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Hurricanes pose a substantial risk to New England forest carbon stocks

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Abstract

Nature-based climate solutions (NCS) are championed as a primary tool to mitigate climate change, especially in forested regions capable of storing and sequestering vast amounts of carbon. New England is one of the most heavily forested regions in the United States (>75% forested by land area), and forest carbon is a significant component of climate mitigation policies. Large infrequent disturbances, such as hurricanes, are a major source of uncertainty and risk for policies relying on forest carbon for climate mitigation, especially as climate change is projected to alter the intensity and extent of hurricanes. To date, most research into disturbance impacts on forest carbon stocks has focused on fire. Here, we show that a single hurricane in the region can down between 121 and 250 MMTCO$_2$e or 4.6%–9.4% of the total aboveground forest carbon, much greater than the carbon sequestered annually by New England's forests (16 MMTCO$_2$e year^{-1}). However, emissions from hurricanes are not instantaneous; it takes approximately 19 years for downed carbon to become a net emission and 100 years for 90% of the downed carbon to be emitted. Reconstructing hurricanes with the HURRECON and EXPOS models across a range of historical and projected wind speeds, we find that an 8% and 16% increase in hurricane wind speeds leads to a 10.7- and 24.8-fold increase in the extent of high-severity damaged areas (widespread tree mortality). Increased wind speed also leads to unprecedented geographical shifts in damage, both inland and northward, into heavily forested regions traditionally less affected by hurricanes. Given that a single hurricane can emit the equivalent of 10+ years of carbon sequestered by forests in New England, the status of these forests as a durable carbon sink is uncertain. Understanding the risks to forest carbon stocks from disturbances is necessary for decision-makers relying on forests as a NCS.

KEYWORDS
carbon offsets, disturbances, forest carbon, future climate change, hurricanes, nature-based climate solutions, New England, wind damage

1 | INTRODUCTION

The impacts of climate change and the failure to meet emission reduction targets are driving a widespread interest in using nature-based climate solutions (NCS) to meet climate policy goals (Ellerman et al., 2016; Galik & Jackson, 2009; Griscom et al., 2017; Roe et al., 2019). Forests are a major focus of NCS strategies, as they sequester the equivalent of nearly 25% of human carbon dioxide (CO_2) emissions globally (Anderegg et al., 2022; Bonan, 2008; Pan et al., 2011), with US forests sequestering the equivalence of 10% of US CO_2 emissions (Birdsey et al., 2006). However, NCS policies often focus on the potential for future sequestration while inadequately accounting for the potential of existing carbon stocks to become a source of emissions due to disturbances (Anderson-Teixeira et al., 2013; Brodribb et al., 2020; Seidl et al., 2017). Therefore, relying on forest carbon offsets to mitigate greenhouse gas emissions has garnered considerable scrutiny, especially under the current regulatory and voluntary carbon market regimes (Badgley, Chay, et al., 2022; Badgley, Freeman, et al., 2022; Gifford, 2020; Haya, 2010).

Using forests as NCS requires an accurate accounting of the risks posed by disturbance regimes, including climate stress, biotic agents, wildfires, and storms (i.e., snow, ice, lightning, and wind). The importance and complexity of accounting for these factors is magnified as climate change alters disturbance regimes and even introduces new confounding factors (Wu et al., 2023). For example, increased droughts will likely lead to increased susceptibility of trees to biotic agents, and an increased likelihood and magnitude of wildfires, especially in the Western United States (Anderegg et al., 2022). Under a changing climate, using historical data to calculate disturbance risks is likely inadequate; for example, the 100-year integrated risk of a moderate and severe wildfire across the United States has doubled from approximately 4%–8% between the periods of 1984–2000 and 2001–2017 (Anderegg et al., 2020). Over a similar 30-year period across the Atlantic basin, warmer sea surface temperatures (SST) corresponded with a 10% increase in hurricane intensity (Emanuel, 2007), and a 2°C anthropogenic warming scenario could see median hurricane intensity increasing by up to 10%, with the likelihood of the most intense storms having a median projected increase of 13% (Knutson et al., 2020).

Hurricanes are a dominant disturbance agent in New England, with the North Atlantic basin being among the most active regions for tropical cyclones, resulting in New England being impacted by catastrophic hurricanes about once a century (Boose et al., 2001; Landsea et al., 2015). Ten hurricanes had a significant impact in New England during the 20th century, the most impactful being: the Great New England Hurricane of 1938, Carol in 1954, and Bob in 1991 (Landsea et al., 2015). For example, the 1938 hurricane downed 70% of the timber volume at Harvard Forest in central Massachusetts (Foster & Boose, 1992). It caused extensive damage throughout New England, destroying over 8900 buildings and damaging an additional 15,000 (Long, 2016; Massachusetts Office of Coastal Zone Management, 2002). It has been suggested that over the 21st century, storm wind speeds may increase by 6%–16% due to increases in Atlantic basin SST (Bender et al., 2010; Emanuel, 2005; Knutson et al., 2009). For example, it has been predicted that hurricane intensity (the maximum wind speed) is likely to increase by 5% for every degree Celsius increase in SST; however, during the last 30 years of the 20th century Atlantic basin hurricane intensity increased by 10% along with a 0.6°C increase in SST (Emanuel, 1987, 2007). It is unknown whether the frequency of storms will change (Landsea et al., 2006; Trenberth, 2005; Webster et al., 2005); however, some meteorologists predict that climate change may lead to fewer, yet more intense hurricanes, with the probability of storm impacts to increase by 200%–300% throughout the next century (Bender et al., 2010; Emanuel, 2005; Knutson et al., 2009; Mann & Emanuel, 2006).

Throughout the last century, New England's forests have served as a critical carbon sink, resulting from widespread reforestation following 19th-century farm abandonment, reduced harvesting, and other land-use impacts (Albani et al., 2006; Bonan, 2008). Currently, New England is among the most forested regions in the United States, with nearly 75% of its land covered by forests (FIA USDA Forest Service, 2022; Thompson et al., 2013), sequestering 16 MMTCO_2e of aboveground forest carbon annually (US EPA, 2022). New England forest carbon is central to regional and national decarbonization strategies, as many states strive to become "Net-Zero" emitters in the coming decades (Thompson et al., 2020; US Climate Change Science Program, 2014; Wayburn, 2009; Wikle et al., 2021), and as industries begin to take part in forest offset markets (Kerchner & Keeton, 2015).

In this study, we quantify the potential impact of 21st-century hurricane-force winds on New England aboveground forest carbon stocks. We analyze three scenarios using historical hurricane data for the 10 most impactful storms of the 20th century: (1) Baseline—no change in hurricane wind intensity; (2) Projected—8% increase in wind speeds from the baseline; and (3) Maximum Severity—16% increase in wind speeds. The extent and intensity of the modeled storms, together with a map of forest composition and carbon density, and a harvested wood products (HWP) model are used to estimate the impact that storms would have on aboveground forest carbon. Specifically, we ask: (1) What risks do hurricanes pose to existing live aboveground forest carbon stocks in New England? (2) How will this risk be affected by projected changes in wind disturbance regimes that may subsequently alter the intensity and geographic extent of hurricanes?

2 | MATERIALS AND METHODS

2.1 | Estimating hurricane impacts on aboveground forest carbon

Our aim was to estimate the forest carbon losses that would occur from hurricanes in New England. The four major components needed to make this estimation are as follows: (1) spatial reconstruction

TABLE 1 Commonly used terms and acronyms.

Category and term	Definition and units
Hurricane wind intensity scenarios	
Baseline	Reconstruction of past hurricanes using HURRECON and EXPOS informed by National Hurricane Center data
Projected	Hurricanes with increased wind speeds (8%) to estimate the potential future impact of hurricanes based on meteorological forecasts
Max severity	Hurricanes with a 16% increase in wind speeds to simulate the maximum potential damage
Enhanced Fujita (EF) scale	Rating of the expected damage caused by severe wind events, based on the maximum three-second wind speed. Predicted damage classes for New England range from EF0 to EF4
Forest carbon	
AFC	Aboveground Forest Carbon: The total initial (pre-hurricane) aboveground forest tree carbon displayed as either a density in megagrams of carbon per hectare ($\mathrm{Mg\,C\,ha^{-1}}$) or in total million metric tons of CO_2 equivalence ($MMTCO_2e$). Aboveground forest biomass is converted to carbon by multiplying biomass by 0.5 (50% of biomass is carbon). Carbon is converted to CO_2e by multiplying by 3.67. Only aboveground forest tree carbon is included in the calculation (herbaceous plants and shrubs are excluded, as well as belowground biomass).
DFC	Downed Forest Carbon: AFC that is downed by a hurricane ($MMTCO_2e$)
Percent downed	The percent of total aboveground forest carbon that is downed by a hurricane (Percent Downed = DFC/AFC*100)
Models	
HURRECON	A meteorological model that estimates wind speed, wind direction, and wind damage as a function of hurricane location and maximum wind speed.
EXPOS	A model of topographic exposure to hurricane winds. It uses a digital elevation model (DEM) to estimate exposed and protected areas across a region for a specified wind direction and inflection angle.
BIGMAP	Big Data, Mapping, and Analytics Platform (BIGMAP), a cloud-based national scale modeling, mapping, and analysis environment for US forests. The BIGMAP project was developed by the USFS Forest Inventory and Analysis (FIA) program using data from national forest inventory plots measured during the period 2014–2018, in conjunction with other auxiliary information.
HWP-C vR	We used the New England variant of the United States Forest Service Harvested Wood Products (HWP) model for carbon stocks and fluxes built in R, to produce estimates of carbon storage and emissions from harvested and unharvested wood. The HWP model tracks harvested wood from milled roundwood to final products and discard fates.

of hurricane paths and their Enhanced Fujita (EF) damage (see Section 2.2), (2) maps of aboveground forest carbon for each of eight tree type-height vulnerability classes (Section 2.4), (3) estimates of the expected percent of trees downed by each experienced EF damage for each tree vulnerability class (Section 2.3), and (4) HWP model to estimate the carbon emissions pathways (Section 2.5; Figure 1). We combined the first three components to calculate the amount of forest carbon downed within each forested pixel in New England based on the EF rating and the tree vulnerability classification. We did this for all 10 storms in each of the three scenarios (30 storms total). We then calculated the amount of downed forest carbon within each state and county following each storm, as well as the size and strength of each hurricane. Finally, we estimated the carbon emissions from downed forest carbon post-hurricane using a HWP carbon storage and emissions model.

2.2 | Hurricane reconstructions and scenarios

We modeled the impacts of 10 20th-century hurricanes that caused EF1 or higher damage in New England (Table 2, Figure 2). These hurricanes were chosen because of the abundance of meteorological and damage data for these storms and because the 20th century is reasonably typical of the 400-year period since European settlement, with somewhat less hurricane activity than the 19th century and somewhat more than the 18th century (Boose et al., 2001). Each storm was modeled as if it occurred in 2020, and each storm was simulated under three disturbance regime scenarios: (1) baseline—actual historical wind speeds from HURDAT2 (Landsea et al., 2015), (2) projected—wind speeds increased by 8%, and (3) maximum severity—wind speeds increased by 16% (Figure S1).

The projected and maximum severity scenario increases in wind speeds of 8% and 16% were chosen as representative values from a broad range of meteorological predictions of future hurricane wind speeds (Bender et al., 2010; Emanuel, 1987, 2005, 2007; Knutson et al., 2009, 2020; Knutson & Tuleya, 2004; Mann & Emanuel, 2006; Vickery et al., 2009). We further highlight the range of the plausible increase in hurricane wind speeds using the relationship between maximum hurricane wind speeds and SST (Webster et al., 2005), which is predicted to increase by ~0.35°C per decade across the Atlantic basin (Alexander et al., 2018). Hurricane maximum wind speeds have been estimated to increase by 3.5%–16.7% for every degree Celsius increase in SST (Emanuel, 1987, 2007; Knutson & Tuleya, 2004). Therefore, in 30 and 60 years respectively, maximum

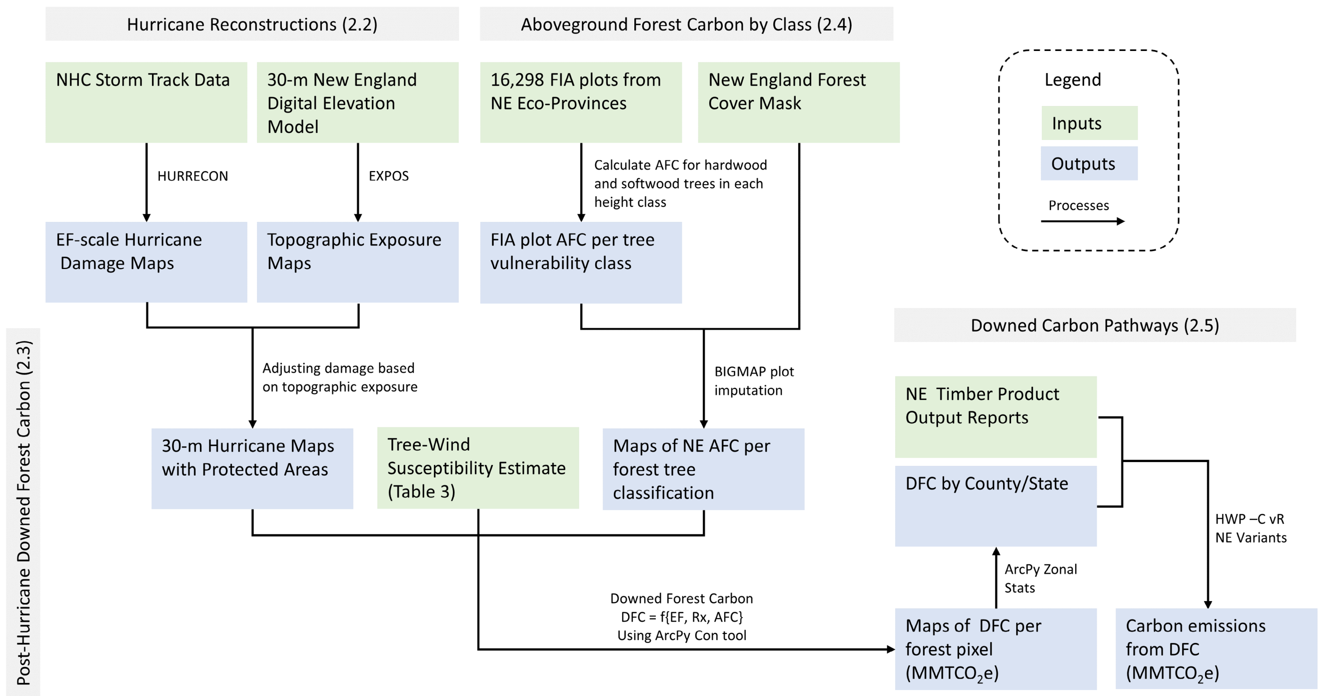

FIGURE 1 Flowchart of methods to calculate downed forest and the emissions from downed forest carbon by combining the hurricane reconstructions (Section 2.2) with the New England aboveground forest carbon estimations (Section 2.4), calculated using the forest tree vulnerability to hurricane-force winds (Section 2.3), followed by the calculations of emissions using the harvested wood products model (Section 2.5). Inputs are represented by green boxes, outputs by blue boxes, and processes (models and major analyses) by arrows. The gray headers represent the different major processes, described in the methods subsections in parentheses.

windspeeds could increase by ~4%–18% and ~7%–35%. Given the vast uncertainty and broad range of predictions, we decided that 8% and 16% were reasonable estimates for our study.

The HURRECON model is a simple meteorological model that estimates wind speed, wind direction, and wind damage as a function of hurricane location and maximum wind speed. The model is based on empirical studies of many hurricanes and can generate results for a single site or an entire region. The updated version of HURRECON used in this study (Boose, 2023a) uses the same equations to estimate wind speed and direction as the original model (Boose et al., 2001). New features include the ability to estimate wind damage on the enhanced Fujita scale (Edwards et al., 2013) instead of the older Fujita scale (Fujita, 1971) and import hurricane track and intensity data directly from the US National Hurricane Center's HURDAT2 database (Landsea et al., 2015). The enhanced Fujita scale is used rather than the more common Saffir-Simpson scale because the former characterizes wind damage at a specific location, while the latter characterizes maximum wind damage anywhere in a hurricane.

Output from HURRECON informs the EXPOS model, which is a simple model of topographic exposure to hurricane winds. It uses a digital elevation model (DEM) to estimate exposed and protected areas at the pixel level, for a specified wind direction and inflection angle. The revised version of the model used in this study (Boose, 2023b) uses the same algorithms to calculate exposure as the original model (Boose et al., 2001). New features include the ability to refine regional maps of wind damage from HURRECON by reducing the level of predicted wind damage at locations that are topographically protected from the predicted peak wind direction at that location. For this study, we used a 30-meter digital elevation model for New England from the Shuttle Radar Topography Mission (USGS EROS, 2018) and a 6-degree inflection angle informed by previous EXPOS studies (Boose et al., 1994, 2001, 2004). Damage in protected areas was reduced by two enhanced Fujita classes (e.g., a protected pixel with an EF2 rating was downgraded to EF0).

The accuracy of the HURRECON model was tested in an earlier study of 67 hurricanes in New England between 1635 and 1996 (Boose et al., 2001). Contemporary reports of wind damage for each storm were used to assign a Fujita damage class to each town where reports were available. The resulting data were used to create maps of actual wind damage by town for each hurricane. These maps were then compared with maps of predicted Fujita damage from the HURRECON model. Compiled results for all hurricanes showed that actual and modeled damage agreed in 62% of the towns and were within one damage class in 99% of the towns, with a slight tendency to underestimate damage (23% one damage class too low, 14% one damage class too high). In most cases, the spatial patterns of agreement between actual and modeled wind damage were evenly distributed across New England and to either side of the hurricane track (in some cases, damage on the left side was underestimated, especially for storms that passed offshore).

The accuracy of the EXPOS model was tested in an earlier study of the 1938 Hurricane in New England and Hurricane Hugo (1989)

TABLE 2 Ten 20th-century hurricanes and their impact in terms of affected area and downed forest carbon across Enhanced Fujita (EF) classes for each of the three hurricane intensity scenarios.

	Total impacted area		Damaged area by EF class (km^2)				Downed forest carbon	
	km^2	% area	EF0	EF1	EF2	EF3	$MMTCO_2e$	% down
Great New England (1938)								
Baseline	68,666	40.2%	27,648	23,460	16,543	1015	280	10.5%
Projected	90,619	53.0%	41,882	19,756	22,684	6298	389	14.6%
Max severity	108,713	63.6%	52,633	20,765	21,820	13,494	472	17.7%
Great Atlantic (1944)								
Baseline	45,905	26.9%	22,413	22,916	576	0	126	4.7%
Projected	55,997	32.8%	24,074	26,193	5730	0	179	6.7%
Max severity	72,395	42.4%	33,723	23,126	15,546	0	259	9.7%
Carol (1954)								
Baseline	76,389	44.7%	30,596	31,289	14,503	0	270	10.2%
Projected	95,224	55.7%	39,845	28,249	22,596	4534	373	14.0%
Max severity	112,681	65.9%	48,160	26,337	26,984	11,200	481	18.1%
Edna (1954)								
Baseline	38,967	22.8%	31,628	7071	267	0	81	3.1%
Projected	64,955	38.0%	49,234	14,527	1194	0	154	5.8%
Max severity	85,742	50.2%	58,707	23,699	3187	149	222	8.3%
Donna (1960)								
Baseline	32,218	18.8%	21,405	10,813	0	0	69	2.6%
Projected	43,186	25.3%	25,478	17,101	607	0	109	4.1%
Max severity	52,755	30.9%	26,165	21,527	5063	0	160	6.0%
Esther (1961)								
Baseline	31,824	18.6%	25,266	6558	0	0	65	2.4%
Projected	41,391	24.2%	28,982	12,409	0	0	101	3.8%
Max severity	50,493	29.6%	31,124	18,315	1054	0	133	5.0%
Alma (1962)								
Baseline	6578	3.8%	6439	139	0	0	9	0.3%
Projected	13,239	7.8%	12,034	1205	0	0	20	0.8%
Max severity	23,255	13.6%	20,735	2520	0	0	41	1.5%
Gerda (1969)								
Baseline	20,468	12.0%	18,929	1539	0	0	32	1.2%
Projected	50,298	29.4%	45,616	4610	71	0	98	3.7%
Max severity	80,145	46.9%	68,139	10,925	1080	0	177	6.6%
Gloria (1985)								
Baseline	61,627	36.1%	38,935	22,692	0	0	148	5.6%
Projected	76,442	44.7%	43,213	31,311	1919	0	206	7.7%
Max severity	89,521	52.4%	43,139	36,712	9670	0	278	10.5%
Bob (1991)								
Baseline	51,350	30.0%	30,447	19,553	1349	0	135	5.1%
Projected	65,780	38.5%	34,522	24,880	6378	0	196	7.4%
Max severity	82,572	48.3%	41,621	26,630	14,028	293	279	10.5%
Storm averages								
Baseline	43,399	25.4%	25,371	14,603	3324	102	121	4.6%
Projected	59,713	34.9%	34,488	18,024	6118	1083	182	6.9%
Max severity	75,827	44.4%	42,415	21,056	9843	2514	250	9.4%

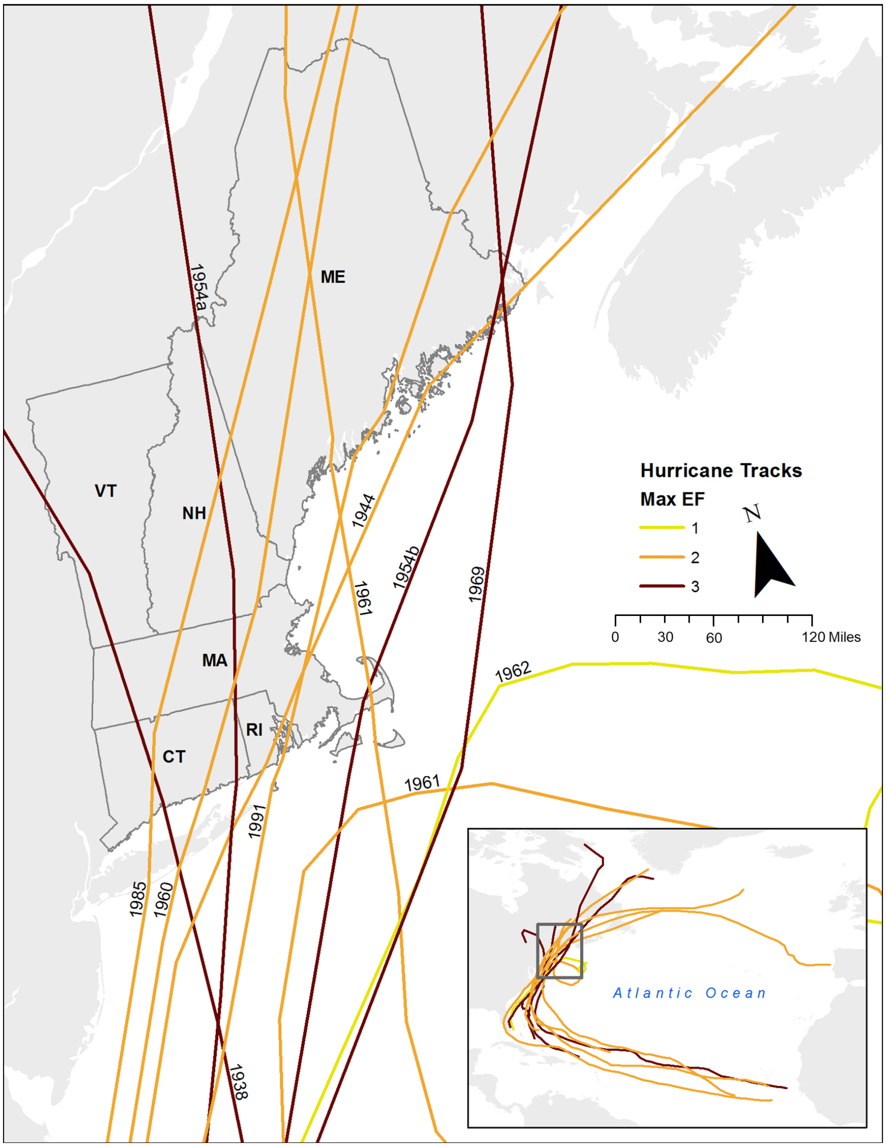

FIGURE 2 Tracks for the ten most impactful 20th-century New England hurricanes. The colors indicate the maximum Enhanced Fujita (EF) value to impact New England (generally the location where the storm made landfall in the region, as storms weaken throughout their trajectory). The EF values represent the baseline scenario, which is the historical strength of the hurricane on record. The inset map on the bottom right shows the entire hurricane tracks across the Atlantic basin with the gray box depicting the region of the main map. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

in Puerto Rico (Boose et al., 1994). In New England, the spatial distribution of undamaged and destroyed stands of mature white pine (a species susceptible to wind damage) after the 1938 hurricane in Petersham, MA was found to closely match the patterns of protected and exposed areas predicted for the town by the EXPOS model, using the predicted peak wind direction from HURRECON. In Puerto Rico, the spatial patterns of windthrow from Hurricane Hugo on the northern slopes of the Luquillo Experimental Forest were also found to closely match the patterns of protected and exposed areas from EXPOS, using the predicted peak wind direction from HURRECON.

2.3 | Forest tree vulnerability to hurricane-force winds

Based on the EF-scale damage predicted for a given location in New England, and the forest composition at the time of the hurricane, we estimate the degree of damage and translate that to percent tree mortality and forest carbon loss. To predict the impact that hurricanes have on aboveground forest carbon, we prescribed the probability that a forest tree is downed by a hurricane based on the two major axes of tree susceptibility to windthrow: (1) tree height and (2) hardwood versus softwood (Busing et al., 2009; Canham et al., 2001; Cooper-Ellis et al., 1999; Raymer, 1962). The probability of downed trees (Table 3) following hurricane disturbances is informed by (1) the observed tree mortality of various species following past wind disturbances (Foster, 1988; Godfrey & Peterson, 2017), (2) differences in the plant structural traits of the common hardwood and softwood species in New England, with conifers tending to be more susceptible to hurricane-force winds (Busing et al., 2009; Cooper-Ellis et al., 1999), and (3) the observation that taller trees are more susceptible to windthrow (Canham et al., 2001; Raymer, 1962). This resulted in eight classifications of tree height and type, with four tree height bins each for hardwood and softwood trees, with the range of expected damage percent across the EF values (Table 3). Under our framework, tall conifers are most susceptible to windthrow, and short hardwoods are least susceptible (Table 3). It is important to note that we only investigated the impacts from hurricane-force winds, and not those of storm surge and/or precipitation that can also lead to catastrophic damages, especially along the coast and steep hillslopes (Knutson et al., 2020; Stanturf et al., 2007).

2.4 | Mapping New England's forested landscape

We mapped aboveground forest carbon for each of the eight tree susceptibility categories representing hardwood and softwood trees across the range of tree heights (Table 3). We used the Big Data, Mapping, and Analytics Platform (BIGMAP), a cloud-based national scale modeling, mapping, and analysis environment for US forests (FIA USDA Forest Service, 2024). The BIGMAP project was developed by the USFS Forest Inventory and Analysis (FIA) program using data from national forest inventory plots measured during the period 2014–2018, in conjunction with other auxiliary information. Vegetation phenology derived via harmonic regression of Landsat 8 OLI scenes collected during the same time period, along with climatic and topographic raster data, were processed to create an ecological ordination model of tree species and produce a feature space of ecological gradients that was used to impute FIA plot data to pixels, and assign values for key forest inventory variables (Ohmann & Gregory, 2002; Wilson et al., 2012, 2013, 2018). For our study, the key variable was live aboveground forest carbon across the eight tree-species-height categories (Table 3).

To create our desired BIGMAP product, we gathered data from 16,298 national forest inventory plots (measured between 2014 and 2018) from across the three ecosystem provinces that are represented by New England forests (212-Laurentian Mixed Forest Province, M212-Adirondack-New England Mixed Forest, and 221-Eastern Broadleaf Forest). For each plot, we used the FIA tree table and inferred tree heights when necessary, using the appropriate site index curve equations (Carmean et al., 1989). We then calculated the aboveground tree carbon across the eight tree height and hardwood/softwood classes (described in Section 2.3 and Table 3) for each inventory plot. These data were extracted from the BIGMAP plot imputation model and resulted in eight 30-meter resolution raster products of predicted aboveground forest carbon for each of the tree susceptibility categories across New England Forests ([dataset] Tumber-Dávila et al., 2024).

2.5 | Harvested wood products carbon storage and emissions estimates

We used the New England variant of the state-level HWP model, HWP-C vR (based on the national-level model, USFS HWP-C v1; Anderson et al., 2013) to produce estimates of carbon storage and emissions from harvested and unharvested wood. The HWP model tracks harvested wood from milled roundwood to final products

TABLE 3 Forest tree vulnerability to hurricane-force winds by tree type and height across the enhanced Fujita scale classes.

Enhanced Fujita scale	Max 3-second wind gust (mph)	Expected tree damage[a]	Down probability (%) by tree height (hardwood – softwood)			
			0–10 m	10–20 m	20–30 m	30+ m
EF0	65–85	Leaves and fruit off, branches broken, tree damage	5%–10%	10%–15%	15%–20%	20%–25%
EF1	86–110	Trees blown down	10%–15%	15%–25%	25%–35%	35%–45%
EF2	111–135	Extensive blow downs	15%–25%	35%–50%	55%–75%	70%–95%
EF3	136–165	Most trees down	25%–35%	45%–60%	65%–85%	85%–100%
EF4	166–200	Catastrophic forest damage	95%	100%	100%	100%

[a]Adapted from Table 1 of Boose et al. (2001).

and discard fates. HWP-C vR has been used for California, Oregon, and Washington wood products carbon inventories (Groom & Tase, 2022; Lucey et al., 2024), and we parameterized this model for New England. Carbon storage pool estimates include products in use (PIU), solid waste disposal sites (SWDS) such as dumps and landfills, and remaining downed wood from storm events (DFC_s). Downed wood from storm events also includes any biomass left in the forest after salvage harvest, and the decay of the downed wood (DFC) was modeled using species group average decay rates (Russell et al., 2014). Carbon emission pools include emitted with energy capture (i.e., fuelwood or burned onsite at mills for energy; EEC), emitted without energy capture (e.g., decay from SWDS; EWoEC), and decay from downed wood left in the forest (DFC_e). Estimated pools and emissions only represent carbon from trees damaged by the storm. Carbon sequestration from regeneration post-hurricane disturbance was not included in these pools or in our analyses.

Using the most recent New England Timber Products Output reports (FIA USDA Forest Service, 2018), we calculated proportions of logging residues by species (reflects harvesting efficiencies), mill residues, and timber product ratios separately for northern and southern New England counties. The northern New England variant included three counties in New Hampshire, five counties in Vermont, and all of Maine. Southern New England included the remaining counties and states in New England. Primary product ratios for New England were created using the most recent northeast regional Timber Product Output report, and national end-use ratios (McKeever, 2009; McKeever & Howard, 2011) were used to estimate proportions of biomass going to end uses as well as decomposition rates after wood products were discarded. From these ratios, we estimate a small proportion of harvested wood is manufactured into short-lived products or emitted during the milling process. The remaining primary products are turned into short- and longer-lived products based on species group, timber product, and most common end use products for these groups (Groom & Tase, 2022).

Former variants of the HWP carbon model were intended to estimate cumulative carbon storage for PIU and in SWDS over time. These estimates were created using annual historical harvest volume records. There were no historical harvest volume records or simulated future harvest volume used for this analysis, only the salvaged wood following the simulated hurricane disturbance. Therefore, we used the HWP model to estimate only the fate of carbon stored and emitted from the salvage harvest following each storm event. We assumed that on average, 25% of down wood would be salvage-harvested after each storm and that salvage harvest occurred the same year as the storm. The ratio of salvage harvest is based on historical salvage rates following hurricane disturbances, affecting forested regions (Foster et al., 1997; Foster & Orwig, 2006; Stanturf et al., 2007), and is limited by sawmill, storage, and transportation capacities, as well as economic pressures (Sanginés de Cárcer et al., 2021). Exact salvage rates and timber product ratios were based on size criteria (height) and hardwood or softwood species. Approximately 26% of the largest size class trees (21 m +) were removed for use in sawtimber and 10% of the medium-sized trees (between 11 and 20 m in height) were also removed for pole timber, to simulate targeted salvage logging of the most usable wood. We ran the HWP model with salvage harvest volume for each of the 10 simulated storms at all three wind intensity scenarios. We then averaged the outputs by county within each wind intensity scenario.

3 | RESULTS

3.1 | Current status of New England forest carbon

New England is 75% forested by area, with an average AFC density of 56.3 Mg ha^{-1} for forested areas (Table 4), according to our BIGMAP product. Rhode Island is the least forested state, 51% of total land area, while Maine contains 55% of all New England's forests, but has the lowest AFC density at 45.8 Mg ha^{-1} (Table 4). Connecticut and Massachusetts have the highest AFC densities, 70.1 and 70.8 Mg ha^{-1} respectively, but are only 56% forested, while New Hampshire and Vermont are both similarly densely forested (~68 Mg ha^{-1} AFC) and have high forest cover (80% and 74% forested by area; Table 4, Figure 3a; Figure S2a).

Cumulatively across all of New England, there are 2660 MMTCO_2e AFC, with Rhode Island again having the lowest total AFC pool (33 MMTCO_2e) and Maine having the largest (1186 MMTCO_2e; Table 5). Greenhouse gas flux data from the US Forest Service show that the AFC pool in New England increases by 15.8 MMTCO_2e on average annually, with New Hampshire and Vermont, being both heavily and densely forested (Table 4, Figure 3a; Walters et al., 2022), accounting for greater than half of the annual AFC flux (Table 5). The AFC flux was calculated using data from 2000 to 2020, a period with no major hurricane-induced DFC. The AFC and DFC

TABLE 4 Total forested area (km^2), proportion of total state area that is forested, and the aboveground forest carbon (AFC) density in Megagrams of carbon per hectare of state area (Mg C ha^{-1}).

State	Forested area (km^2)	Percent forested	AFC (Mg C ha^{-1})
Connecticut	7200	56%	70.1
Maine	70,467	83%	45.8
Massachusetts	11,800	56%	70.8
New Hampshire	19,326	80%	68.4
Rhode Island	1457	51%	62
Vermont	18,509	74%	68.3
New England	128,759	75%	56.3

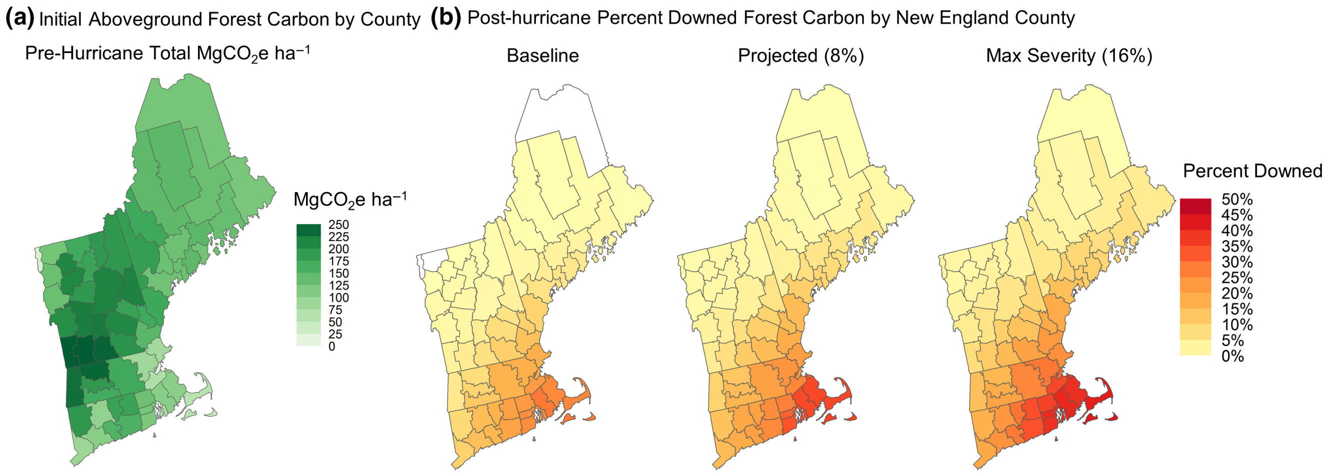

FIGURE 3 Initial (pre-hurricane) live aboveground forest carbon density in $MgCO_2e\,ha^{-1}$ (a) and the average percent of forest carbon downed immediately following a hurricane (DFC/AFC*100) across the three scenarios (b) summarized by New England counties. The aboveground forest carbon (AFC) values represent the carbon stored across our eight hardwood and softwood pools (Table 2), with dark green shades representing high forest carbon density and light green shades representing low forest carbon. Darker red and orange colors represent higher fractions of downed forest carbon (DFC), with lighter yellow shades represent lower percentages of DFC, and white represents zero DFC. Alternatively, Figure S2 shows the cumulative AFC and DFC values across New England counties in $MMTCO_2e$. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

TABLE 5 Initial aboveground forest carbon (AFC) and annual AFC flux by state, along with total DFC ($MMTCO_2e$) and percent downed per hurricane across the hurricane intensity scenarios.

	Initial forest conditions ($MMTCO_2e$)		Baseline		Projected (8%)		Max severity (16%)	
	Annual AFC flux[a]	Total initial AFC	DFC	% down	DFC	% down	DFC	% down
Connecticut	−2.2	185	26	14.3%	36	19.3%	46	25.0%
Maine	−2.4	1186	16	1.3%	30	2.6%	49	4.1%
Massachusetts	−2.9	307	42	13.6%	57	18.7%	71	23.2%
New Hampshire	−4	485	23	4.8%	36	7.5%	51	10.4%
Rhode Island	−0.2	33	8	23.5%	10	30.0%	13	37.6%
Vermont	−4.1	464	7	1.5%	13	2.7%	21	4.5%
New England	−15.8	2660	121	4.6%	182	6.9%	250	9.4%

[a]Flux Data from Walters et al. (2022).

values do not account for tree carbon in non-forested areas (25% of the landscape), or any carbon stored in plants that do not fall within our hardwood and softwood tree bins, such as shrubs, grasses, and forbs.

3.2 | Extent of hurricane damage across hurricane wind intensity scenarios

The average hurricane in the baseline scenario downs 4.6% (SD = 3%) of AFC, while hurricanes under the projected and max severity scenarios down 6.9% and 9.4% of AFC respectively (Table 5, Figure 4). The largest impacts occur in southern and coastal New England (Rhode Island, Connecticut, Massachusetts, and southern New Hampshire), as these regions are more susceptible to experiencing high-severity EF2 and EF3 level damage; however, increases in wind speeds also lead to greater hurricane impacts both inland and northward (Figure 3b; Figure S2b).

On average, hurricanes from the baseline scenario impact 4.3 million hectares (SD = 2.1 Mha) and create 121 $MMTCO_2e$ of DFC per storm (SD = 92; Tables 5 and 6, Figures 4 and 5). The same hurricanes from the projected scenario (8% increase) impact 6 million hectares and create 182 $MMTCO_2e$ of DFC on average per storm, an increase of 37.8% and 50.3% from the baseline scenario respectively. The maximum severity scenario (16% increase) storms have an average per storm impact of 7.6 million hectares and create 250 $MMTCO_2e$ of DFC, a DFC increase of 74.7% and 106.1% from the baseline scenario respectively.

In the baseline scenario, 25% of the land area of New England is impacted by hurricanes on average (Table 6). Most of the

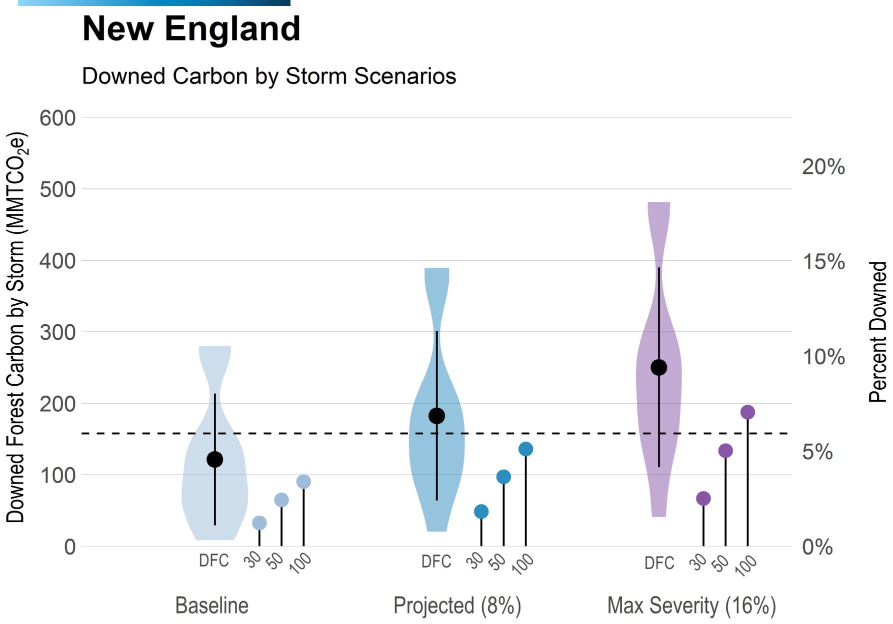

FIGURE 4 Average downed forest carbon (DFC; $MMTCO_2e$) for each hurricane across the hurricane intensity scenarios for all of New England. The black points represent the average DFC across the 10 hurricanes in each scenario (range represents the standard deviation) and the violins represent the distribution of DFC across hurricanes (Tables 2 and 5). The lollipop plots represent the cumulative net emissions from the average hurricane by scenario after 30, 50, and 100 years. The dashed line is the decadal carbon flux (absolute value, i.e., the decadal flux into the forest is −158 $MMTCO_2e$) for New England forests (2000–2020) for reference (Walters et al., 2022). The secondary y-axis (right) is the proportion of New England forest carbon downed by a storm (DFC/AFC*100).

baseline scenario hurricane impacts are concentrated in southern New England, with less than 10% of the area of Vermont and Maine impacted by the average hurricane, and 90% of the damage in those two states are in the lowest damage class (i.e., EF0; Table 6), resulting in very little DFC (Table 3). Rhode Island, being the southernmost and coastal state, is the most affected by hurricane damage, with the average damaged area percent ranging from 90% to 97% across the hurricane scenarios (Table 6). As wind intensities increase, 35% of New England is impacted under the projected scenario and 44% under the maximum severity scenario (Table 6), with impacts shifting northward and inland with increasing wind intensity (Figure 3b). The largest impact across the scenarios came from the increase in the high-intensity EF3 damage from the baseline to the projected and maximum severity scenarios, with EF3 damage extent increasing by 1066% and 2475% respectively from the baseline (Table 6).

The 10 hurricanes we modeled have a wide distribution in their extent and damage (Table 2), with the Great New England Hurricane (1938) and Hurricane Carol (1954) being the most damaging hurricanes of the 20th century (Figure 5—upper right points; Figure S1). For example, the 1938 hurricane affected 69, 91, and 109 thousand km^2 of New England land area and resulted in 280, 389, and 472 $MMTCO_2e$ of DFC respectively across the three hurricane scenarios (Table 2; Figure S1). Alternatively, the weakest hurricane we included in our analysis, which occurred in 1962, impacted 7, 13, and 23 thousand km^2 of New England land area and resulted in only 9, 20, and 41 $MMTCO_2e$ of DFC, respectively, across the three hurricane scenarios (Table 2; Figure S1).

3.3 | Emissions pathways of downed forest carbon

We estimated the emissions pathways from downed wood in the forest following a hurricane disturbance. This included modeling estimates of the decay of DFC remaining in the forest, as well as using the HWP to model the storage and emissions from the salvaged wood (estimated to be 25% of the total DFC pool). The salvaged wood is initially separated into various carbon pools, based on timber product ratios, and those pools are reconfigured through time based on the lifespans of timber products. Across scenarios, the fraction of DFC in the various pools are similar, given that the same timber product ratios are applied to the model, whereas differences in the pools are due to the composition of DFC (hardwood/softwood and tree height) and the overall magnitude of DFC (Figure S3).

Table 7 and Figure 6 show the carbon pools for key years following the disturbance (0, 30, 50, 100), while Figure S4 shows the continuous trajectory of the carbon pools for 100 years following the disturbance. Figure 7 displays the net emissions and the total stored and emitted DFC across the three scenarios. Immediately following a hurricane (year 0), most of the DFC is remaining in the forest (DFC_s), with 4% of the DFC being emitted without energy capture (EWoEC), and 20% becoming timber PIU (Table 7, Figure 6; Figure S4). After 19 years, the DFC goes from a net store of carbon to a net emission of carbon across all three scenarios (Figure 7), as the DFC_s remaining in the woods starts to decay and becomes emitted (DFC_e), and the PIU carbon begins to be stored as solid waste (SWDS) or is emitted with or without energy capture (EEC & EWoEC; Figure 6; Figure S4). After 30 years, 64% of the total DFC has been emitted (Figure 4) and

TABLE 6 Average impacted area (km^2) by hurricane scenario across Enhanced Fujita (EF) class for New England states.

	Total impacted area		Damaged area by EF class (km^2)			
	km^2	%	EF0	EF1	EF2	EF3
Connecticut (12,933)[a]						
Baseline	8548	66%	3971	3548	935	94
Projected	10,057	78%	3969	4061	1556	471
Max severity	10,969	85%	3444	3953	2666	905
Maine (84,903)						
Baseline	7513	9%	6787	726	0	0
Projected	14,611	17%	12,970	1513	128	0
Max severity	23,300	27%	19,850	3130	320	0
Massachusetts (21,256)						
Baseline	15,048	71%	6474	6705	1870	0
Projected	17,230	81%	5841	7692	3370	327
Max severity	18,390	87%	4908	7582	4825	1075
New Hampshire (24,039)						
Baseline	7453	31%	5524	1915	14	0
Projected	10,709	45%	7451	2915	342	0
Max severity	13,398	56%	8047	4437	913	0
Rhode Island (2846)						
Baseline	2575	90%	630	1432	505	7
Projected	2738	96%	536	1203	713	285
Max severity	2772	97%	328	893	1018	533
Vermont (24,903)						
Baseline	2263	9%	1985	278	0	0
Projected	4369	18%	3721	639	8	0
Max severity	6999	28%	5837	1061	101	0
New England (170,880)						
Baseline	43,399	25%	25,371	14,603	3324	102
Projected	59,713	35%	34,488	18,024	6118	1083
Max severity	75,827	44%	42,415	21,056	9843	2514

[a]Value in parentheses reflects the total area (km^2) for each state/region.

only the longest-lived wood products remain as PIU. After 50 years, 77% of the initial DFC is emitted (Figure 4), with only a small fraction of the DFC remaining in the forest or in SWDS. After 100 years, 88% of the DFC is emitted (Figure 4), with ~9% of the DFC in SWDS.

4 | DISCUSSION

4.1 | A single hurricane can emit decades worth of carbon sequestration by New England's forests

Across the hurricane scenarios, a single storm downs 121–250 MMTCO$_2$e (4.6%–9.4% of total aboveground forest carbon), the impact of which is much greater than the carbon sequestered annually across all of New England forests (15.8 MMTCO$_2$e; Figure 4, Table 5). Across the continental United States from 1980 to 1990, the CO_2 released by hurricane-damaged trees is equivalent to 9%–18% of the forest carbon sink for that period (Zeng et al., 2009). The majority of the impacts occur from a handful of large infrequent disturbances that have the capacity to alter landscapes and affect the net carbon flux (Foster et al., 1998; Zscheischler et al., 2014). For example, Hurricane Katrina in 2005 led to the mortality and damage of ~320 million trees totaling 385 MMTCO$_2$e, the equivalent of 50%–140% of the net annual US forest tree carbon sink (Chambers et al., 2007). In our study, 2 out of the 10 most impactful hurricanes of the 20th century in New England (The Great New England Hurricane of 1938 and Carol in 1954) accounted for 50% of the total aboveground forest carbon downed by hurricanes (Table 2, Figure 5). Under the baseline scenario, without increased wind speeds, the impact of each of those two storms to the region is equivalent to roughly 18 years of the carbon sequestered by New England's forests. The predicted warming of Atlantic basin SST as a result of climate change could strengthen hurricanes (Knutson et al., 2009), leading those two previous hurricanes to each negate

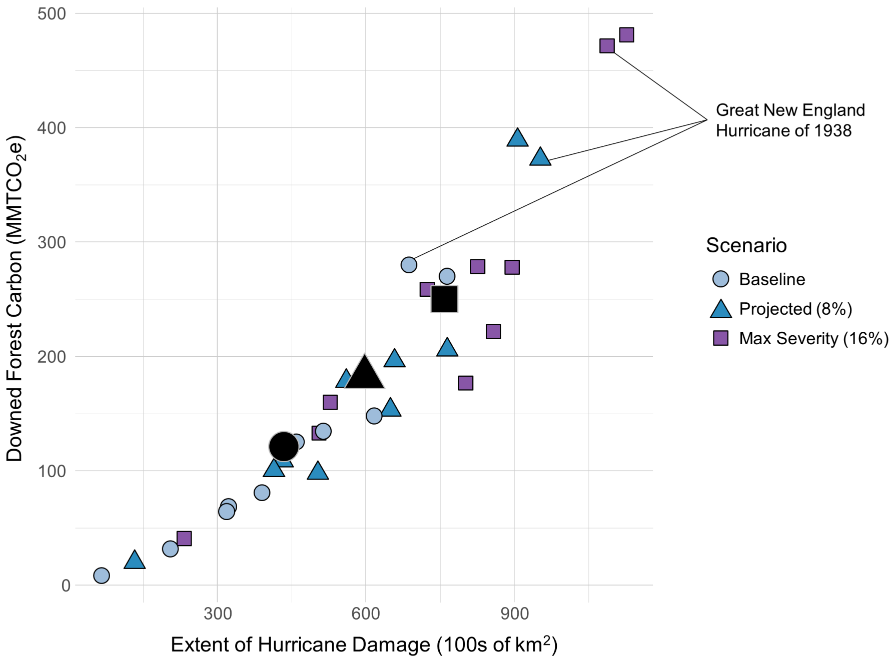

FIGURE 5 Extent of damage and downed forest carbon for the ten hurricanes we modeled across each of the three hurricane intensity scenarios. The points represent a single hurricane under each scenario: baseline (light blue circles), projected 8% wind speed increase (steel blue triangles), and the maximum severity scenario with a 16% wind speed increase (purple squares). The large black points represent the mean values for the 10 hurricanes under each scenario. The 1938 hurricane reconstructions are labeled to show the impact of increased wind speeds on an individual hurricane.

25–30 years of carbon sequestration across our projected and max severity scenarios.

4.2 | Risks to New England forests as a nature-based climate solution

Sequestering carbon in live forest biomass is widely considered as a premier NCS. With New England being one of the most heavily forested regions in the United States, 75% forested by area (Table 4), containing 2660 MMTCO$_2$e of AFC, while also serving as an active carbon sink (Table 5), these forests are critical toward reaching our national and regional climate mitigation goals (Thompson et al., 2020; US Climate Change Science Program, 2014; Wayburn, 2009; Wikle et al., 2021). For example, Massachusetts is relying on the carbon sequestered in its natural and working lands (including forests) to sequester and "offset" up to 15% of its emissions as part of the Commonwealth's Clean Energy and Climate Plan for 2050 (EEA, 2022). New England forest landowners are also participating in the voluntary and compliance carbon markets, albeit only 6.7% of the forest carbon credits sold in California's compliance market are in New England as of 2020 (Kaarakka et al., 2023), but participation in forest carbon offset projects in the region is expected to increase, due to regulatory incentives and reduced participation barriers (Kerchner & Keeton, 2015; Meyer et al., 2022; Pan et al., 2022). However, public perception regarding controversies surrounding the manner in which carbon offsets are calculated and market pressures, such as the current low and fluctuating prices of carbon offsets, may discourage and disincentivize participation in carbon offset markets (Calel et al., 2021; Gifford, 2020; Groom & Venmans, 2023; Haya et al., 2020; Watt, 2021; Zhu et al., 2023). Furthermore, current policies and carbon markets that rely on the land sector do not adequately account for the risks posed by hurricanes.

Using forest carbon as an offset for actualized emissions requires an adequate accounting of risks, to ensure that the forest carbon is additional, verifiable, and permanent (Badgley, Chay, et al., 2022; Roopsind et al., 2019). While there are considerable concerns regarding the actualized additionality and verifiability of forest offset credits, permanence is an exceptionally vulnerable aspect with regard to the viability of using temporary forest carbon pools to offset realized emissions (Haya et al., 2023; Pan et al., 2022). This is partly because a change in forest land ownership could result in altered management practices that remove the "offsetted" carbon, but also because forests are vulnerable to ecological disturbances, such as fires, droughts, biological agents, and catastrophic risks (including severe wind and precipitation), which could result in carbon losses (Hurteau et al., 2009; Ruseva et al., 2017). This is why many regulatory programs have created self-insurance programs to account for natural risks. For example, California's cap-and-trade program, one of the largest regulatory markets for carbon offset credits, has created a buffer pool consisting of 8%–12% of the credit to account for losses from natural risks (California Air Resources Board, 2015). However, 95% of California's buffer pool set aside to mitigate fire risk (2%–4% of all credits) has been depleted in less than 10% of the credits' 100-year commitment (Badgley, Chay, et al., 2022).

The California buffer pool also includes a 3% discount for catastrophic risks like hurricanes, as well as other disturbance agents. Our results suggest that a single hurricane can down 4.6%–9.4% of all AFC in New England, with southern New England forests expected to lose 13.6%–37.6% of AFC, and northern New England forests 1.3%–10.4% of AFC from any given storm (Table 5). Therefore, any single hurricane will likely deplete the buffer pool. With New England experiencing roughly 10 major storms per century, the catastrophic risk buffer pool would need to be increased by 10-30x at a minimum to adequately account for this single disturbance type. This demonstrates that the risk to forest offsets from natural

TABLE 7 Trajectory of DFC carbon as either emitted or stored carbon following a hurricane across each scenario.

Year	Emitted carbon pools[a] ($MMTCO_2e$)				Stored carbon pools[b] ($MMTCO_2e$)				Net emissions	
	EEC	EWoEC	DFC_e	Sum emitted C	DFC_s	SWDS	PIU	Sum stored C	$MMTCO_2e$	% DFC
Baseline										
0	0.3	5	0	5.3	−90.5	−0.9	−23.9	−115.3	−110.1	4.4%
30	10.8	5	60.9	76.7	−29.6	−9.7	−4.7	−44	32.7	63.6%
50	12	5	75.7	92.7	−14.8	−10.3	−2.9	−27.9	64.8	76.9%
100	13.2	5	87.4	105.5	−3.1	−10.6	−1.4	−15.1	90.4	87.5%
Projected (8%)										
0	0.4	7.4	0	7.9	−136.6	−1.4	−35.2	−173.2	−165.3	4.30%
30	15.9	7.4	91.6	114.9	−45.1	−14.3	−6.9	−66.2	48.7	63.40%
50	17.7	7.4	114	139.1	−22.6	−15.1	−4.2	−41.9	97.2	76.80%
100	19.4	7.4	131.7	158.6	−4.9	−15.6	−2	−22.5	136.1	87.60%
Max severity (16%)										
0	0.6	10.4	0	11	−188.2	−1.9	−48.5	−238.6	−227.6	4.40%
30	22	10.4	125.8	158.2	−62.3	−19.6	−9.5	−91.4	66.8	63.40%
50	24.4	10.4	156.8	191.6	−31.3	−20.8	−5.9	−58	133.6	76.80%
100	26.8	10.4	181.4	218.6	−6.8	−21.5	−2.8	−31.1	187.5	87.60%

[a]The emitted carbon pools are as follows: EEC—emitted with energy capture (fuelwood or burned onsite at mills for energy), EWoEC—emitted without energy capture (e.g., decay from SWDS), DFC_e—decay/emissions from downed wood left in the forest.

[b]The stored carbon pools are: DFC_s—downed wood remaining in the forest, SWDS—solid waste disposal sites such as dumps and landfills, PIU—products in use.

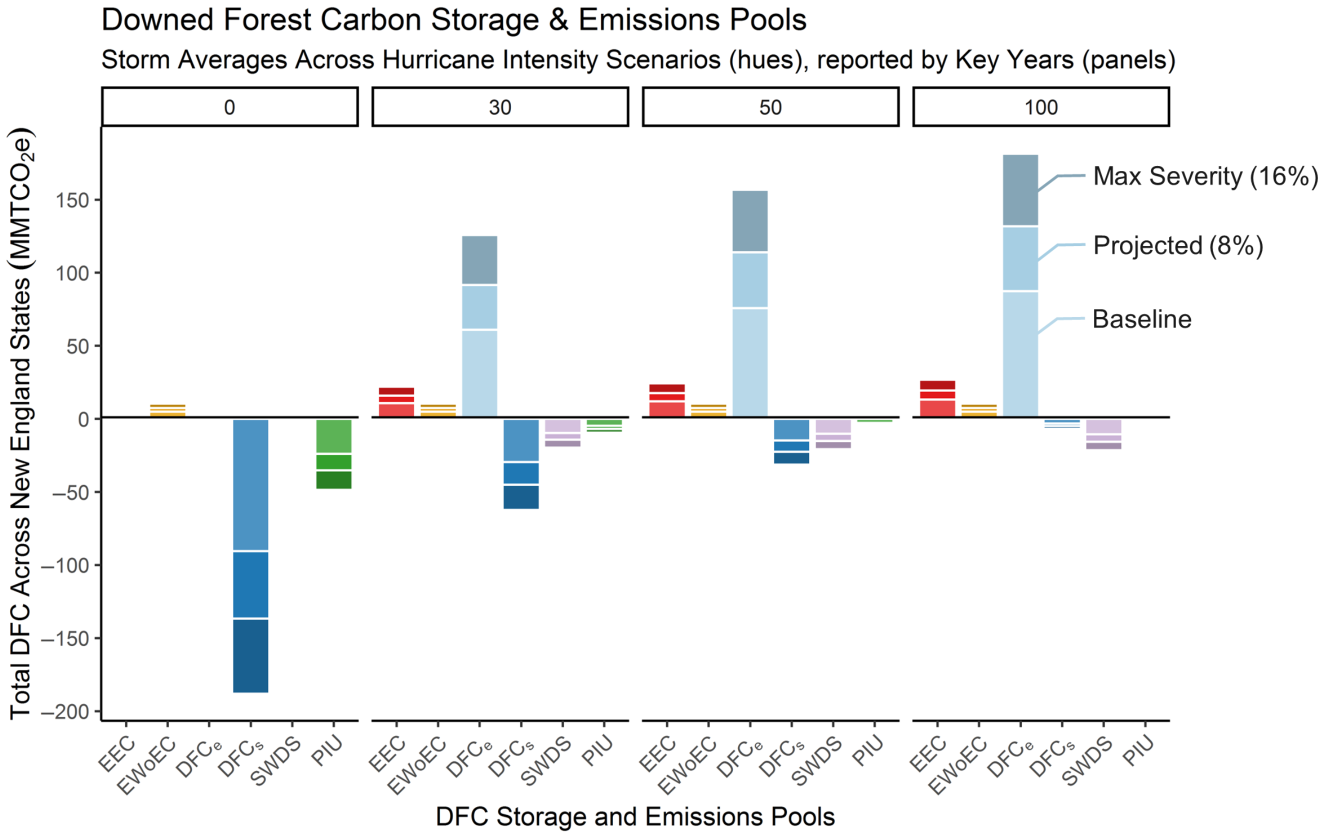

FIGURE 6 Storage and emissions pools of downed forest carbon (DFC) based on the harvested wood products model across scenarios and through time. The *y*-axis is the average hurricane DFC for all of New England in $MMTCO_2e$. Each panel represents certain years post-hurricane disturbance. The bars represent the hurricane wind-intensity scenarios, with the baseline first in the lightest shade, followed by the projected scenario, and the maximum severity scenario in the darkest shade (see callout text in the last panel for example). The bars are cumulative (i.e., the Projected value is the overall height of both the baseline and projected bars). The storage and emissions pools are as follows: EEC—emitted with energy capture (fuelwood or burned onsite at mills for energy), EWoEC—emitted without energy capture (e.g., decay from SWDS), DFC_e—decay/emissions from downed wood left in the forest. DFC_s—downed wood remaining in the forest, SWDS—solid waste disposal sites such as dumps and landfills, and PIU—products in use. Figure S4 displays the continuous trajectory of DFC across the various storage and emissions pools for 100 years post-disturbance.

disturbances is significantly underestimated, thus undermining the permanence and feasibility of using forest carbon to offset carbon emissions.

4.3 | Stronger storms may lead to unprecedented impacts to northern and interior forests

Increases in hurricane wind speeds will likely lead to stronger and farther-reaching impacts. We found that the greatest increase in hurricane-induced forest carbon losses occurs due to the greater spatial extent of higher damage classes (EF2 and EF3). Meteorological predictions estimate that the frequency of category 4 and 5 hurricanes will double by the end of the 21st century, suggesting that these higher impact storms could happen more frequently (Bender et al., 2010). Our hurricane reconstructions and projections found that, respectively, an 8% and 16% increase in wind speeds correspond to a 1066% and 2475% increase in the extent of EF3 level damage (where most trees are likely to succumb from wind-induced mortality). While most of the EF2 & EF3 damage is relegated to southern and coastal New England under the baseline scenario, stronger storms, as projected, will lead to unprecedented northward and inland shifts in high damage classes, affecting heavily forested regions in western Massachusetts and northern New England. Extended land coverage from hurricanes has already been documented, as from the 1990s to 2000s there was a 63% increase in the length of hurricane-related storm tracks over US land areas (Kasischke et al., 2013).

4.4 | Disturbance agents differ in their forest carbon emissions consequences

Emissions from hurricane-induced downed forest carbon are not instantaneous, as it takes roughly 19 years for the carbon to transition from a net storage to a net emission, based on the decay rates of unsalvaged biomass and the lifespan of harvested timber products (Figure 7; Figure S4). Two-thirds of the downed carbon is

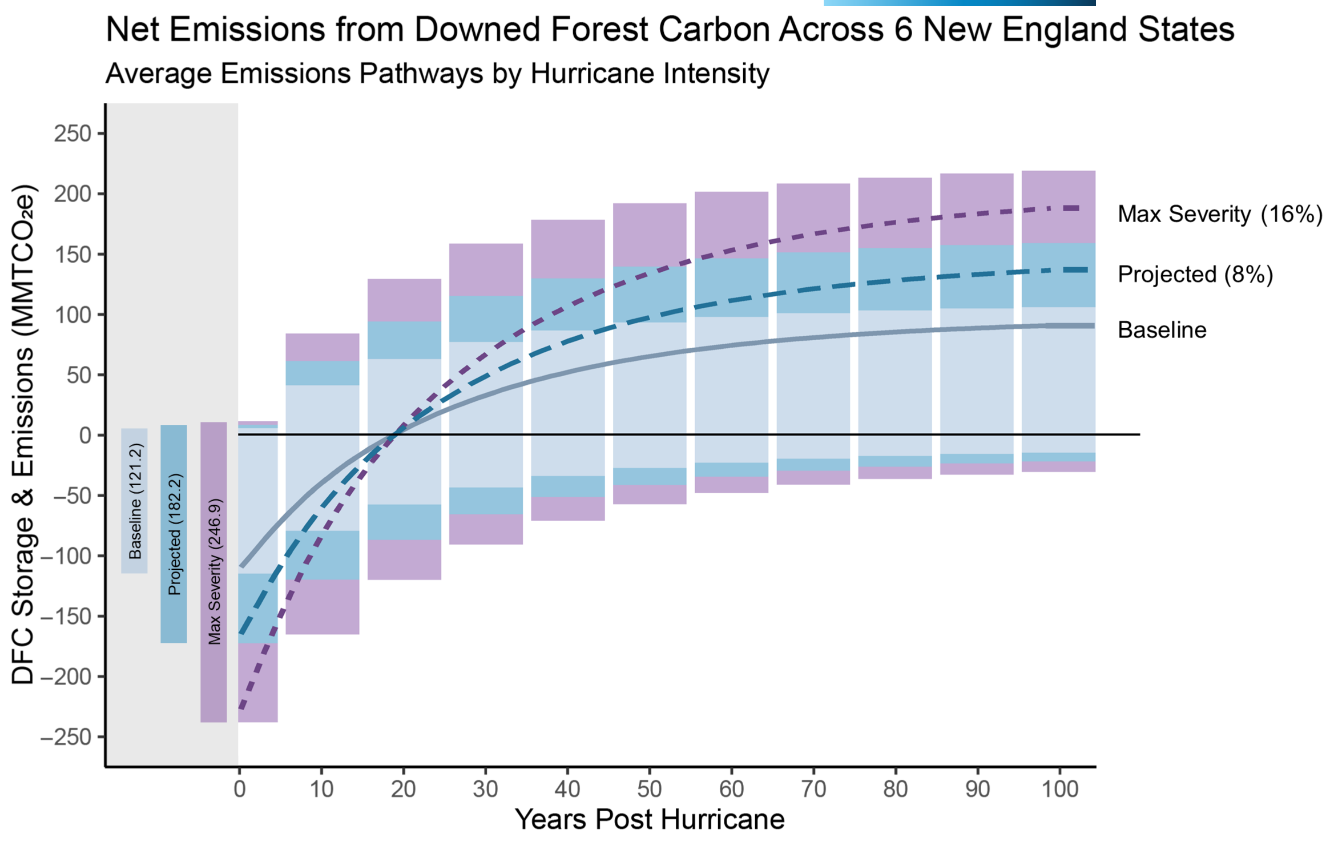

FIGURE 7 Net emissions from downed forest carbon (DFC) across the baseline (light blue, solid), projected (steel blue, long dash), and maximum severity (purple, short dash) scenarios following a hurricane according to the harvested wood products model. The gray region shows the total DFC pool, with the size of the pool in parentheses (MMTCO_2e). The white region shows the trajectory of DFC as either storage (negative) or emissions (positive) pools across the scenarios through time. The bars are cumulative. The lines depict the net emissions (storage + emissions).

emitted after 30 years, 77% after 50 years, and 88% after 100 years (Table 7). Hurricanes differ substantially in their carbon consequences when compared to other disturbance types. For example, most previous research has focused on pyrogenic emissions from wildfires that are emitted relatively instantaneously, and impact not just the live AFC, but can also combust necromass, litter, and soil carbon (Campbell et al., 2007; Chen et al., 2017). In contrast, trees damaged by biotic agents and storms can either decompose in place over longer periods of time or potentially be stored in HWP, all of which would uniquely affect the permanency of the forest carbon and may alter the balance between forests serving as a carbon source or sink (Fisk et al., 2013; Seidl et al., 2017; Zscheischler et al., 2014). The residence time of hurricane-induced DFC left to decompose in the forest can be several decades, with an estimated necromass decay of 90% after 40 years across various temperate forests (Khanina et al., 2023; Vrška et al., 2015). The half-life of downed woody debris in eastern US forests is estimated to be 10 years for hardwoods and 20 years for softwoods (Russell et al., 2014). Additionally, windthrown trees can often survive for a few years, demonstrated by the results of a simulated hurricane, where 90% of windthrown trees survive the first season, with 80% mortality within 6 years, with some trees even resprouting or regrowing after windthrow (Foster & Orwig, 2006). Windthrow events also increase landscape heterogeneity by creating forest clearings and opportunities for the establishment of new species and by creating microsites through pit-and-mound topography from uprooting (Carlton & Bazzaz, 1998; Ulanova, 2000). Furthermore, the influx of necromass following windthrow can increase biodiversity and soil carbon (Franklin et al., 1987; Peterson & Pickett, 1995).

Insect disturbances, similarly to hurricanes, are relevant yet largely neglected in carbon policy discussions in New England. Insect and disease outbreaks can greatly alter the forest carbon balance directly and indirectly, differing substantially from hurricanes and wildfires, which are acute disturbances occurring over brief periods of time (Goetz et al., 2012; Kasischke et al., 2013). Insects/disease affect forests in various and complex ways such as growth and productivity reduction (i.e., defoliation, herbivory, and disease), or they can directly lead to widespread mortality (i.e., bark beetles and pathogens) and reductions in forest carbon stocks (Hicke et al., 2012). These disturbances are difficult to estimate, because a variety of factors determine their impact: number of trees affected, density of targeted trees (insects/disease often impact specific species or groups), type of disturbance agent, the duration of attack, and interactions with biotic and abiotic factors (Hicke et al., 2012). In New England, forests have been impacted by numerous biotic disturbance agents in recent decades, such as hemlock wooly adelgid which has decimated hemlock stands in southern New England, and emerald ash borer which has rapidly spread leading to mortality within a few years of infestation (D'Amato et al., 2023; Ignace et al., 2018; Orwig et al., 2008). Many of the biotic agents in New England target specific species, leading to legacy shifts in forest composition; whereas windthrow indiscriminately impacts large and exposed trees, uprooting roughly 70% of trees (compared with stem breakage), especially trees with unstable soils or root systems, or breaking trees that are more vulnerable to stem failure (Foster & Orwig, 2006).

4.5 | Emissions from downed forest carbon are influenced by salvage efficiency and timber product decisions

The emissions pathways and carbon consequences of hurricane-induced DFC is governed by three processes: (1) the decay rate of biomass left in the forest, (2) the salvage harvest efficiency, and (3) the half-lives of timber products from salvaged biomass. For our study, we assumed a 25% salvage rate based on historical trends and policy goals regarding disturbance responses, and limitations on timber processing, transportation, and storage capacity (Foster et al., 1997; Sanginés de Cárcer et al., 2021; Stanturf et al., 2007). In southern New England, the region most impacted by hurricanes, salvage capacity is incredibly low, as forestry has been declining steadily over the past several centuries. In the late 1930s, Connecticut, Massachusetts, New Hampshire, and Vermont annually harvested about 500 million board feet of timber. The Great New England Hurricane of 1938 downed over 3 billion board feet, or about 70% of the merchantable timber in Central New England; therefore, the hurricane downed 5 years of timber harvests in just 5 h (Long, 2016). This spurred a massive response from the federal government and a previously declining forestry sector, as demonstrated by the rapidly increased number of active sawmills and storage sites for logs salvaged from the hurricane in the region, salvaging more than 1.5 billion board feet of lumber (Foster & Orwig, 2006; Long, 2016).

Would the forestry sector in New England respond at the scale necessary to salvage and process great quantities of timber following a disturbance? Northern New England has a larger forestry sector, but the largest impacts occur in Southern New England. The carbon emissions from salvaged wood products are dependent on the efficiency and products that the wood goes into. DFC used for biomass energy would be emitted rapidly, whereas salvaging timber for use in longer-lived wood products would increase the length of time that the DFC is stored. Therefore, the ability to salvage greater quantities of DFC following a disturbance and to store that carbon in longer-lived goods could decrease the carbon footprint of the disturbance. However, salvage harvests can also drastically alter biogeochemical cycles, leading to abrupt environmental and structural changes due to the disturbance caused by harvesting, whereas forests left to regenerate post-disturbance have been capable of recovering rapidly with low to modest disruptions (Bowden et al., 1993; Foster & Orwig, 2006; Houlton et al., 2003; Patric, 1974).

4.6 | Forest recovery following hurricanes and study limitations

We focused on the fate of New England forest carbon downed by a hurricane. Future research will examine the role of post-hurricane forest recovery on the carbon balance in the region. The impact that tropical cyclones have on the forest carbon balance in the United States is hotly debated. A synthesis of the forest carbon impacts from tropical cyclones across the continental United States from 1851 to 2000 found that tropical cyclones affect roughly 97 million trees per year, leading to an average carbon release of 92 MMTCO_2e year^{-1} from DFC (Zeng et al., 2009). However, forest recovery following tropical cyclones has the potential of exceeding the carbon losses from downed trees, with the net annual flux of recovery potentially accounting for 17%–36% of the US forest carbon sink (Fisk et al., 2013). The net carbon consequences of catastrophic wind events, such as hurricanes, on forest carbon remain unclear due to the difficulty of isolating the source-sink dynamics of the storms from other processes, and the impact that harvest and land-use decisions have on the carbon consequences of disturbances (Goetz et al., 2012; Williams et al., 2012). Future modeling will isolate the impacts that disturbances have on the net carbon balance of forests both immediately following the disturbance and throughout the recovery period.

Additionally, the scope of our study is limited to understanding the impact that any given singular hurricane can have on the current standing aboveground forest carbon stocks of New England. Therefore, there are several factors that could both positively and negatively impact our estimations. One of these factors being that we applied the same initial forest conditions, representing New England aboveground forest carbon stocks circa 2020, to all the storms, and we acknowledge that the amount of forest carbon present can vary temporally. For example, frequent and subsequent disturbances with overlapping geographic extents may have a limited impact if forest carbon stocks are already diminished by previous disturbances. There are several temporal dynamics, such as the frequency of disturbances, that could affect the long-term carbon consequences. However, there are various indications that the carbon consequences of hurricanes we estimated could be relatively conservative for the following reasons: (1) we only consider forest tree carbon stocks, (2) we do not account for belowground carbon stocks, and (3) we only account for damage from windthrow and not from storm surge or precipitation. Regarding the forest-centric approach, forests make-up 75% of New England's land cover, with the remaining 25% being concentrated in the southern and coastal regions where hurricane impacts (especially from storm surge, precipitation, and flooding) are more pronounced (Gori et al., 2022). Tree carbon in non-forested areas is not included in our analyses, neither is non-tree carbon under any land cover type. Second, 20%–50% of temperate forest biomass is belowground (Mokany et al., 2006); however, we are only estimating aboveground forest carbon impacts. Finally, windthrow is only one of the three primary damaging features of hurricanes (rainfall, storm surge, and winds; Stanturf et al., 2007). Storm surge and rainfall can cause tree mortality directly, or compounding effects such as soil erosion, soil saturation, and mass movement, may make trees more susceptible to windthrow (Knutson et al., 2020). While there are various factors deserving of further research consideration with regard to the impacts of hurricanes on forest carbon stocks, such as temporal dynamics, impacts to belowground and non-forest tree carbon stocks, and the effects of storm surge and precipitation, we provide a conservative baseline estimate for the risk to New England aboveground forest carbon stocks from hurricane-force winds.

5 | CONCLUSIONS

Large infrequent disturbances, such as hurricanes, pose a major risk to the permanence of forest carbon stores. Our study of New England, one of the most forested regions of the United States and a significant carbon sink, demonstrates the impacts that hurricanes can have on forest carbon stocks and the risk of forests as NCS. Future research will investigate the recovery dynamics of post-disturbance forests and the long-term carbon balance of forested ecosystems. Here, we show that a single hurricane can emit decades worth of carbon sequestered by forests, with New England hurricanes downing between 4.6% and 9.4% of all aboveground forest carbon in the region across our scenarios. Furthermore, we find that increases in hurricane wind speeds due to the projected warming of Atlantic basin SST could lead to unprecedented impacts both inland and northward into the heavily forested regions of New England.

AUTHOR CONTRIBUTIONS

Shersingh Joseph Tumber-Dávila: Conceptualization; data curation; formal analysis; investigation; methodology; validation; visualization; writing – original draft; writing – review and editing. **Taylor Lucey:** Data curation; formal analysis; methodology; software; visualization; writing – original draft; writing – review and editing. **Emery R. Boose:** Conceptualization; data curation; methodology; software; writing – review and editing. **Danelle Laflower:** Conceptualization; formal analysis; methodology; visualization; writing – review and editing. **Agustín León-Sáenz:** Conceptualization; data curation; formal analysis; methodology; writing – review and editing. **Barry T Wilson:** Data curation; resources; software; writing – review and editing. **Meghan Graham MacLean:** Conceptualization; formal analysis; methodology; software; supervision; writing – review and editing. **Jonathan Robert Thompson:** Conceptualization; funding acquisition; project administration; resources; supervision; writing – original draft; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data and scripts that support the findings of this study are openly available in the Environmental Data Initiative and Harvard Forest Archives at https://doi.org/10.6073/pasta/424e9fd380718bc53a46e17c47b24fb4 reference number knb-lter-hfr.444.2 ([Data set] Tumber-Dávila et al., 2024). The knb-lter-hfr.444.2 data-set includes the data tables and scripts for the analyses in addition to the 30-meter resolution New England aboveground forest carbon rasters. The historical hurricane track and windspeed data that support the findings of this study are available from the US National Hurricane Center's HURDAT2 database (Landsea et al., 2015) at https://www.nhc.noaa.gov/data/#hurdat.

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