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Impacts of hurricanes on forest markets and economic welfare: The case of hurricane Michael

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ABSTRACT

This paper develops methodologies and identifies data gaps for understanding the impacts of hurricanes on forest product markets. Using the case of Hurricane Michael, we simulate damage to forest growing stock and forest area from alternative damage estimations (inventory and remote sensed). We then consider alternative scenarios for replanting, and the spatial distribution of salvage consumption. Beyond previous analyses we examine both short run and long run market outcomes resulting from the age demographics of standing timber post-hurricane. The simulation framework developed allows for the comparison of welfare and forest carbon consequences. Across scenarios the hurricane causes a welfare increase for pine sawtimber producers ranging from 1.2 to 1.5 times the no-hurricane baseline, and a loss for pine sawtimber consumers ranging from 0.6 to 0.8 times the baseline. Hardwood sawtimber producers gain by equivalent factors of 1.8, and consumers lose half. All scenarios gained forest carbon on the order of 1.2 times the pre-hurricane forest carbon, however, the no-hurricane case exhibited both higher carbon and carbon per unit area after a 40-year simulation.

1. Introduction

Hurricanes leave a lasting imprint on forest structure by damaging standing inventory, potentially altering the age class structure and species distribution in an impacted area (Xi et al., 2008). The effect of hurricanes on forests is a function of both storm severity and physical factors such as soil and other landscape factors (Rutledge et al., 2021). Further, hurricanes affect the spatial and temporal availability of forest products, leading to a different path for markets within an impacted basin and surrounding regions. In the U.S. South, the downed material that is not salvaged tends to decay precipitously, leading to a pulse in carbon emissions (McNulty, 2002; Zeng et al., 2009).

With the potential increase in storm frequency or intensity due to climate change (Knutson et al., 2021; Emanuel et al., 2008), understanding the impacts of hurricanes is crucial to both landowners and policymakers. Previous work on the market impacts of hurricanes has relied on econometric modeling of past prices (Prestemon and Holmes, 2000; Yin and Newman, 1999a, 1999b). Prestemon and Holmes (2010) reviews the literature and provides theoretical and empirical support for sustained price impacts due to forest inventory effects. However, much of the preceding economics literature is backward-looking, and hence does not inform landowners or policymakers about expected impacts under changing market and environmental conditions. Toward the aim of filling that gap, this paper simulates the impact of a hurricane on forest markets using an empirical forest sector model which tracks forest demographics over time.

The objectives of this manuscript are as follows. First, we develop methods for and provide guidance on the impact of hurricanes on forest structure. Our methods rely on a combination of forest inventory and remote sensed products to assess damages from the impacted area, offering a unique comparison of these alternative approaches. We first estimate damages using the Forest Inventory and Analysis dataset, using only remote sensed products, and then through a hybrid inventory and remote sensing method. We offer a comparison of simulation results using these damage estimation methods in the supplemental material. Second, we quantify and describe the impact of Hurricane Michael on forest resources (across species and age class) using our damage estimation methods. Third, we combine pre- and post-hurricane inventory

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estimates, estimate salvage supply from damaged inventory, incorporate assumptions regarding replanting responses, and conduct simulation analysis to assess both the short- and long-term market implications of Hurricane Michael. Finally, we use results from our sensitivity analysis to quantify the forest carbon storage and economic welfare implications of Hurricane Michael. For economic welfare, we restrict our analysis to forest sector consumer and producer surplus measures across scenarios.

This manuscript develops and applies a flexible methodology for conducting impact assessments of hurricanes that is applicable in other settings. We provide new insight into the potential implications of a strong hurricane on forest resources in the Southeastern U.S. and suggest potential policies to help mediate adverse impacts.

2. Methods

For this analysis, we evaluate the impact of Hurricane Michael on the forest resources of the Florida Panhandle and adjacent areas of Alabama and Georgia that were affected by the storm.

To conduct the simulation analysis, we use the Sub-Regional Timber Supply (SRTS) model (Abt et al., 2009). The model is documented in Henderson and Abt (2020), and the modifications to this structure and particular assumptions for the analysis are described here.

Our study area is a 150-mile region which extends well beyond the area damaged by Hurricane Michael. The model finds one equilibrium price which satisfies the demand specified by an aggregate demand curve. SRTS specifies supply curves at a finer scale—by sub-region and owner for each product and time—and the market-level supply is the sum of these curves (Henderson and Abt, 2020; Supplementary Materials Eqs. 1A through 3A). The model solution is derived by goal programming and optimizes the quantities removed across sub-regions and owners with the objective of achieving the projected product mix while minimizing the deviation from empirical removal to inventory ratios across age classes and management types (Abt et al., 2009). Therefore, our design allows spatially explicit shocks to supply (such as the present hurricane application) to produce alternative spatially optimal solutions while meeting the same aggregate demand.

The parameters used to define products and supply and demand curve parameters are given in Table 1. The initial conditions of the model derive from summarized Forest and Analysis (FIA) data on forest growing stock, removals, and growth by several heterogeneous features (sub-region, ownership, species, management type, age class, diameter-at-breast-height (DBH, in inches) class) (USDA Forest Service, 2021a). The FIA data represent multi-year panels of field-measured plots, approximately one plot per 6000 acres. The respective FIA data release years for Alabama, Florida and Georgia are 2018, 2016 and 2017, respectively.

Therefore, we first run the SRTS model from 2015 to 2018 to update the initial pre-hurricane forest condition. In FIA data, removal dates precede inventory dates, so we use Timber Product Output data to adjust the starting point and trajectory of removals in 4 pine products (large sawtimber, sawtimber, chip-n-saw and pulpwood) and 2 hardwood products (sawtimber and pulpwood) (USDA Forest Service, 2021).

2.1. Hurricane damage

To estimate impacts of Hurricane Michael on forest structure, we develop three methods for estimating damage by age class. In the first method, we apply data from analyses of a previous hurricane (Hurricane Hugo) to the Hurricane Michael damage zones. In the second method, we use remote-sensed damage estimates and apply uniform damage across age classes. In a hybrid method, we use the remote-sensed damage estimates and distribute the damage in an age-dependent manner derived from our Hugo analog method. For all three methods of estimating damage, we use summarized losses in acres and/or volume at the level of multi-county sub-regions. The sub-regions consist of portions of Alabama, Georgia and Florida within 150 miles of Lake Seminole in Georgia (30.711856, −84.864345). To construct sub-regions for the analysis, we first intersected circles with radii of 50, 75, 100, 150 miles with counties. As in Sheffield and Thompson (1992), we then categorized counties within the radial zones as Severe, Moderate or None according to the methodology that follows (Fig. 1).

2.1.1. Hugo analog

The first method relies on FIA data that was collected before and after Hurricane Hugo, which made landfall in September 1989 as a Category 4 hurricane. We use Hugo as an analog due to the intensive remeasurement of inventory which took place post-hurricane (Sheffield and Thompson, 1992) and because Michael was also a Category 4 storm. These data were analyzed to assess the damage according to damage classes which were designated as *Severe* or *Moderate*. These data and analysis show that damage from Hurricane Hugo varied by age class and slightly by management type (Table 2).

We apply the above damage proportions by age class and management types to the relevant variables in the model. For Moderate and Severe regions, we treat the damage as a reduction in growing stock volume within a given age class. For Severe regions, the damage process also transfers a quantity of forest area to the youngest age class category, because we assume that the high percentage of damage is analogous to a clearcut. We use the modified forest area and growing stock distribution from this simulated hurricane as the input for subsequent model runs.

2.1.2. Hybrid and remote-sensed damage

The second and third damage estimation methods use remote-sensed data. Following Hurricane Michael's impact, state forestry agencies in Florida and Georgia collected remote-sensed information on damage within counties. The damage categories used by these two states were different from each other and different from the Severe and Moderate categories discussed previously. Given the county level data and alternative damage class categories (percent damage thresholds), we first merge the two state data sets by volume damage percentage, adopting damage class categories from the Georgia data due to its higher detail. We further classify collections of counties into damage zones to relate damage classes to the Hurricane Hugo case. The relationships between the Georgia damage classes and the Hugo damage zones are shown in Table 3. Within the Severe zone, for example, 51.2% of forest area was labeled catastrophic, and catastrophic means 95% of the forest is

Table 1
Product specifications and parameters, including diameter cutoffs (DBH) in inches, cull (percentage treated as pulpwood), price elasticity of demand (ε), price elasticity of supply (γ), and growing stock elasticity (τ).

					Corporate		Non-Corporate	
Species	Product	DBH	Cull (%)	ε	γ	τ	γ	τ
Pine	Pulpwood	[5–9)	100	−0.3	0.3	1	0.3	1
Pine	Chip-n-saw	[9–11)	50	−0.3	0.4	1	0.4	1
Pine	Sawtimber	[11–17)	10	−0.3	0.5	1	0.5	1
Pine	Lg. sawtimber	17+	10	−0.3	0.5	1	0.5	0.7
Hardwood	Pulpwood	[5–15)	100	−0.3	0.3	0.7	0.3	0.7
Hardwood	Sawtimber	15+	25	−0.3	0.5	0.7	0.5	0.7

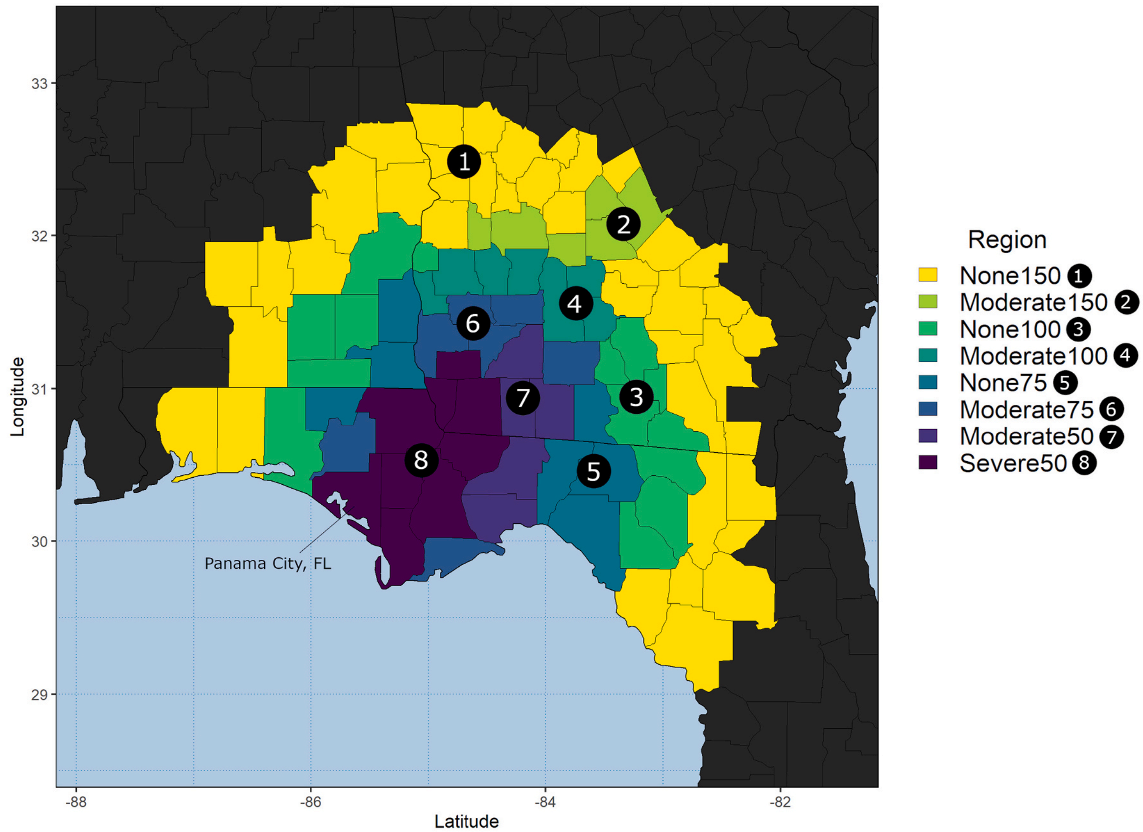

Fig. 1. Sub-regions by severity (Severe, Moderate, None) and radius, preserving county boundaries.

Table 2
Volume damage rates (percent) assessed following Hurricane Hugo (1989) by age class, management (pine plantation, other) and damage zone (Moderate, Severe).

	Pine plantation		Other	
Age class	Moderate	Severe	Moderate	Severe
1	12.1	38.1	11.9	40.3
2	11.8	40.4	10.8	36.4
3	15.2	52.6	15.0	57.0
4	14.5	55.2	13.9	53.3
5	28.2	56.6	27.0	56.3
6	27.7	58.8	27.6	56.1
7	21.1	59.7	24.0	57.2
8	21.3	59.4	22.2	57.3
9	16.1	61.0	17.8	61.8
10	–	–	16.2	62.3
11	–	–	18.1	52.0

Table 3
Distribution of damage classes within damage zones (top section) and aggregate damage percentage by damage zone. All values are percentages and are used for both the remote-sense and hybrid methods.

	Damage zone			
Damage class	Severe	Moderate	None	Damage percentage
Catastrophic	51.2	0.8	0	95
Severe	21.4	5.3	0	75
Moderate	15.5	41.0	0	20
Light	7.9	21.8	0	10
None	4.0	31.1	100	0
Aggregate Volume Damage	68.6	15.1	0	
Aggregate Area Damage	64.7	4.7	0	

damaged. We calculate the aggregate damage rate to volume from the dot product of the damage class distribution within a damage zone and the damage percentage. For the Severe damage zone, this results in 68.6% damage to volume. For area damage, we follow an identical procedure, but only use the catastrophic and severe damage classes. As in the methods based on Hugo, for the remote sensed methods we assume that forested areas which experience catastrophic and severe damage have essentially undergone a clearcut, and therefore move to the first age class to be replanted or naturally regenerated. Areas that received none to moderate damage lose volume only.

The remote-sensed data alone provides no mechanism to distribute damage among age classes. In the hybrid case, we use a linear regression of the Hugo damage by age class to distribute damage among classes, which leads to an increasing damage estimate with age. This differs from the remote-sensed method where we assume uniform damage across age classes (Table 4).

2.2. Treatment of salvage

Timber salvage is ephemeral, and in the US Southeast downed woody material decays quickly, often precluding use of timber for product after a few months to at most a year. Therefore, we assume that merchantable salvage is only available in the first year, 2018, like Sun (2020). Because the SRTS model uses annual time steps, we cannot model at smaller time scales anyway. Given an empirical relationship between diameter class and age class structure derived from FIA data, we merchandize the assumed damaged inventory by the diameter class cutoffs noted above in Table 1. We further apply a "cull" percentage to sawtimber volumes, representing the portion of sawtimber that would be merchandized as pulpwood in normal harvesting operations (recall Table 1). Next, we assume a portion of sawtimber growing stock in non-pulpwood product

Table 4
Comparison of the volume damage distribution by 5-year age class (percent) for the hybrid and remote-sensed damage methods.

	Hybrid		Remote-sensed	
Age class	Pine plantation	Other	Pine plantation	Other
1	8.27	6.32	11.11	9.09
2	8.98	6.87	11.11	9.09
3	9.69	7.43	11.11	9.09
4	10.40	7.98	11.11	9.09
5	11.11	8.54	11.11	9.09
6	11.82	9.09	11.11	9.09
7	12.53	9.65	11.11	9.09
8	13.24	10.20	11.11	9.09
9	13.95	10.75	11.11	9.09
10		11.31		9.09
11		11.86		9.09

categories degrades into pulpwood due to splitting from wind damage (an "additional degrade" of 20%, which increases the cull to pulpwood). Finally, we assume salvage rates by species based on a special post-hurricane survey conducted by FIA and taking the average salvage utilization rates across the entire region (Brandeis et al., 2021). Salvage percentages by product are 13% for all pine products except large sawtimber, which is 6%, and 1% for both hardwood products.

Eqs. 1 and 2 generalize these assumptions and transformations, where S is salvaged quantity, the particular or generalized subscript i is product number by species, j is the sub-region, k is species, H is damaged quantity of growing stock, n is number of products by species (4 for pine, 2 for hardwood), C is the cull factor, D is additional degrade, r is the salvage rate.

$$S_1^{jk} = r_1^{jk}\left(H_1^{jk} + \sum_{i=2}^{n}\left(C_i^{jk} + D_i^{jk}\right)H_i^{jk}\right) \quad (1)$$

$$\forall i > 1 : S_i^{jk} = r_i^{jk}\left(H_i^{jk}\left(1 - \left(C_i^{jk} + D_i^{jk}\right)\right)\right) \quad (2)$$

To predict how the quantity of salvage by diameter class affect the market equilibrium for products, we use a method different from previous empirical and theoretical work. Prestemon and Holmes (2000, 2010) and Sun (2020) treat salvage as a shift in the supply curve. This framing of salvage achieves the desired empirical effect of lower timber prices due to salvage because the supply curve shifts right and thus travels down the demand curve.

However, this framing is not technically consistent with the structure of SRTS, which models a market for green stumpage. It is necessary for accounting purposes that salvage and green stumpage are separable. To adopt the theoretical arguments that salvage causes a *rightward* shift in the supply curve would mean the equilibrium quantity is undifferentiated salvage plus stumpage. Thus, we treat salvage as an exogenous quantity, based on our volume damage methods and empirical salvage rates. In the short term we assume mill capacity is fixed, and we assume that the quantity demanded by mills in the hurricane scenarios is the same as in the base scenario. Thus, with a salvaged quantity known, we can model the market for green stumpage as a leftward shift of the *demand* curve. Salvage utilization is measured on the quantity axis as the change in quantity of green stumpage demanded resulting from a shift in the demand curve.

The hurricane also causes a leftward shift in the supply curve due to the damage and loss of growing stock. Fig. 2 shows a classic timber market, with supply and demand curves intersecting at the market equilibrium (denoted by letters). The black lines represent the no-hurricane case, with supply and demand intersecting at 'A'. Immediately following the hurricane, the red lines show how salvage is assumed to move the demand curve for green timber inward and the damage to the inventory will move the supply curve, also inward. The resulting effect is a decrease in the price of stumpage ('B').

After one year the available salvage will have mostly decayed and therefore does not reduce demand. Fig. 2 represents the year following the hurricane with green curves and the price quantity equilibrium with 'C'. The rightward shift in the supply curve is due to inventory growth, and the green demand curve overlays the blue demand curve, representing a return to the aggregate demand conditions that would have occurred in the case of no hurricane. For comparison, the blue supply curve represents a shift in supply due to inventory growth from the black baseline. For the same aggregate demand, the baseline produces higher quantity and lower prices at 'D' compared to the hurricane case at 'C'.

We assume that not all green stumpage in a sub-region would be substituted by salvaged stumpage. Given the quantities derived in Eqs. 1 and 2, we introduce a constraint on the percentage of demand that can be offset by salvage in each sub-region. We add these assumptions (20 and 40%) to our scenario permutations. Upon meeting this constraint, we allow regions with excess salvage to trade with outlying regions such

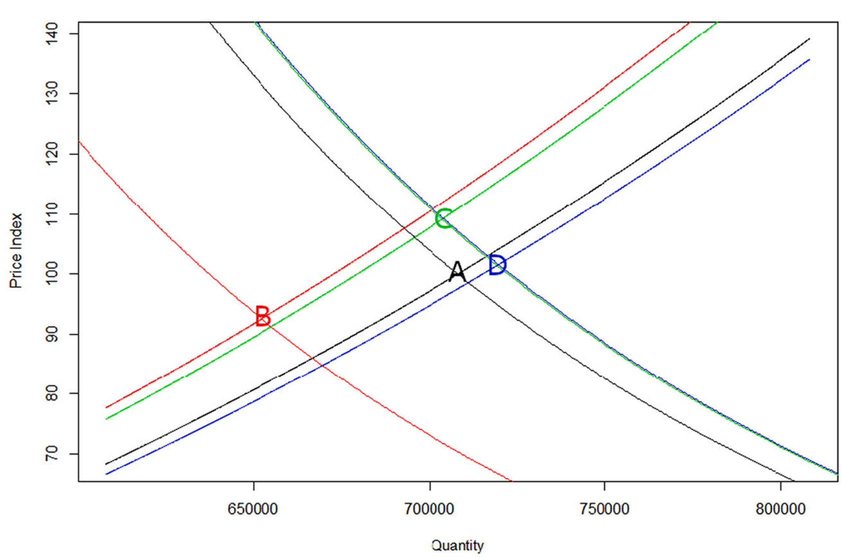

Fig. 2. Representation of supply (positive sloped curves) and demand (negative sloped curves) dynamics for the no-hurricane base case (black), the hurricane case (red), one year post-hurricane (green) and the no-hurricane case one year later (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

that regions closest to the severe region must meet their maximum salvage utilization before trading the excess. The net impact on green removals is shown in Supplementary Materials (Fig. A1). In Fig. A1, salvage use in each sub-region is represented by the difference with the Base scenario. The total salvage is the same for both the 20% and 40% substitution cases. Excess salvage supply moves outward from the central basins. In the Severe50 region and in the higher (40%) case of subregional salvage utilization, for example, green stumpage removals are lower than in the 20% case because more stumpage has been substituted by salvage. In the 40% case, excess salvage runs out and barely changes the None150 region. In contrast, the 20% case results in excess salvage supply that reduces green removals in the None150 region. These scenarios can be interpreted as changing the spatial distribution of green removals, with the 20% case spreading salvage substitution across all subregions, and the 40% case concentrating salvage substitution in regions labeled 2 through 8 in Fig. 1.

2.3. Replanting decision

The SRTS model's management types include pine plantations, natural pine, mixed pine/hardwood, upland hardwood, and bottomland hardwood. Pine plantations are intensively managed compared to the other types and contribute about 75% of removals in this region based on the summarized FIA data for the region. Changes in the area of pine plantations would therefore alter the wood available for mills. Since we do not have independent estimates of replanting that took place, we make assumptions about the proportion of damaged pine plantation area that will be replanted following a hurricane. If a plantation is not replanted, natural regeneration is assumed. We model three replanting scenarios shown in Table 5. The Replant1 scenario assumes that pine plantation area remains the same after the hurricane, or 100% replanting. The Replant2 and Replant3 scenarios assume less replanting and more natural regeneration, retaining constant forest area.

Applying the three hurricane damage methods to the inventory data and allocating damaged areas with the replanting scenarios resulted in large losses in the Severe region and smaller losses in the Moderate region as expected. The impacts of area damage on the basins, Severe50 and Moderate75, are shown in Fig. 3. Damage to growing stock and area for all sub-regions are presented in Supplementary Materials (Figs. A2 and A3, respectively).

2.4. Demand assumptions

We use one common demand scenario by product for all model runs in order to run a controlled experiment on modeled scenarios. The demand scenario is derived from a model projecting housing starts in the United States (Prestemon et al., 2017) and includes a temporary drop in sawtimber demand in 2020 due to the Covid-19 recession. Based on mean model outcomes from the housing starts model, the long run growth rates in demand we assume are 0.29% per year for pine and hardwood pulpwood, 0.57% for pine chip-n-saw, and 0.8% per year for all sawtimber products.

Table 5
Redistribution proportion of pine plantation acres to alternative management types for three replanting scenarios.

	Replanting scenario		
Management type	1	2	3
Pine plantation	1	0.5	0.25
Natural pine	0	0.3	0.5
Mixed Pine/hardwood	0	0.2	0.25
Upland hardwood	0	0	0
Bottomland hardwood	0	0	0

2.5. Summary of scenarios

The scenario with no hurricane is our Base scenario, which we also identify as the "counterfactual" case in subsequent discussion. This run is contrasted with several hurricane scenarios. The full suite of scenarios examined are permutations of (1) Hurricane vs. no hurricane, (2) Hugo analog vs. hybrid vs. remote-sensed, (3) salvage utilization by subregion {20, 40%}, (4) Replanting scenario {1,2,3}. Initial sensitivity analysis revealed that the three damage methods provided similar damage estimates. Further, damage methods were identified as the element with the least consequence for simulated growing stock, removals, and price dynamics. Therefore, we report the simplest method, remote sensing, in the main body of results.

3. Results

The growing stock, removals and price results show the key impacts of the scenarios. After discussing general observations, we provide additional analysis on the welfare impacts.

3.1. General observations

Consistent with the study design, the results show a reduction in growing stock in 2018 due to hurricane damage (Figs. 4 and 5). The removals in the hurricane year are reduced, for salvage substitution, and the following year do not return to the absolute quantity observed in the baseline, as previously illustrated in Fig. 2. This is consistent with lower growing stock volume and higher prices. Like Prestemon and Holmes (2000) we demonstrate a negative price response in the hurricane year followed by an upward shift in prices post-hurricane. However, the price increase is eventually mediated by the onset of replanted area. The response is first observed in pulpwood products. In pine pulpwood, several scenarios result in lower prices than the no-hurricane case. As the forest grows into successor products (pine chip-n-saw and pine sawtimber), we observe fewer scenarios producing lower prices than the base case, such that by the time regrown area reaches the large pine sawtimber product class, there is no scenario with lower prices. The scenario that best represents a "return to normal" varies by product.

For hardwoods, due to very low salvage rates (1%) and negative shifts in growing stock, we see higher prices for the entire study period, except in the very long term for hardwood pulpwood. This is due to the slower growth of hardwoods. Hardwood sawtimber exhibited insensitivity to the range of scenarios.

3.2. Salvage substitution

Recall that the substitution constraint controls how much green harvest quantities can be substituted by salvage harvest quantities at the subregional level, while total salvage volume remains the same. Excess salvage supply in the more damaged subregions is then traded to outlying subregions. The 20% case allowed less substitution per subregion than the 40% case and consequently resulted in more excess salvage supply to be traded. In other words, the 20% case facilitated more trade, resulting in reduced green harvests in the base year even in non-damaged subregions (see Fig. 1A). We observe lower prices in the 20% case compared to the 40% case.

The cases with higher prices, particularly for pine sawtimber, induce recruitment of new pine plantation acres through the model's land use change module. The area expansion leads to a bifurcation between the 20% and 40% cases in the growing stock results for pine pulpwood and pine chip-n-saw, such that the 40% cases surpass the no-hurricane growing stock 40 years after the hurricane (Fig. 4). An opposite effect is observed in hardwood pulpwood, where the 40% case leads to lower growing stock in hardwoods due to higher shares of pine plantation and lower shares of hardwood management types.

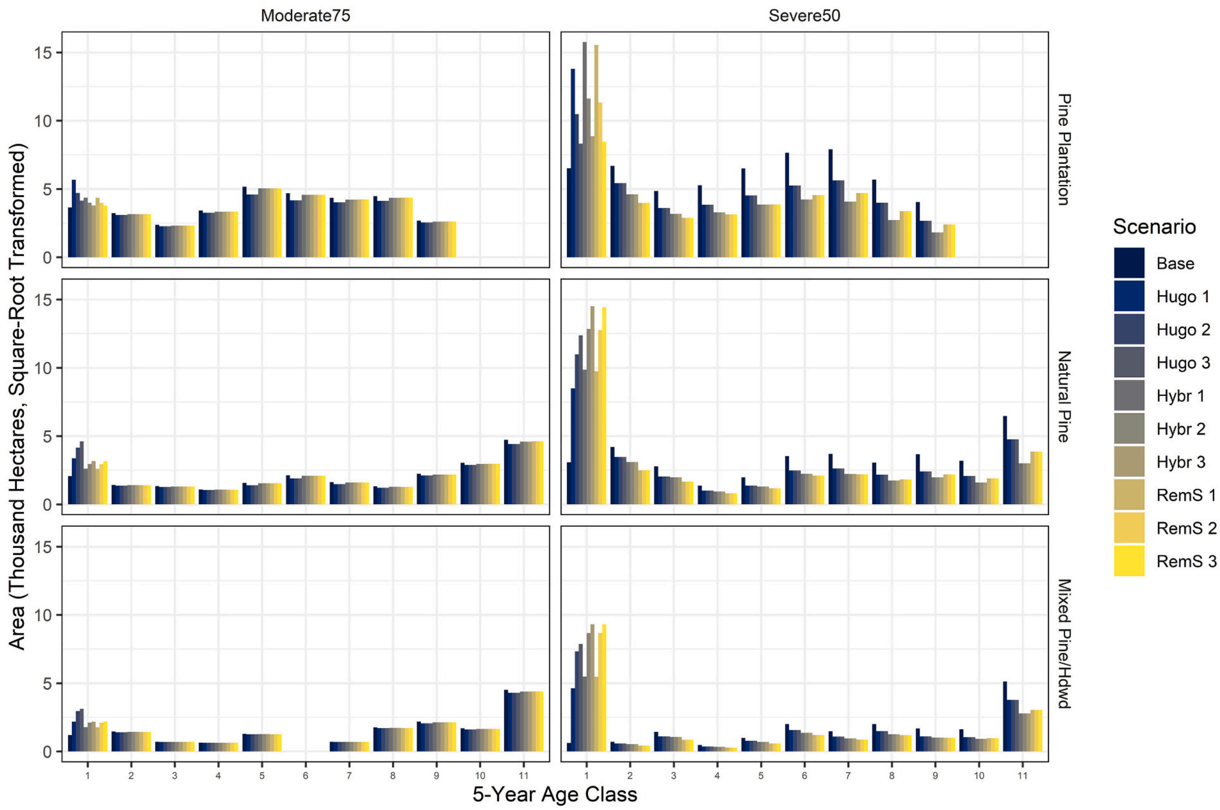

Fig. 3. Age class distribution of forest area for two basins (Severe50, Moderate50) and three management types for: the Base scenario and the three damage estimates (Hugo, Hybr, RemS) and the three replanting scenarios (1,2,3).

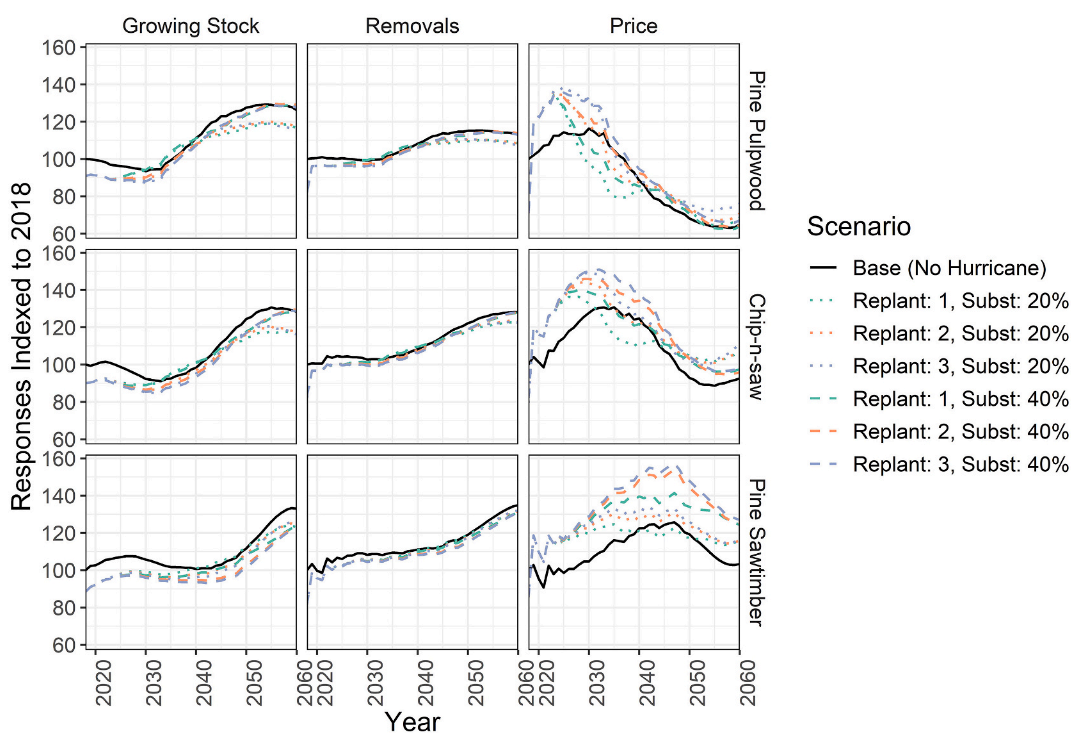

Fig. 4. Growing stock, removals, and prices for pine pulpwood, chip-n-saw and pine sawtimber, where the no-hurricane baseline is black. Replanting scenarios 1, 2 and 3 are green, orange and purple, respectively. The 20% salvage substitution case is dotted, and 40% is dashed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

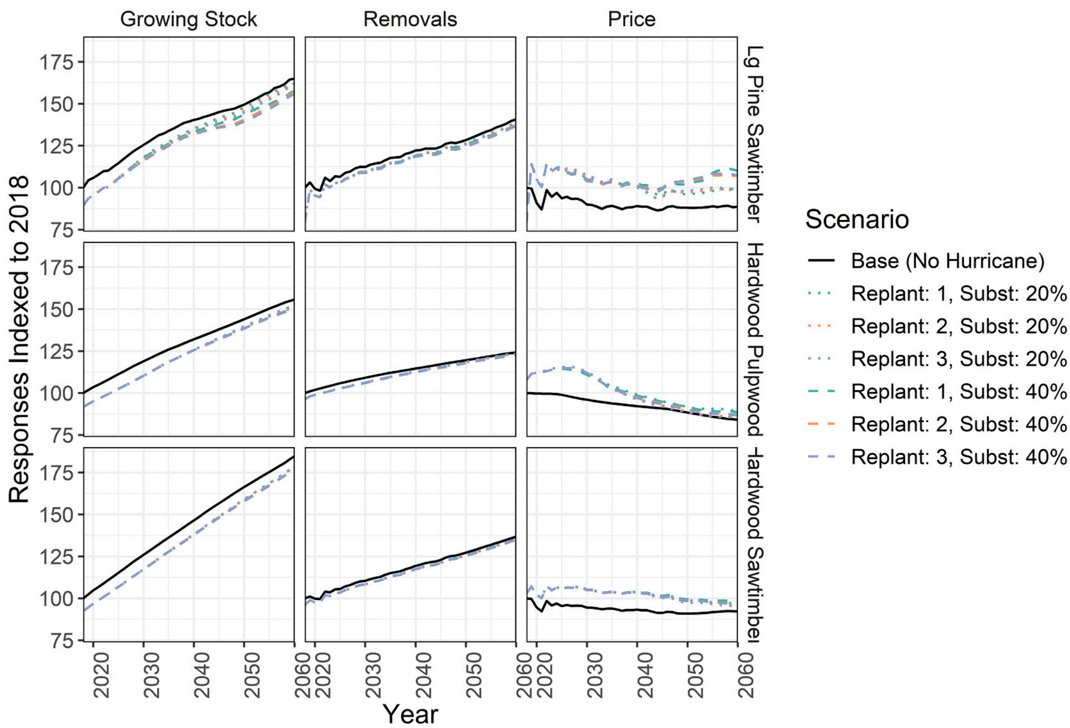

Fig. 5. Growing stock, removals, and prices for large pine sawtimber, hardwood pulpwood, and hardwood sawtimber, where the no-hurricane baseline is black. Replanting scenarios 1, 2 and 3 are green, orange, and purple, respectively. The 20% salvage substitution case is dotted, and 40% is dashed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.3. Replanting scenarios

The largest variation resulting from the replanting scenarios appears in the price responses. The effects of replanting on pine prices are generally observed as a vertical difference among scenarios that diminishes as the age class structure develops toward higher diameter products (Fig. 4).

Prices diverge among hurricane scenarios for pine pulpwood around 2025 when replanted area grows to merchantable diameters (Fig. 4). The ordering from low pine pulpwood prices to high prices corresponds with high replanting rates to low replanting rates. As in the base case, the price peak in pine pulpwood is transmitted to higher diameter products over time as forests mature. The Replant 1 and Replant 2 scenarios led to a period of lower pine pulpwood prices than the base scenario. For chip-n-saw, only the Replant 1 scenario combined with 20% salvage substitution case showed prices that dipped below the Base scenario.

The effects of replanting scenarios on hardwood prices and other responses are small, but a delayed price response starting after 2030 is observed in hardwood pulpwood due the reallocation of some pine plantation area to the mixed pine and hardwood management type in replanting scenarios 2 and 3 (Fig. 5). The ordering here is reversed compared to the pine pulpwood response—high replanting in pine plantations results in higher hardwood pulpwood prices, and vice versa.

3.4. Welfare analysis

The market consisted of 8 sub-regions within a 150-mile radius. Based on the stumpage market results alone and the elasticities in Table 1, we calculate the discounted value of market-level consumer and producer surplus (at a 4% rate), indexed to the base scenario. We find that Hurricane Michael scenarios increase the economic welfare of landowners (producers) in the market (Table 6). This stems from the higher stumpage prices in the years following the hurricane, despite the drop in price during the hurricane year. In only one case do producers show lower welfare than the baseline (pine pulpwood, Replant1, 20% substitution), resulting from low prices. In products and scenarios with large relative increases in producer surplus, stumpage consumers (mills) experience corresponding decreases in welfare (consumer surplus). This

Table 6
Indexed consumer surplus (CS; mills) and indexed producer surplus (PS; landowners) relative to the base scenario by scenario and product.

		Product					
Scenario	CS or PS	1	2	3	4	5	6
Replant 1, Subst: 20%	PS	0.95	1.09	1.25	1.65	1.40	1.92
Replant 2, Subst: 20%	PS	1.05	1.18	1.36	1.64	1.35	1.89
Replant 3, Subst: 20%	PS	1.12	1.22	1.40	1.66	1.33	1.88
Replant 1, Subst: 40%	PS	1.00	1.16	1.56	1.72	1.36	1.93
Replant 2, Subst: 40%	PS	1.09	1.24	1.67	1.70	1.35	1.90
Replant 3, Subst: 40%	PS	1.13	1.28	1.72	1.70	1.34	1.91
Replant 1, Subst: 20%	CS	0.94	0.86	0.84	0.60	0.70	0.51
Replant 2, Subst: 20%	CS	0.86	0.76	0.79	0.59	0.73	0.52
Replant 3, Subst: 20%	CS	0.81	0.72	0.76	0.57	0.73	0.53
Replant 1, Subst: 40%	CS	0.95	0.81	0.70	0.54	0.72	0.50
Replant 2, Subst: 40%	CS	0.87	0.72	0.63	0.54	0.72	0.51
Replant 3, Subst: 40%	CS	0.82	0.67	0.60	0.54	0.73	0.51

Note: products are: (1) pine pulpwood, (2) pine chip-n-saw, (3) pine sawtimber, (4) large pine sawtimber, (5) hardwood pulpwood, and (6) hardwood sawtimber.

exchange in welfare is more pronounced in higher diameter products since it takes longer for the forest to recover supply of large-diameter products and the stumpage price premium for these products lasts through the end of the projection. We additionally tested how sensitive our welfare measures were to the inclusion of welfare from salvage. The value of salvage is small compared to the discounted welfare measures. The largest welfare changes from including salvage would come from assuming perfectly elastic supply and inelastic demand curves and using the same bounds for integration. Making this calculation, we determine that including welfare effects from salvage would at most increase producer surplus by about 0.5% and consumer surplus by about 1.5%. Including salvage welfare discretely shifts the welfare measure for all scenarios, but does not change the pattern among scenarios.

3.5. Forest carbon and area

We consider the effects of the hurricane disturbance on forest carbon and forest area using an index of values relative to 2018 in the base scenario. In all scenarios, after 40 years the forest carbon increases by at least 20%, but no hurricane case attains the level of forest carbon in the Base scenario (Table 7). Forest area increases slightly in all scenarios, and among hurricane scenarios the carbon per unit area index is marginally highest in the second replanting scenario.

4. Discussion and conclusion

Results show that market dynamics alone are not sufficient to recover the total growing stock (and thus, carbon) lost due to the hurricane within the study horizon. However, a late uptick in the trajectory of pine pulpwood and chip-n-saw growing stock for the 40% substitution case suggests that a longer model horizon may show improved recovery of growing stock and forest carbon, especially for higher planting scenarios. The spatial distribution of salvage alters the optimal spatial distribution of removals in subsequent years as regions with access to salvage do not draw as much from the growing stock inventory initially. Improvements in data on the spatial consumption patterns of salvage would aid our understanding of which of our scenarios better mirrors what is occurring, and whether a policy intervention targeting the distribution of salvage consumption could have positive long-term impacts on carbon. In our analysis, we handled the accounting of salvage exogenously in the quantity domain, using an estimate of damage and an empirical salvage rate. Establishing empirical relationships between the price of salvage and salvage supply, consumption, and ratio of salvage to other removals post-hurricane will assist in future impact assessments of similar events.

Price trends generally deviate from the baseline – decreasing initially, then rising once demand for green stumpage returns to normal, and then eventually converging to trends that resemble the baseline. Replanting has the greatest short-term impact on pulpwood prices. The effect of replanting on pulpwood prices diminishes over time but begins to show observable impacts on pine sawtimber prices after about 15 years.

While hurricanes can be disastrous for individual landowners, at the market level we find an increase in producer surplus due to the disturbance, and a decrease in consumer surplus. In terms of welfare, producers of pine products as a whole benefit from less replanting. However, even 100% replanting of pine plantations does not lead to a return to baseline pine sawtimber prices. So, comparing to the counterfactual no-hurricane situation, landowners are better off even in our highest replanting scenario due to the price effects. This result raises an important contrast with stand level analysis of natural disturbance (e.g. van Kooten et al., 2019; Mei et al., 2019). Whereas an individual landowner may shorten rotations due to the risk of a catastrophic loss, our results suggest that an individual landowner could also gain indirectly from enhanced prices and may extend rotations as a result. This is a research question that is generally outside the scope of both stand level and market models, but it could be pursued in the context of an agent-based model which integrates the stand level and market perspectives (Henderson and Abt, 2016).

Our analysis did not account for a carbon payment policy, which would have the effect of restricting harvests to a greater degree, enhancing timber prices. The specific impact of carbon payments in combination with a hurricane disturbance requires future empirical analysis and modeling. However, if carbon payments for delaying harvest are treated like a leftward shift of the supply curve, the effect would be negative for consumer welfare in the affected area.

Complementary policies supporting additional replanting in the wake of a hurricane (beyond 100%) would counterbalance the effect over the long-term. Alternatively, areas damaged by hurricanes could receive tailored incentives to replant for the purpose of carbon sequestration through existing federal or state programs like the Conservation Reserve Program (CRP).

The welfare results show that pulpwood consumers and producers are only modestly affected by the hurricane disturbance compared to other products. The flexibility inherent in sourcing pulpwood – as thinnings or cull – renders them relatively more resilient to hurricane market impacts and shocks to forest structure, though potentially with greater variability in price changes. Consequently, while pulpwood is not a high return for landowners, pulpwood consumers could be considered well-adapted to hurricane-prone regions.

Interestingly, we found that exogenous simulation assumptions such as replanting and salvage substitution were more impactful on simulation results than methods used to quantify damages and adjust the initial inventory. In general, damage and salvage estimates using the inventory, hybrid, and remote sensing approaches were similar, and thus changing inventory impacts using these alternative methods did not have meaningful impacts on projections (Fig. A1 and A2 in the supplement). This result serves as a validation (at least in our case study region) that remote sensing technologies can facilitate rapid impact assessments in affected regions. This is important given the potential time lag associated with using forest inventory data to assess natural hazard impacts.

Our paper includes several limitations. First, given the lack of a detailed inventory following Hurricane Michael, we opted to use Hurricane Hugo as an analog for estimating damages across forest types and age classes. Second, our simulation framework is myopic to future change, so management responses (e.g., planting decisions) do not respond to expectations of future price shifts. Third, we restrict our analysis to a single event over the full simulation horizon to isolate the impact of Hurricane Michael. Over a multi-decadal simulation horizon, effects of multiple hurricane events will be cumulative. Even in the time since Hurricane Michael, we have experienced hurricanes and tropical storms in the Gulf Coast region that have affected forest systems (e.g., Hurricane Ida in 2021). Further analysis is needed to quantify the cumulative long-term impact of recent hurricane events on the forest industry in the US South. Nonetheless, our analysis highlights several areas for future research, including new empirical work on salvage consumption and replanting, and analysis of potential mitigation strategies or policy action to ameliorate the long-term effects of hurricanes post-disturbance.

Table 7
40-year carbon, forest area, and forest carbon per area indexes for all scenarios (index relative to 2018 in the Base scenario).

Scenario	Forest carbon	Forest area	Forest carbon per area
Base	1.264	1.028	1.229
Replant 1, Subst: 20%	1.215	1.016	1.197
Replant 2, Subst: 20%	1.220	1.014	1.203
Replant 3, Subst: 20%	1.218	1.014	1.201
Replant 1, Subst: 40%	1.228	1.031	1.192
Replant 2, Subst: 40%	1.232	1.028	1.199
Replant 3, Subst: 40%	1.230	1.028	1.196

Author statement

Jesse D. Henderson: **Conceptualization, Methodology, Software, Writing – Original Draft, Validation.** Robert C. Abt: **Conceptualization, Methodology, Data Curation, Software.** Karen L. Abt: **Validation, Writing – Review & Editing.** Justin S. Baker: **Validation, Writing – Review & Editing.** Ray Sheffield: **Data Curation, Formal Analysis.**

Declaration of Competing Interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.forpol.2022.102735.

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