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Base-Hurricane: A new extension for the Landis-II forest landscape model

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ABSTRACT

Hurricanes in the southeast United States are infrequent disturbances that affect large areas and have a large effect on forest succession. In order to understand and quantify this effect, we added a new module to the LANDIS-II landscape change model. Focusing on the southeast coast of the United States, we simulated stochastic hurricanes for 50 years. For each simulated storm, the new model extension generates the maximum sustained wind speed over the region and uses the resulting parameter surface to compute maximum sustained wind speed for each cohort cell in a raster grid. Mortality is estimated for each species and age cohort in each cell based on the maximum sustained wind speed, altering forest succession. Results indicate that hurricanes reduce average aboveground biomass by > 20% over 50 years on a landscape in Fort Bragg, North Carolina (USA) compared to a scenario without hurricanes and increased uncertainty of projected succession.

1. Introduction

Forest disturbances cause mortality (Chambers et al., 2007; Hicke et al., 2012), change the direction of succession (Turner et al., 1998), alter ecosystem service delivery (Thom and Seidl, 2016), and create substantial uncertainty that challenges forest management predicated on consistent growth and yield (Kurz et al., 2008). In the southeastern region of United States, hurricanes are an infrequent but catastrophic disturbance that alter forest succession. In the western United States, wildfire and insects (Hicke et al., 2015) cause the most mortality and have recently surged due to climate-change related increases in temperatures and reductions in snowpack (Westerling et al., 2006). In boreal regions, wildfires have been increasing in size and intensity over the past 20 years (Walker et al., 2019). Across the southeastern US, harvesting of saw timber is the dominant source of recurring mortality (Fagan et al., 2018) although hurricanes generate substantial localized mortality. For example, in South Carolina in 1989 Hurricane Hugo damaged 1.8 million ha of forest, an area larger than the state of Connecticut (Hook et al., 1991). In addition, hurricane frequency and intensity (Bender et al., 2010; Bacmeister et al., 2018) may increase as the climate warms, adding additional uncertainty to forest change and management (Dale et al., 2001; Chambers et al., 2007). The effects of hurricanes are similar to that generated by downbursts, derechos, and tornados across the Midwestern and northeastern US (Peterson, 2000; Frelich, 2002; Lucash et al., 2018) although vastly exceeding those events in their spatial extent. Typically, a hurricane that makes landfall in the southeastern US will disturb 50–100,000 km^2 (Foster et al., 1998). Hurricanes play a critical ecological role in maintaining structure, function, and fuel dynamics in longleaf and other fire-dominated coastal systems (Myers et al., 1998; Chambers et al., 2007; Xi et al., 2008a,b; O'Brien et al., 2008; Cannon et al., 2017). Similar to other wind events, the tallest trees are most vulnerable to uprooting or snapping (Boose et al., 1994); interspecific differences also exist although they are less well quantified (Busing et al., 2009; Cely, 1989; Hook et al., 1991; Sharitz et al., 1992; Xi et al., 2008b). Within the zone of hurricane mortality, the effects can vary from near total mortality (for example, the areas adjacent to the landfall of Hurricane Michael in 2018, Beven et al., 2019) to sparse mortality of a few trees per ha. Where mortality is greatest, there will be a loss of economic value (Haight et al., 1995), long-term release of forest carbon as dead trees decay (McNulty, 2002), and changes to long-term successional trends. For example, if a site is dominated by conifers with a hardwood understory – a common situation where fire has been excluded for extended periods in the southeast (Glitzenstein et al., 2003) – moderate hurricane winds may accelerate succession towards hardwood dominance. On the contrary, if a site dominated by shade-intolerant conifers experiences near total mortality, conifers will likely reestablish given high light conditions.

We developed a hurricane model (the Base Hurricane extension) that

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is an extension to the landscape change model, LANDIS-II (Scheller et al., 2007) to incorporate the simulation of hurricane wind mortalities into LANDIS-II. Our goal was to forecast long-term interactions between forest, disturbance, and prescribed fire across large extents. Previous work has emphasized fine-scale interactions of hurricanes and forest mortality (Boose et al., 1994). We therefore developed a model of hurricane mortality and hurricanes effects that interfaces with existing models of succession, management, and other natural disturbances (e.g., insect mortality). We focused on Ft. Bragg, North Carolina, as it is broadly representative of southeastern forests, falls within the zone of hurricanes, and forest managers are concerned about the potential for hurricanes to interfere with their long-term management goals. Fort Bragg is a US Army military reservation in the sandhills region of North Carolina. A US Commerce Department shapefile indicates the area of the base is 61,728.4 ha. The raster model used in this research included 45, 947 ha of forested area.

2. Methods

First, we describe the conceptual hurricane model. Next, we describe how the model was specifically parameterized for our study area.

2.1. Conceptual hurricane model

Base Hurricane is a new extension to the landscape change model which simulates stand-level mortalities due to hurricane wind forces. In this context, ‘Base’ indicates that this extension is compatible with all other extensions. LANDIS-II simulates succession, disturbance, and management across large and heterogeneous landscapes, typically 50,000–5,000,000 ha in size. Incorporating our hurricane model into an existing model of succession, disturbance, and management allows us to leverage prior efforts to integrate multiple processes across a landscape (e.g. Scheller et al., 2011; Lucash et al., 2018; Serra-Diaz et al., 2018). All of our code is open-source (https://github.com/LANDIS-II-Foundation/Extension-Base-Hurricane).

LANDIS-II represents trees and shrubs on the landscape as species-age cohorts, not individual trees. Each cohort represents multiple individual trees and typically has other associated attributes. The landscape is represented as a grid of spatially-interacting cells. Each cell can contain one or more cohorts with an unlimited number of species. The processes of succession, disturbance, and management interact through their effects on cohort composition within each cell.

The Base Hurricane extension runs on an annual time step in which it randomly determines the number of storms that make landfall on the southeastern coast of the US for that year. This hurricane count is in the range 0 to n where n may be adjusted by the user. For our simulations we used a maximum of 3 hurricanes per year.

The location of each storm is controlled by three parameters: landfall latitude, storm track direction, and maximum sustained wind speed at landfall. For each storm, the particular value of each of these three is set from a random number generator. Landfall latitude is the latitude along the coast line where the storm makes landfall (See Fig. 1.). Storm Track direction is an azimuth value between 280 and 360°. Maximum sustained windspeed at landfall is determined from a Log-Normal distribution as shown in Fig. 4. The geometry resulting from these three parameters define the parametric surface of maximum sustained wind speed (MSWS) (See Fig. 7.). Base Hurricane then computes MSWS for each site in the study area, treating the entire duration of the event as a single moment in model time. Mortalities are generated stochastically for each raster cell based on the maximum sustained wind speed of the site (see below). One may consult the Base-Hurricane user guide for complete explanation of all user parameters (https://github.com/LANDIS-II-Foundation/Extension-Base-Hurricane/blob/master/docs/LANDIS-II%20Base%20Hurricane%20v0.1%20User%20Guide.docx).

For any given location within a hurricane impact area, surface wind speeds vary over the duration of the event in both sustained wind speed

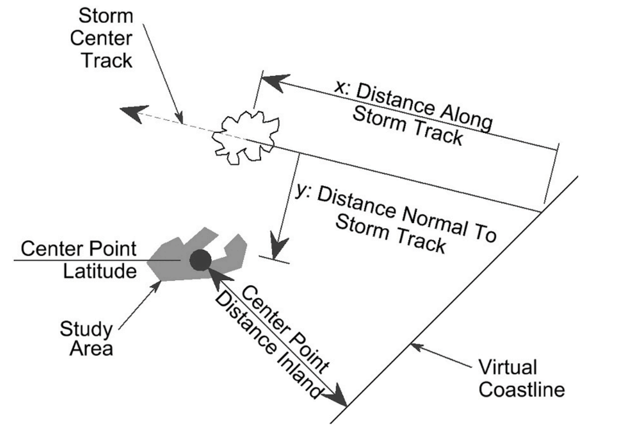

Fig. 1. Schematic of geographic relationship between a simulated hurricane and the study site. The value labeled “x" is “x" in Equation (1) and “Distance from Landfall” in Fig. 2. The value labeled “y" is the distance from the storm center perpendicular to the storm track and serves as “x" when Equation (1) is applied to the perpendicular equation.

and gust speed. A storm whose center passes two hundred kilometers away from a location may potentially cause mortality. Given these factors, we elected to represent the wind field as a parametric surface representing MSWS over the duration of the storm. Wind-induced mortality is computed as a function of the MSWS, cohort age (older cohorts are taller and therefore more vulnerable), and species (some species are more vulnerable than others). Maximum wind gust and duration of exposure are included implicitly in the species mortality table (Table 3) without being explicitly modeled. This approach reduces computation time compared to a more precise model, e.g., Boose, et al., 1994.

Specifically, actual historic MSWS is available in the HURDAT2 dataset, but hectare-scale maximum wind gusts are not. As the present model is stochastic and not deterministic, we elected to model overall probability of mortality with a single random number comparison. Where a hurricane strikes, we anticipate the structural resistance of the soil to overturning is reduced by rainfall saturation for all scenarios. Likewise, where there is a given maximum sustained wind speed, wind gusts will be approximately 25%–35% higher. Yet gust direction and length have not been researched and modelling them is not in our scope. The general effect is that high winds blow trees down. We have synthesized all of these factors to simplify our model in a way which we believe does not reduce accuracy over a large area simulated with a computerized random number generator.

The Base Hurricane extension simulates the MSWS at the center of the storm track. The storm track direction is modeled as a straight line at a random azimuth direction proceeding inland from the shoreline. The distance from the storm track to the study site is determined from landfall latitude and track direction for each hurricane simulated (Fig. 1).

The coastline is represented as linear with a fixed axis. After a storm makes landfall and moves inland, MSWS at the center of the storm declines over distance along the storm track as well as perpendicular to the storm track. This creates a ‘wind field’, the geographic distribution of the MSWS relative to the storm track. We used the second derivative of the hyperbola, as shown in Equation (1) to estimate the MSWS centerline profile.

$$MSWS = \frac{a^2(S_L - S_b)}{(a^2 + x^2)\sqrt{\frac{x^2}{a^2} + 1}} + S_b \qquad \text{Eq 1}$$

where MSWS is the maximum sustained wind speed along the center track (km hr^{-1}), $a/2$ is the distance from landfall to the inflection point of the profile curve (km); x is the track distance from landfall (km), S_b is

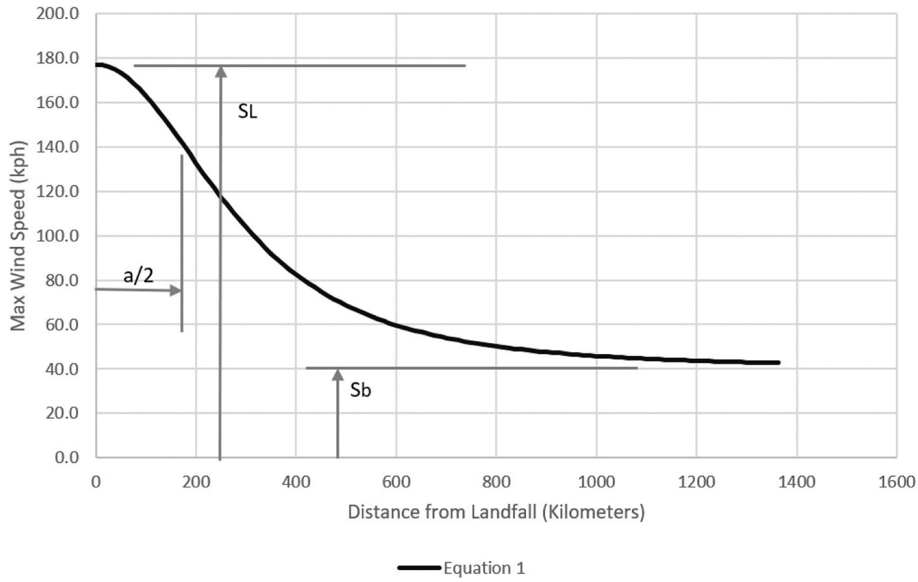

Fig. 2. Plot of Equation (1), MSWS versus x, showing graphic interpretation of *a*, S_l, and S_b. *a*/2 is the inflection point of the equation and originates with the equation for a hyperbola, which is the second integral of Equation (1).

Table 1
Number of years where 0 through 3 Tropical Cyclone Landfalls occurred along the coast of Georgia, South Carolina, North Carolina, and Virginia from 1969 to 2018 from HURDAT2.

Number of Occurrences	Count of Years	Percentage
0	29	58%
1	16	32%
2	5	10%
3	0	0%

Table 2
Input values for Equation (1) used to fit Hurricane Katrina from the HURDAT2 database.

Parameter	Value
a	367 km
Sb	40 kph
SL	177 kph

the wind speed at final reading (km hr^{-1}), S_L is the maximum sustained wind speed at landfall (km hr^{-1}). The profile shown in Fig. 2 represents MSWS along the line in Fig. 1 labeled "x: Distance Along Storm Track."

To represent a parametric field surface over a region, we also modeled maximum sustained wind speed perpendicular to the storm track again using Equation (1). For the cross section, i.e., wind speeds perpendicular to the center, S_L is taken from MSWS along the centerline from equation (1). Because Atlantic hurricane wind speeds are asymmetrical, the wind speed decline as a distance from center differs on the left and right sides of the hurricane (relative to their primary direction). This is expressed as differing values of *a* for the left and right sides; while *x* represents the distance from the centerline (or *y*, in Cartesian space). The combination of equations produces a parametric surface of the maximum sustained wind speed over the duration of the event. The resulting parametric surface is oriented with the x-axis following the storm track with its origin at the landfall location. The y-axis of the parametric surface is perpendicular to the storm track (See Fig. 1).

After sustained wind speed is calculated for each raster cell for each hurricane, the final step is the determination of mortality of tree species by age. Each tree species and each cohort age (binned into user-specified age ranges) is assigned a probability of mortality given the wind speed as set by the user in Table 3. The model MSWS is computed according to location using Equation (1) in "x" and again in "y" (See Fig. 1). This probability is compared against a random number generated for each cohort. If a cohort is selected for mortality, the entire cohort is killed; partial mortality of an individual cohort is not modeled.

2.2. Parameterization for the southeastern US

Our study landscape is located in southeast North Carolina approximately 90 km from the Atlantic coast. Fort Bragg is dominated by longleaf pine (*Pinus palustris*), loblolly pine (*P. taeda*), and contains hardwoods (*Quercus* spp., *Liquidambar styraciflua*, *Lirodendron tulipifera*) and shortleaf pine (*P. echinata*). Ft. Bragg is an active military base with large areas directly affected by training exercises, including tank maneuvers and shelling. In addition, Fort Bragg is carefully managed with scheduled prescribed fire and harvest rotations. Forested areas are managed for red-cockaded woodpecker (RCW, *Dryobates borealis*) habitat, a federally listed endangered species. RCW prefers older longleaf pine for nesting (Hooper et al., 1995) and therefore Ft. Bragg natural resource managers actively encourage this habitat. Due to their proximity to the coastline, forests in this region are susceptible to incurring high mortality if a hurricane passes over or close to them. Therefore, RCW habitat inside Fort Bragg's limits is vulnerable to hurricanes.

We simulated hurricanes on a baseline maps of 100 × 100 m cells (1 ha each) across Fort Bragg for 50 years from 2019 to 2069. The baseline map consisted of species composition and species' age at a resolution of 1 ha by imputing FIA data from North Carolina, South Carolina and Virginia onto a land cover map provided by FBDPWED. Since the FIA database contains diameter and height for each tree, but not tree age as required for cohort simulation, We used site index curves to calculate age for every tree in the FIA database for VA, SC and NC. We also added old growth longleaf and loblolly pine to the landscape based on the maps of old pines provided by FBDPWED.

In addition to the new hurricane extension, we simulated forest succession and disturbance with the NECN extension (v6.2) to simulate forest succession (Scheller et al., 2011), the Biomass Harvest extension (v4.3) to simulate harvesting (Gustafson et al., 2000), and the SCRPPLE extension (v2.3) to simulate prescribed fires (Scheller et al., 2019). Growth rates in NECN were calibrated to Forest Inventory and Analysis (Bechtold, Patterson, 2005) data for plots in North Carolina, South Carolina and Virginia (Lucash et al. in review). Simulated harvesting

Table 3
Age, wind speed, and mortality data summarized from empirical sources for tree species common to Ft. Bragg, NC. Age bins are represented in the table by the maximum value; thus the second data row with a Maximum Age of 60 is the lookup row for cohorts >30 and≤60 years. Under Mortality Probabilities, the wind minimum wind speed is left of the colon, and the probability of mortality is right of the colon.

Tree Species	Maximum Age (yrs)	Mortality Probabilities (wind speed [kph]: mortality probability)				Source
Loblolly Pine	30	96.6:0.05	120.7:0.18	177:0.75	225.3:1.0	1,2,3
Loblolly Pine	60	96.6:0.1	120.7:0.23	177:0.75	225.3:1.0	1,2,3
Loblolly Pine	999	96.6:0.1	120.7:0.29	177:0.75	225.3:1.0	1,2,3
Longleaf Pine	30	96.6:0.05	120.7:0.18	177:0.75	225.3:1.0	1
Longleaf Pine	60	96.6:0.1	120.7:0.23	177:0.75	225.3:1.0	*
Longleaf Pine	999	96.6:0.1	120.7:0.29	177:0.75	225.3:1.0	*
Short Pine	30	96.6:0.05	120.7:0.18	177:0.75	225.3:1.0	1
Short Pine	60	96.6:0.1	120.7:0.23	177:0.75	225.3:1.0	*
Short Pine	999	96.6:0.1	120.7:0.29	177:0.75	225.3:1.0	*
Slash Pine	30	96.6:0.05	120.7:0.18	177:0.75	225.3:1.0	1
Slash Pine	60	96.6:0.1	120.7:0.23	177:0.75	225.3:1.0	*
Slash Pine	999	96.6:0.1	120.7:0.29	177:0.75	225.3:1.0	*
White Oak	20	96.6:0.01	120.7:0.05	152.9:0.45	177:1.0	1,3
White Oak	60	96.6:0.01	120.7:0.10	152.9:0.55	177:1.0	1,3
White Oak	999	96.6:0.1	120.7:0.30	152.9:0.65	177:1.0	1,3
Turkey Oak	20	96.6:0.01	120.7:0.05	152.9:0.45	177:1.0	1
Turkey Oak	60	96.6:0.01	120.7:0.10	152.9:0.55	177:1.0	**
Turkey Oak	999	96.6:0.05	120.7:0.30	152.9:0.65	177:1.0	**
Sweet Gum	20	96.6:0.01	138.4:0.06	177:0.45	225.3:1.0	1,2,4
Sweet Gum	90	96.6:0.01	138.4:0.06	177:0.45	225.3:1.0	1,2,4
Sweet Gum	999	96.6:0.01	138.4:0.06	177:0.45	225.3:1.0	1,2,4
Red Maple	20	96.6:0.01	138.4:0.06	177:0.45	225.3:1.0	1,3
Red Maple	90	96.6:0.01	138.4:0.06	177:0.45	225.3:1.0	1,3
Red Maple	999	96.6:0.01	138.4:0.06	177:0.45	225.3:1.0	1,3
Tulip Tree	30	96.6:0.1	120.7:0.50	177:0.833	225.3:1.0	1
Tulip Tree	50	96.6:0.1	120.7:0.80	177:0.833	225.3:1.0	1
Tulip Tree	999	96.6:0.1	120.7:0.80	177:0.833	225.3:1.0	1

1. Hook et al., 1991, 2. Sharitz et al., 1991, 3. Xi et al., 2008, 4. Cely 1989.
*Estimated from loblolly pine. **Estimated from white oak.

(thinning and removal of slash pine followed by replanting with longleaf) and prescribed fires were calibrated to match the spatial, temporal, and target species as indicated by current forest management plans (Ft. Bragg Natural Resources Division, *personal communication*). Slash pine was removed at 0.25% every year for the next 20 years and 1500–2000 acres of thinning was performed annually. Approximately 450 prescribed fires occur on Fort Bragg each year. Across the landscape, prescribed fire return intervals vary between one to three years.

To parameterize the new hurricane extension for our study, we first determined how many storms occur in a given year on the east coast of the United States. We only included storms that made landfall on the east coast from 30.7° N to 38.45° N, which includes the coast from Georgia to Virginia and that have a reasonable likelihood of causing forest mortality on our landscape. The coastline was represented as a straight line with a heading of 45° to approximate the southeast coast of the United States. To determine the historic landfall incident counts per year and the historic percentages of storm wind speed at landfall, we used the National Hurricane Center's Best Track Data (HURDAT2: https://www.nhc.noaa.gov/data/#hurdat). HURDAT2 contains data for all tropical cyclones in the Atlantic basin since 1851; HURDAT2 data were recorded every six hours and include location (latitude and longitude of the center of the eye), MSWS (knots), central pressure (millibars), and wind field size (in nautical miles from the center). We processed the HURDAT2 data using Python (see https://github.com/PaulSchrum/Hurdat2FC).

We estimated the number of storm occurrences per year using the HURDAT2 dataset, from 1969 to 2018 occurring on the coast of Georgia, South Carolina, North Carolina, and Virginia, approximately 1125 km of coastline. Only storms with landfall wind speed greater than or equal to 80 kph (43 knots) were included in the count. We selected 80 kph based on our judgement for the minimum speed that would generate wind-induced mortalities. This value is slightly less than the minimum MSWS for mortality as found in Table 3. For the period, the number of occurrences in a given year varied from 0 to 2 (Table 1).

We also estimated the maximum recorded storm center MSWS for the lifetime of the storm and the size of each storm. We then determined the statistical distribution of maximum sustained wind speed of storms at landfall restricted to this range. Finally, we characterized the wind field size to facilitate parameterization of our suitable maximum sustained wind field model.

The latitude of simulated storms varied from 30.7° to 38.45° and was generated using a uniform random number generator. The storm track direction was simulated from a random azimuth direction between 280° and 360° using a uniform random generator. Maximum Sustained Wind Speed at Landfall (S_L) was determined stochastically. We estimated S_L by comparison against the actual distribution of historic landfalls. Using the HURDAT2 dataset, we looked at all tropical storm landfalls on the east coast from Georgia to Virginia from 1971 to 2018 (the period of record with the most complete data). We found 26 storms by these criteria and plotted the count of storms that made landfall at given wind speeds (Fig. 3).

We fit a lognormal distribution to these data. When Base Hurricane stochastically determines S_L for each individual hurricane, the distribution is scaled and translated via minimum, maximum, and mode wind speeds (Fig. 4).

We parameterized the distribution of hurricane wind speeds along a storm centerline track from the southeast US based on Hurricane Katrina (2005) from the HURDAT2 data (Fig. 5).

Although Katrina did not make landfall on the east coast, we selected it because it is recent enough that the HURDAT2 data for the wind field was complete. By contrast, Hurricanes Hugo (1989) and Fran (1996) affected our landscape but occurred at a time when the wind field values away from the centerline track were not included in the database.

We elected to use Katrina and Sandy as exemplar hurricanes for parameterization. We used Katrina for the lateral parameterization because Katrina and Sandy were the only storms with straight paths in which the HURDAT dataset also included the wind field information. We set the values for a in Equation (1) according to Katrina, then compared to Sandy and found similar results. We determined parameters to equation (1) (Table 2) to approximate the Katrina centerline MSWS

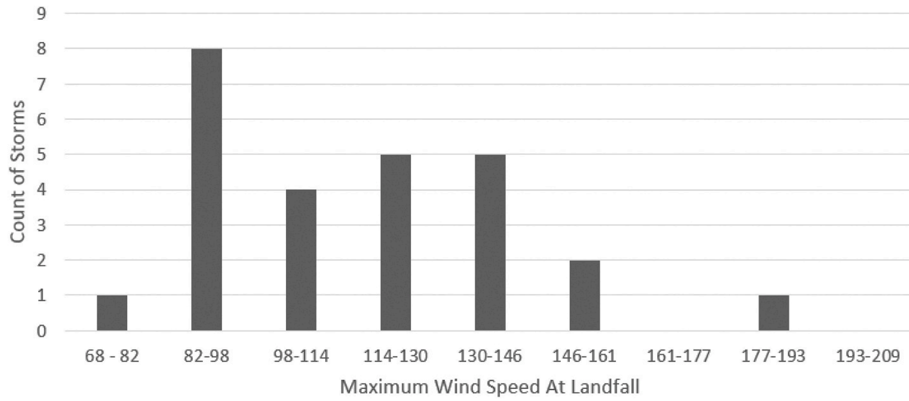

Fig. 3. Count of storms by landfall wind speed, estimated from tropical cyclone landfalls along the coast of Georgia, South Carolina, North Carolina, and Virginia from 1969 to 2018.

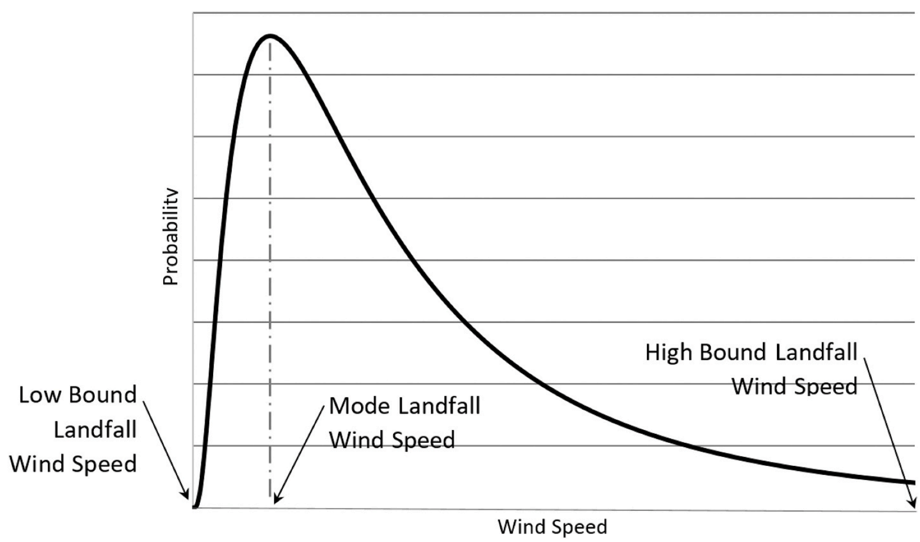

Fig. 4. Probability Density of the Log-Normal Distribution, used for randomly generated landfall wind speed values. The three values labeled here are the user input which allows the user to control landfall likelihoods of MSWS at Landfall. Image modified from https://wiki.analytica.com/images/d/d9/LogNormal%28median%3D3%2Cstddev%3D2%29.png.

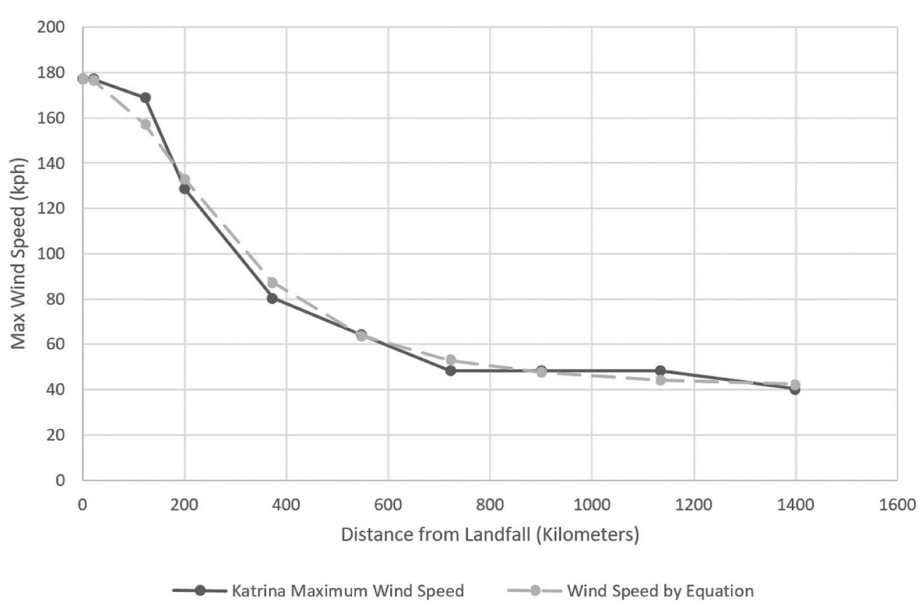

Fig. 5. Maximum Sustained Wind Speed versus distance inland for Hurricane Katrina 2005 (centerline) with the Wind Speed Equation.

values (Fig. 5). We sets values for a and Sb that were used for all hurricanes. We also used Hurricane Katrina to determine a-values lateral to the storm track because the HURDAT2 dataset contains wind field extents for this hurricane that are not present other recent hurricanes.

For each sampled point for Hurricane Katrina, we plotted the wind speeds to the left and right of the centerline. We developed wind speed profiles perpendicular to the storm track (Fig. 5) and found that those profiles have characteristics similar to Equation (1). Based on this study, the MSWS extends perpendicular to the storm track direction of Katrina were higher for a on the right side of the storm (240 km) than on the left (162 km). The profile of Katrina's maximum sustained wind speed plotted against its distance inland follows a logarithmic decline approaching an asymptote. We compared these equations and parameters to historic values found in the HURDAT2 database for hurricanes Katrina, Hugo, and Fran (Fig. 6).

When a simulated storm is spawned, landfall latitude, storm track direction, and S_L are stochastically generated, and the MSWS field is determined by the wind speed equation (Equation (1)). Thus MSWS values are computed according to the geographic location of each cell relative to the storm track, and cohort mortalities are simulated based on the MSWS of each cell. To illustrate how the parametric surface relates to the landscape, we estimated the wind speed parameter field set to the values for Hurricane Hugo (Fig. 7).

The Base Hurricane extension uses an input table (Table 3) to determine cohort mortality probabilities. Cohort mortality probability was binned according to species and age and wind speed. We derived mortality estimates (by species, age, and wind speed) from empirical data (Busing et al., 2009, Cely, 1989, Hook et al., 1991, Sharitz et al., 1992; Xi et al., 2008b). Where species data were missing, we used taxonomic analogs, e.g., substituting sugar maple to estimate sweetgum mortality risk given their similarities. Cohort mortality includes all causes of death, including snapping, uprooting, neighbor-tree falls, and delayed mortality. We did not include experimental studies of tree mortality vulnerabilities (e.g., Garms and Dean, 2019) because winching studies do not capture the structural fatigue due to storm-duration stress, micro-bursts (e.g., isolated tornados), and soil saturation.

3. Results and discussion

Previous research has focused on hurricane effects on local diversity (Xi et al., 2008, 2019), singular hurricane effects (Zimmerman et al., 1995; Busby et al., 2008), or simulated localized hurricane wind speeds without forest mortality (Boose et al., 2004). By contrast, our objective was to simulate many hurricanes over a broad extent and duration within a modeling framework that also integrates other disturbances and management.

Our simulations demonstrate the substantial effects and large stochastic variation of hurricanes on tree biomass (Fig. 8).

At the start of the simulation, average aboveground live biomass (AGB) across the Ft. Bragg landscape was 5700 g m^{-2} The baseline scenario (no hurricanes) resulted in a 400% increase in average AGB, to 21,600 g m^{-2}, over 50 years. Simulated hurricanes across the landscape resulted in average AGB of 16,800 g m^{-2} at the end of the 50-year simulation (Fig. 9). In addition, there was a strong legacy effect of simulated hurricanes. That is, AGB never fully recovered back to no-hurricane scenario levels on average, though two simulations with early hurricanes did come close to recovering to the baseline scenario before the end of the fifty years.

There is also an effect on the distribution of species at the clade level between AGB of conifers versus angiosperms. In the baseline scenario, AGB is 95.6% conifer with the remainder being angiosperms and increases to 96.8% over the 50 year span of the model. When simulations are run to include hurricanes, the average conifer ABG decreases to 93.7% (Fig. 10).

Simulated hurricanes altered the ratio of coniferous and angiosperm AGB in favor of angiosperms due to their lower probability of hurricane mortality with conifers declining from ~95% dominance to ~93%. Although this particular landscape is intensively managed for RCW habitat, and therefore large deviations in successional trajectories are limited, we would expect neighboring areas that are unmanaged to experience larger shifts in forest composition and structure after hurricanes (Zimmerman et al., 1995).

Hurricanes substantially increased overall model ABG variability. Whereas the baseline scenario was essentially deterministic (simulated fires and harvest instances follow a proscribed schedule and species are broadly intermixed, minimizing stochastic variation due to seed

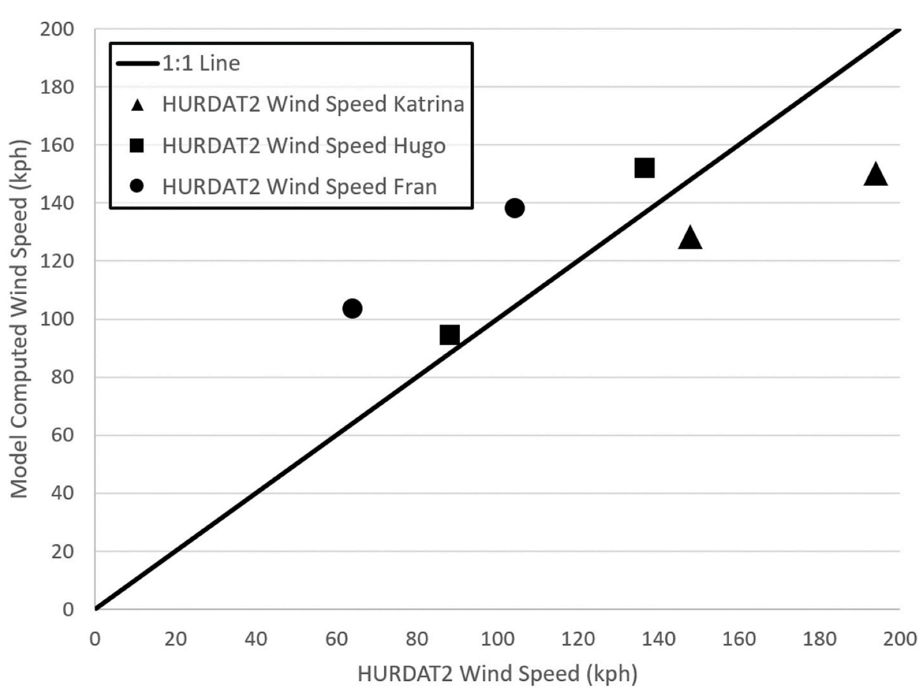

Fig. 6. Comparison plot of Wind Speeds showing HURDAT2 values against Model computed values.

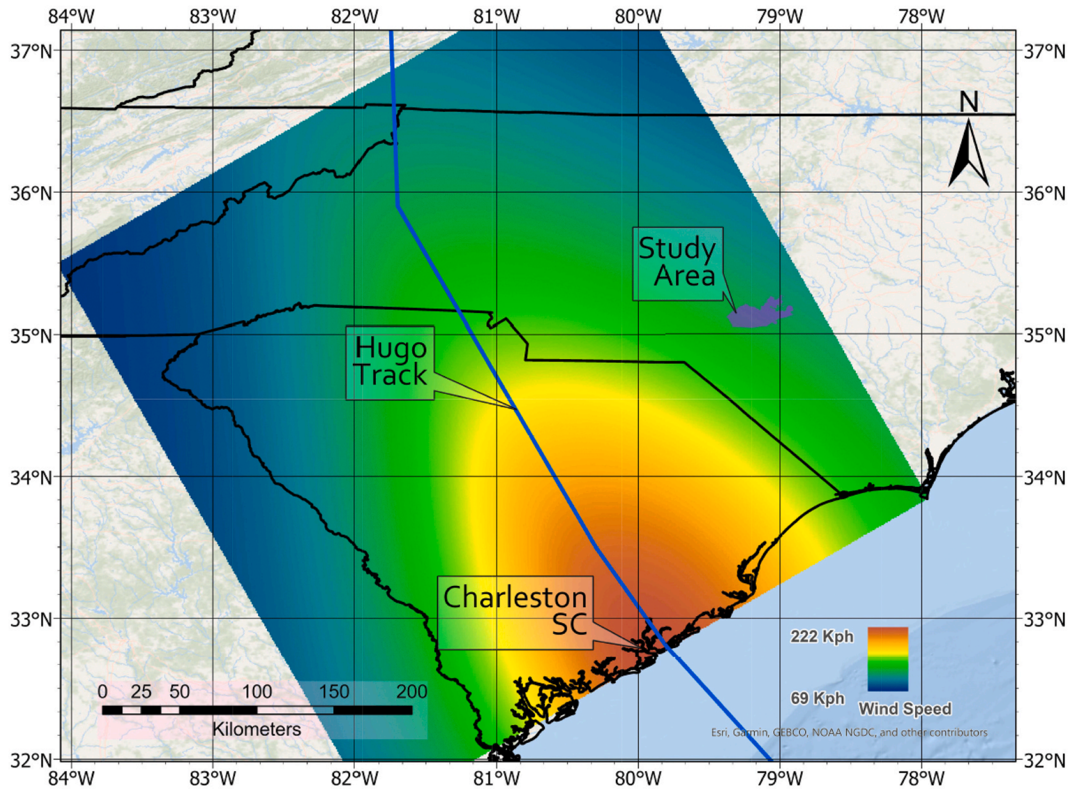

Fig. 7. Maximum Sustained Wind Speed map approximating Hurricane Hugo, which made landfall near Charleston, SC in September 1989. Only a 500 km × 500 km area calculated. The study area, Fort Bragg, NC, is indicated for reference.

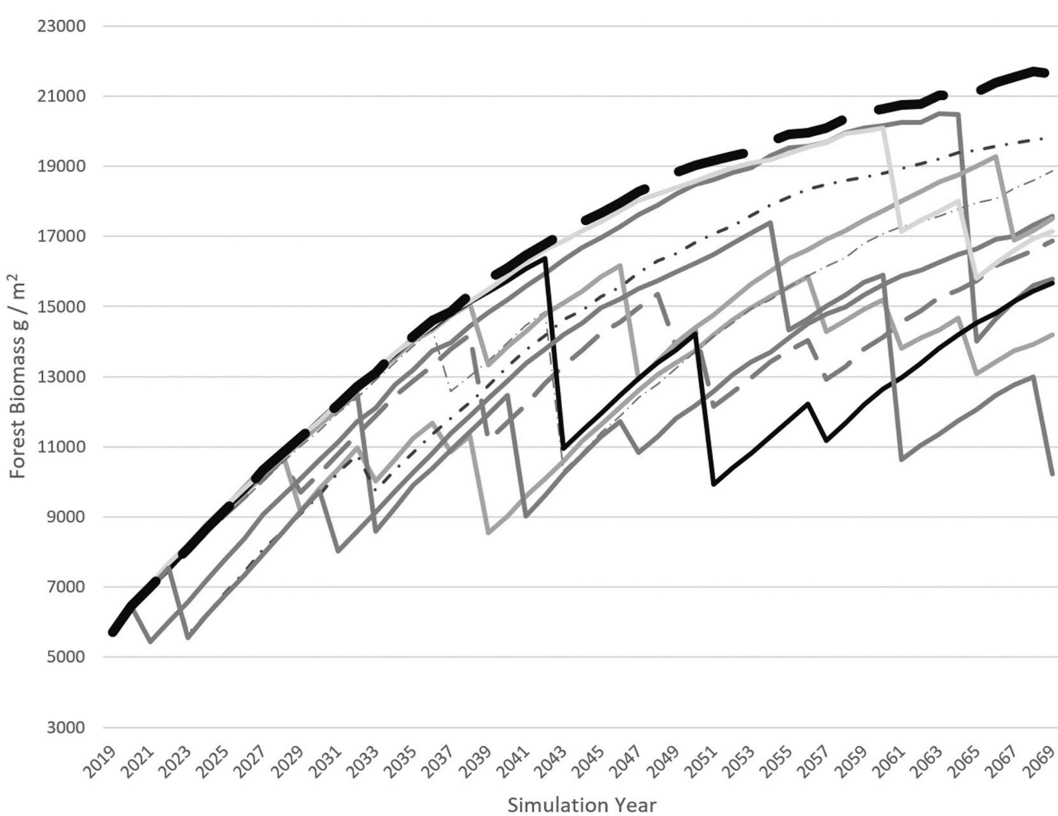

Fig. 8. The effect of simulated hurricanes on average aboveground biomass across Ft. Bragg, NC. The dark dashed line represents a baseline scenario with no hurricanes. Other lines represent 10 replicates of the hurricane simulation.

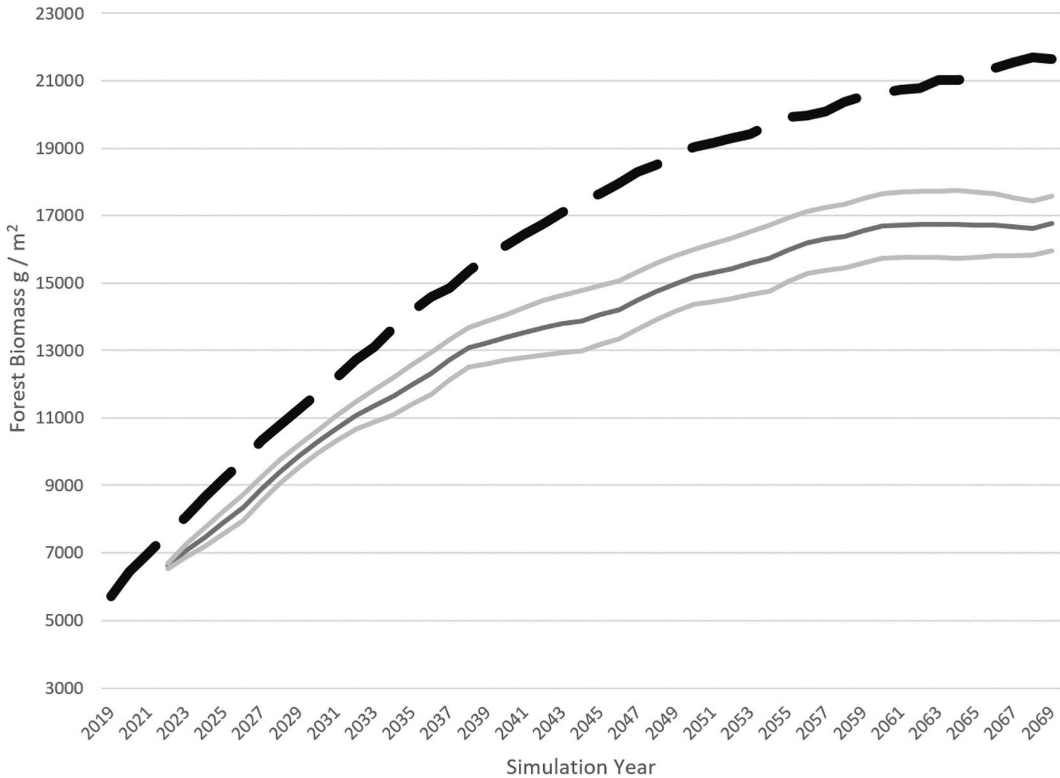

Fig. 9. Four-year moving average of Aboveground Biomass across Ft. Bragg, NC, from 10 replicates of the hurricane simulation. The dashed black line represents a baseline scenario with no hurricanes. The solid black line is the four-year moving average of all ten replicates. The gray lines are the four-year moving average of the 95% confidence interval.

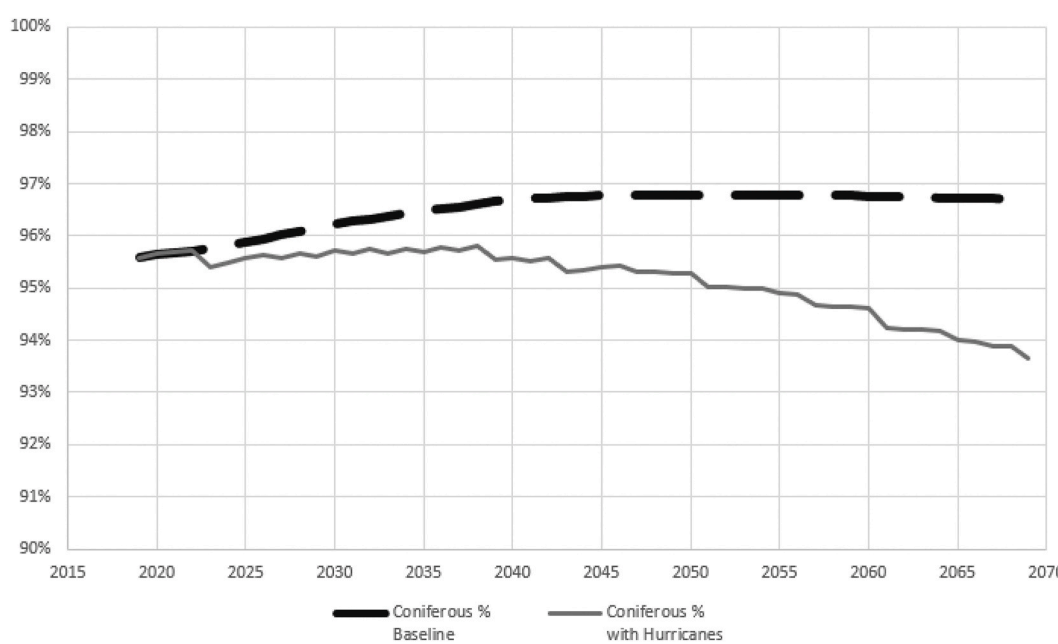

Fig. 10. Percent of Aboveground Biomass embodied in coniferous species for the baseline scenario and for the 10 replicates.

dispersal), the simulation with hurricanes highlight larger inherent variability of final ABG. In addition, the new extension adds further parameter uncertainty, which is exacerbated by uncertainty in climate change effects on hurricane frequency and intensity (Walsh et al., 2016). There will also be many subsequent effects and uncertainties not explored here: variation in RCW habitat; variation in fuel loading that would likely alter prescribed burning planning. Extrapolated to the broader southeastern US, there are large economic implications for any given hurricane (Haight et al., 1995) and these effects will be cumulative over time. Given this uncertainty, land managers may be motivated to shorten harvest rotation times to minimize economic risks (Reed, 1984). As climate change amplifies hurricane frequency and/or intensity, these effects may increase (Webster et al., 2005, but also see Walsh et al., 2016), and these potential consequences should be evaluated as landscape change model, such as LANDIS-II, offer the possibility to include climate scenarios in simulations."; a future manuscript will explore these potential consequences.

3.1. Limitations

Our goal was to simulate forest mortality due to tropical storm and hurricane strength winds over a multi-decadal time horizon. As a result, there are several aspects of hurricanes which we have not included. We do not model rainfall, inland flooding due to rainfall, soil saturation, coastal flooding due to storm surge or the resulting saltwater damage (DeLaune et al., 1987). Although we did not explicitly model soil saturation and wind gusts, they are implicitly accounted for by the forest mortalities derived from empirical data.

Further, we did not consider wind gusts, hurricane rotation, embedded tornados, or terrain (Boose et al., 1994); we only modeled the maximum sustained wind speed at each cell over the duration of a simulated storm. Local spatial variation in damage identified by Xi et al. (2008a) was therefore not modeled. Because we are considering hurricane effects decades into the future, the downscaling necessary to include wind gusts and wind direction would require extensive additional parameterization and computation, and would improve precision (but not accuracy) that is not parsimonious with our goals of long-term forecasting of trends and uncertainty. Finally, the Base-Hurricane extension provides no way to model specific historic storms, which could be used to compare model results with field measurements such as Cely (1989) and Xi et al. (2008a).

Despite these acknowledged limitations, we have successfully demonstrated the efficacy of simulating large-area high winds from hurricanes altering landscape succession.

4. Conclusions

Hurricanes are infrequent and large disturbance events (Foster et al., 1998) that have the potential to alter the successional trajectories (Lugo, 2008) of large areas across the southeastern US. Though hurricane damage takes place on the time scale of a single day, the influence of a single storm on ecosystem-wide high mortality alters the succession trajectory for decades afterwards as seen in Fig. 8. Further, the selection bias of very high winds preferring taller trees tends to leave younger stands with lower mortality rates, further altering the succession trajectory in ways that differ from several other kinds of disturbances.

Our extension to an existing landscape modeling framework enables hurricane effects to be integrated into other research on the effects of prescribed fire (e.g., Krofcheck et al., 2019), forest management, successional trajectories, and recovery planning of threatened species (e.g., Cadieux et al., 2019). For example, Lucash et al. (in review) used the Base-Hurricane extension to assess RCW habitat changes at Fort Bragg due to multiple disturbances including hurricanes. Incorporating the hurricane effects described herein will allow a more complete assessment of long-term uncertainty across large areas.

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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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envsoft.2020.104833.

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