.

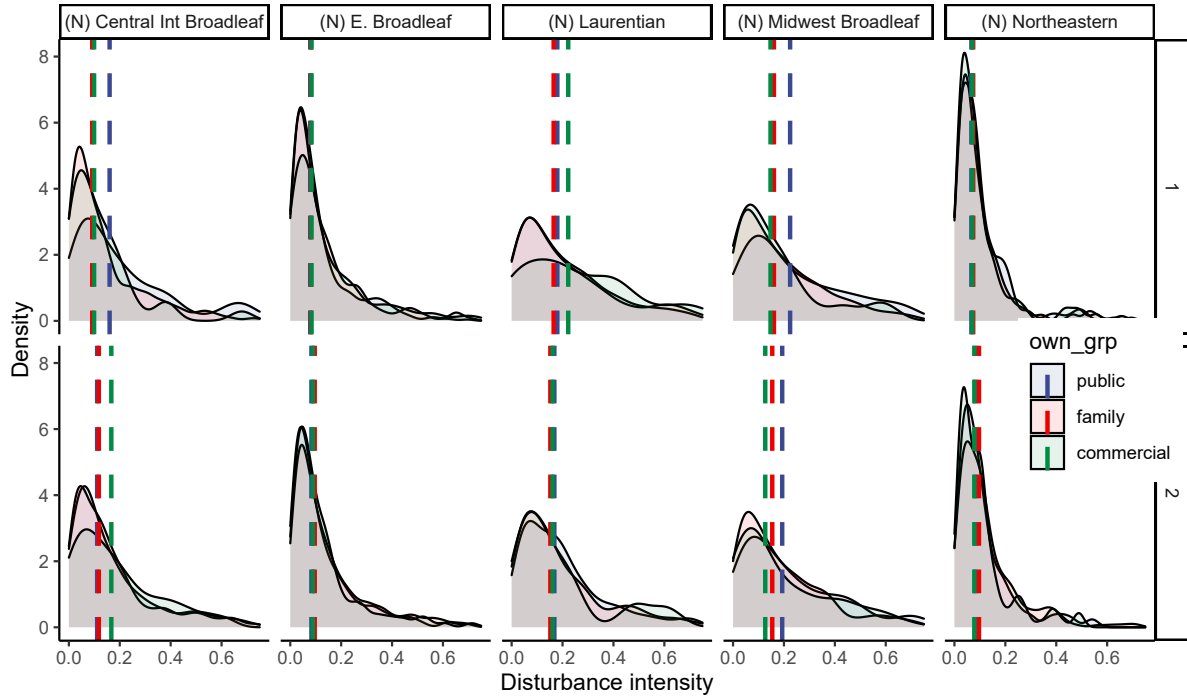
Figure A6. (A) Annual Losses (Million Dollars) Due to Disturbances in Time Period 2 and (B) Share of Losses That Were Unanticipated



Note: Losses in panel (A) in time period 2 are fall under either anticipated losses based on expected losses from time period 1 rates or unanticipated losses. SE = Southeast, E = Eastern, Miss. = Mississippi, Int. = Interior.

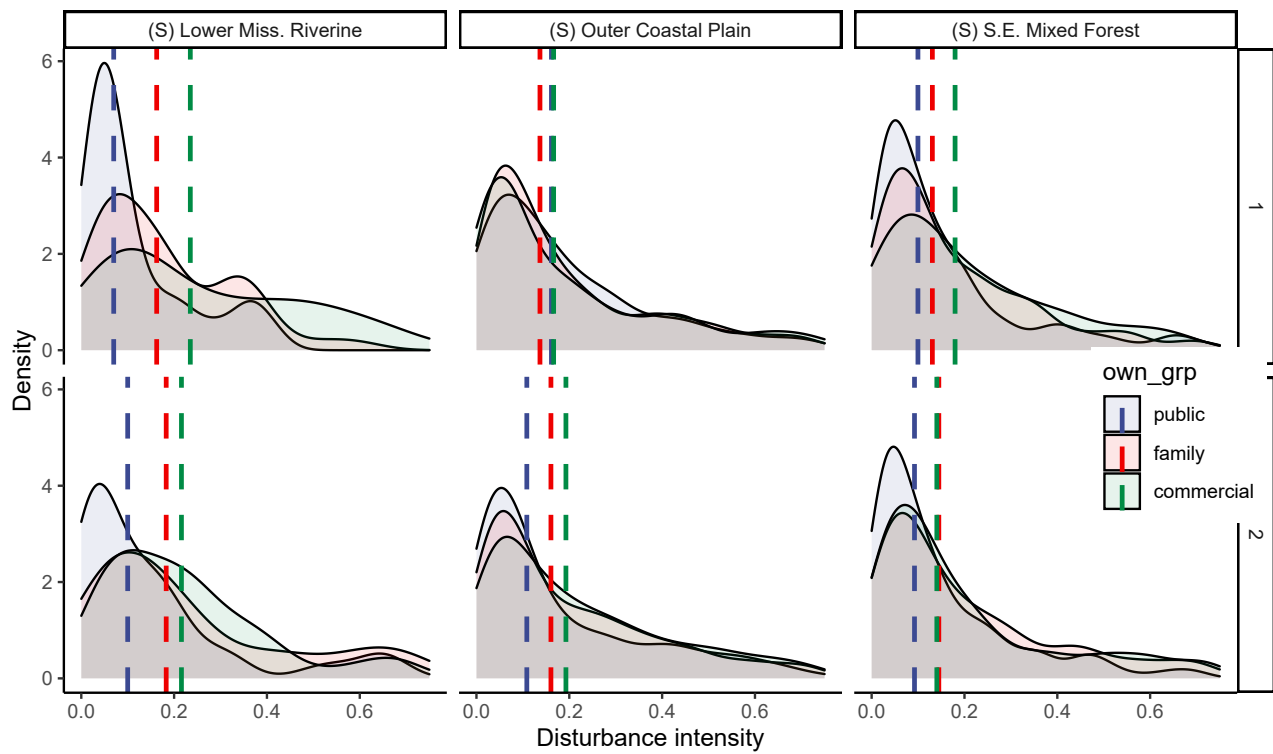
S1. Supplemental Material

Figure S1a. Mortality rates for Plots with Disturbances in the Northeastern United States, by Ecoregion, Forest Ownership, and Time Period



Note: Mortality rates are measured by mortality per beginning inventory in cubic feet. Time periods 1 and 2 are shown in the graph. Vertical lines indicate median values by ownership group (e.g., public, family, and commercial). own_grp = ownership group. E = Eastern, Int. = Interior.

Figure S1b. Mortality rates for Plots with Disturbances in the Southeastern United States, by Ecoregion, Forest Ownership, and Time Period



Note: Mortality rates are measured by mortality per beginning inventory in cubic feet. Time periods 1 and 2 are shown in the graph. Vertical lines indicate median values by ownership group (e.g., public, family, and commercial). own_grp = ownership group. SE = Southeast, Miss. = Mississippi.

Figure S2. Implied Forest Land Price Adjustment Rates to Account Anticipated and Unanticipated Impacts of Disturbances



Note: Results in the figure assume a seven-year remeasurement period. SE = Southeast, E = Eastern, Miss. = Mississippi, Int. = Interior.

