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Informing adaptive forest management: A hazard rating tool for southern pine beetle *Dendroctonus frontalis* in pitch pine barrens

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Abstract

1. Climate change is facilitating a novel range expansion of southern pine beetle (SPB) into globally rare north-eastern pitch pine barrens.
2. By assessing stand conditions present in SPB-infested and uninfested pitch pine stands on Long Island, NY, USA, we developed a regionally-calibrated hazard rating model that predicts stand-level SPB susceptibility.
3. The model indicates that a stand's SPB susceptibility increases with (1) increasing pitch pine basal area, (2) increasing instances of previous year SPB spots nearby, and (3) sandy soil texture.
4. The model informs adaptation strategies to a novel pest dynamic by supporting the identification and prioritization of high hazard stands for prevention management.
5. An alignment between treatments effective in reducing SPB vulnerability and conserving pine barrens communities indicates that pine barrens can be managed both to improve resilience to future threats and preserve historic ecological conditions.

KEYWORDS
Dendroctonus frontalis, forest management, hazard rating, pine barrens, *Pinus rigida*, range expansion

INTRODUCTION

Insect pests are globally important drivers of forest landscape dynamics due to their impact on key forest components, including vegetation structure and composition, water and nutrient cycling, and wildlife habitat (Adams et al., 2009; Boon, 2012; Dale et al., 2001; Hicke et al., 2012; Mcshea et al., 2007; Veblen et al., 1991). Given the importance of climate to the physiological and ecological determinants of pest distribution and dynamics, climate change is indirectly affecting forests by altering the range, frequency, or severity of pest outbreaks (Ayres & Lombardero, 2000; Deutsch et al., 2008; Dukes et al., 2009; Jactel et al., 2019; Logan et al., 2003; Pureswaran et al., 2018). Such climate change-induced alterations to historic disturbance regimes can present novel ecological effects and management challenges.

As temperatures rise, there are a growing number of examples of phytophagous insect populations expanding their ranges (Carroll et al., 2003; Dale et al., 2001; Jepsen et al., 2008; Niemelä et al., 2001; Parmesan, 2006; Pureswaran et al., 2018). One of the most well-understood examples has occurred among bark beetles (Coleoptera: Curculionidae: Scolytinae) in North America. Southern pine beetle [*Dendroctonus frontalis* Zimmermann (SPB)] is a bark beetle whose wide-scale ecologic, economic, and social impacts have deemed it one of most destructive pests of pine forests (Clarke & Nowak, 2009; Coulson & Klepzig, 2011; Dodds et al., 2018; Payne, 1980; Price et al., 2006). Despite its short generation time, high dispersal capabilities, and wide host distribution, SPB's lower lethal air temperature (−16°C) has historically limited it to the south-eastern United States, Mexico, and Central America, with northern populations reaching Ohio, Pennsylvania, and Maryland (Payne, 1980; Price et al., 2006; Ungerer et al., 1999). However, warming minimum winter air temperatures in the last two decades have enhanced beetle fitness at northern distributions and allowed for damaging populations to expand (Lesk et al., 2017; Ungerer et al., 1999; Weed et al., 2013).

The ongoing northward expansion of SPB threatens ecosystems dominated by potential host species with limited historical exposure to the beetle, including the globally rare north-eastern pitch pine barrens (Lesk et al., 2017; Tran et al., 2007; Ungerer et al., 1999; Williams & Liebhold, 2002). In SPB-infested pine barrens, high levels of mortality in canopy pitch pine (*Pinus rigida* Mill.) are accelerating the ongoing transition of open-canopy, fire-dependent pitch pine barrens to forests dominated by less pyrophilic species like oaks (genus *Quercus*), red maple (*Acer rubrum* L.), and white pine (*Pinus strobus* L.; (Heuss et al., 2019; Howard et al., 2011; Nowacki & Abrams, 2008). SPB damage may extend to more northern pine barrens as SPB-suitable climates are expected to reach 78% of pitch pine forests by 2050 (Lesk et al., 2017).

SPB populations follow a pulse eruptive cycle in which favourable environmental conditions lead to irregular explosive population growth and the death of a large portion of host species (Berryman, 1986). During these outbreaks, semiochemical communication between SPB organizes mass attacks that can overwhelm resin defence systems of healthy trees and cause host death in a matter of days to weeks (Hain et al., 2011; Hassett et al., 2017; Sullivan, 2011). Incidences of SPB infestation in the south-eastern United States have been reduced in some stands through the application of forest management treatments such as stand thinning and prescribed burning that promote stand vigour and disrupt SPB pheromonal communication (Brown et al., 1987; Burkhart et al., 1986; Nebeker & Hodges, 1983; Nowak et al., 2015; Showalter & Turchin, 1993). With the exception of relatively small-scale applications, these silvicultural treatments have not been widely implemented in pitch pine-dominated communities in the north-eastern United States (Dodds et al., 2018). This is attributed to many obstacles, including the high cost of thinning operations stemming from an absence of local markets and the low value of harvested materials relative to south-eastern pine systems (Dodds et al., 2018), the lack of pitch pine-specific stocking guides and other management tools, and public resistance to management in a rapidly expanding wildlife–urban interface (Blanchard & Ryan, 2007; Radeloff et al., 2005; Ryan, 2012). Together, these obstacles, the looming threat of SPB, and the disturbance requirements of pine barrens ecosystems make it important for management decisions to be ecologically and economically effective.

Hazard rating is a powerful tool for understanding the relationships between pest activity and forest conditions. Based on factors that predispose stands to pest infestation, its purpose is not to predict when or if damage will occur, but to identify conditions where infestations are most likely to occur and areas where damage (e.g., tree mortality) is expected to be greatest (Mason et al., 1985). Hazard rating models thus provide land managers with information useful in identifying areas that may require preventative management, increased surveillance, accelerated suppression action, or post-damage appraisal (Hicks et al., 1987). Hazard models have successfully been applied in the south-eastern United States to determine stand-level SPB susceptibility using various predictors based on stand and site conditions, including host species abundance, site quality, age structure, density, landform, and SPB abundance (Billings & Upton, 2010; Dodds et al., 2018; Hicks et al., 1980, 1987; Mason et al., 1985). As part of the National Insect and Disease Risk Map (NIDRM) effort in 2012, a GIS-based multi-criteria/weighted modelling framework was utilized to classify SPB hazard (based on weighted inputs of pine basal area, quadratic mean diameter of pines, stem density index, and history of past SPB outbreaks) at 240-meter resolution across all lands/ownerships in the south-eastern United States (Krist Jr. et al., 2014). The results were subsequently 'rolled up' to classify SPB hazard at the county scale across the south-eastern United States, for use by federal and state partners in targeting prevention and surveillance activities (https://www.fs.fed.us/foresthealth/applied-sciences/mapping-reporting/spb-hazard-rating-maps.shtml). Due to the comparatively small and isolated distribution of north-eastern pine-dominated forests and the unique species composition, SPB hazard models developed for south-eastern forests have limited applicability to the north-east (Dodds et al., 2018). Even so, one preliminary hazard rating model was successfully used to help prioritize at-risk areas in state-owned pitch pine stands on Long Island, New York (NY) for thinning and suppression (Dodds et al., 2018). Expansion of this work to a more comprehensive model developed specifically for pitch pine forests would be an important component of adaption to SPB in the north-east (Dodds et al., 2018).

We aimed to expand hazard rating capabilities to inform adaptation strategies to this novel pest dynamic across a broader landscape. We developed a regionally-calibrated hazard rating model that uses (1) site characteristics, (2) stand conditions, and (3) previous SPB activity to predict stand-level susceptibility of north-eastern pitch pine-dominated communities to SPB. This tool can be applied to reduce landscape-scale vulnerability to SPB by supporting the identification and prioritization of highly susceptible stands for prevention management.

METHODS

We selected the pine barrens of Long Island, NY as our study area because it is a core region of pitch pine dominance containing SPB-infested and uninfested stands. New York State Department of Environmental Conservation (NYS DEC) has been gathering information about SPB on Long Island since it was first identified there in 2014. Furthermore, these pine barrens are similar to other pitch pine barrens across the north-east in ecological characteristics and ownership patterns (Heuss et al., 2019). These attributes make the pine barrens of Long Island an ideal system in which to evaluate and compare characteristics of infested and uninfested pine barren forests and develop hazard rating models with wider application (Figure 1).

Located on the Atlantic Coast, the Long Island pine barrens are vulnerable to hurricanes. High wind speeds and saltwater spray

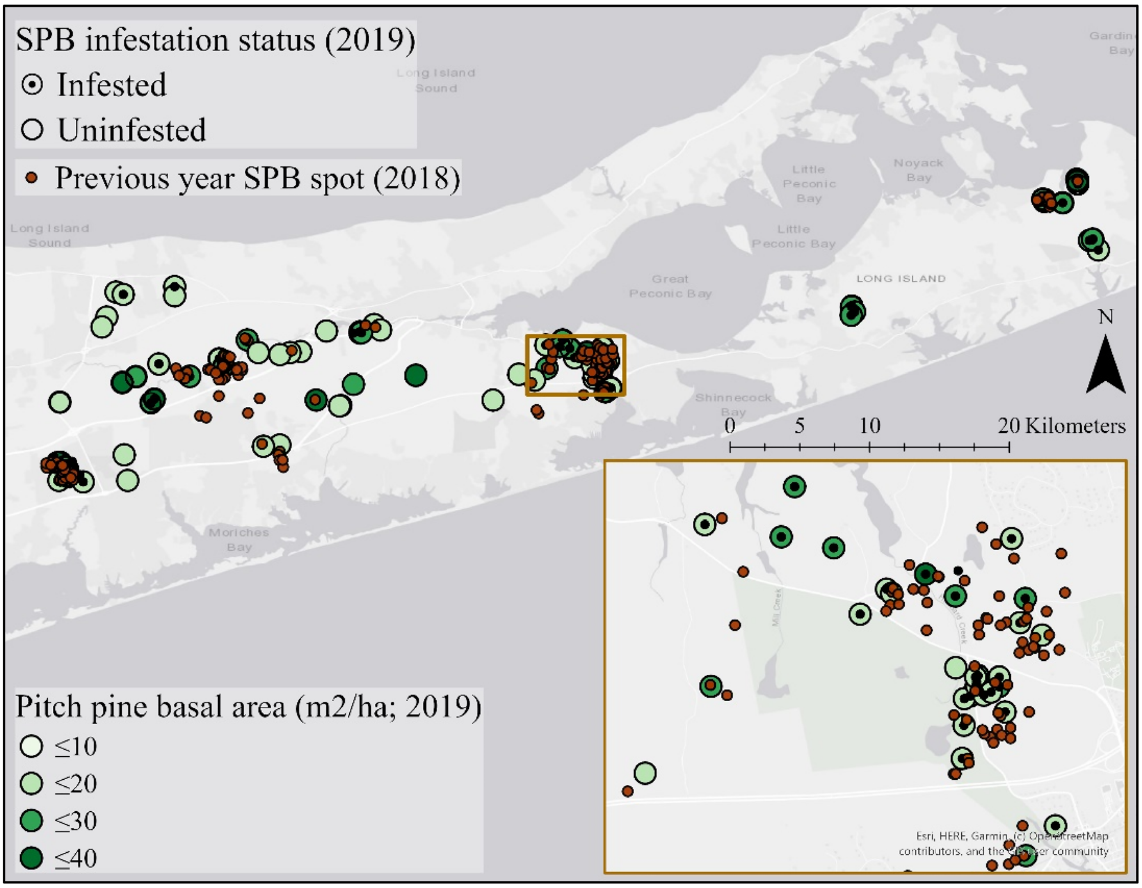

FIGURE 1 Map of studied pitch pine stands on Long Island, NY showing southern pine beetle (SPB) infestation status, previous year SPB spots, and pitch pine basal area.

associated with Hurricane Sandy in 2012 may have elevated tree stress and predisposed forests to the 2014 SPB infestation (Asaro et al., 2017; Griffiths & Orians, 2004). As trees recover from this stress, SPB vulnerability may decrease; however, projected increases in the intensity of hurricanes for this region suggest these events are likely to remain a component of the disturbance regimes for these ecosystems into the future (Holland & Bruyère, 2014).

Sample stands were concentrated in large (at least 50 trees cut) and recent (0–2 years old) SPB infestations that were identified through communication with the NYS DEC and other local stakeholders. We sampled a total of 23 stands, although one was excluded from analysis due to outlying stand conditions. Additionally, NYS DEC provided 2018–2019 SPB survey and treatment data (SPB presence/absence data and basal area estimates from a prism) for 95 pitch pine stands on Long Island, NY. In total, we assessed 2019 stand conditions within 117 stands: 78 of which were SPB-infested. Soil texture for each stand was obtained from the SSURGO database through the USDA Web Soil Survey (Soil Survey Staff n.d.).

Fieldwork was conducted from June to July 2019. Within sample stands, three 400 m^2 fixed-radius plots were randomly established with a distance of at least 40 m between plot centres. Tree species, health status (live or snag), crown class (dominant, codominant, intermediate, or suppressed), and diameter at breast height (DBH; 1.37 m) were recorded for every living tree and snag larger than 7.5 cm in diameter within plots. Stage of SPB attack (0, 1, 2, or 3) was recorded for host species (pitch pine and white pine) with 0 indicating an uninfested tree, 1 indicating a newly attacked tree, 2 indicating a tree containing developing brood, and 3 indicating a tree that had been killed and vacated by SPB (Billings & Pase, 1979). Because we aimed to identify conditions that facilitate SPB infestation, SPB-killed trees and stumps of trees cut during sanitation harvests were included in data collection efforts so stands could be reconstructed to pre-infestation conditions. To predict a tree's diameter at breast height (DBH) from its stump diameter (SD), DBH and SD measurements were taken from 58 additional pitch pine trees. DBH and SD exhibited a linear relationship modelled by the following equation, which had an R^2 value of 0.986:

$$\mathrm{DBH} = 0.916(\mathrm{SD}) - 1.339.$$

We limited our analyses to stand conditions recorded by the NYS DEC during SPB survey and treatment efforts so that stand inventory data from 95 additional stands could be included. Statistical analyses were conducted in R (R Core Team, 2021). Non-parametric Wilcoxon rank-sum tests (*stats* package; *wilcox.text* function) were first used to compare stand conditions between SPB-infested and uninfested

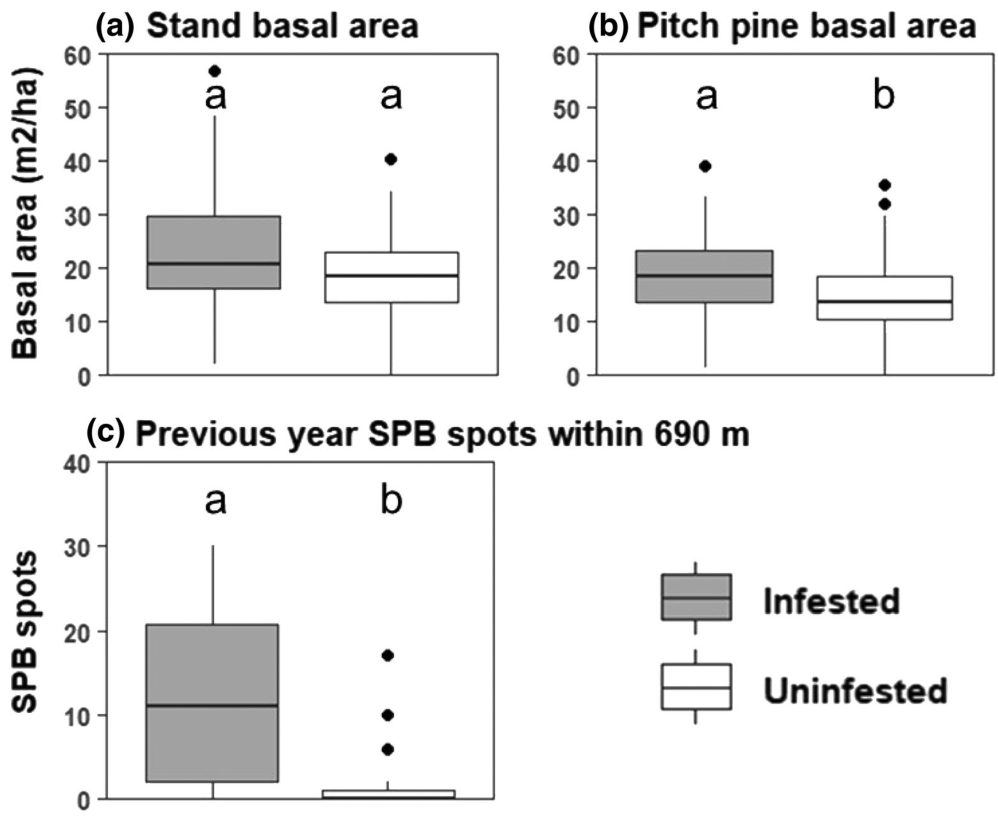

FIGURE 2 Stand basal area (a), pitch pine basal area (b), and previous year southern pine beetle (SPB) spots within 690 m (c) of infested and uninfested stands on Long Island, NY. Different letters indicate significantly different group means (α = 0.05) according to Wilcoxon rank-sum tests.

stands (R Core Team, 2021). Logistic regression (*stats* package; *glm* function; binomial family) was then used to model and analyse stand-level SPB susceptibility (R Core Team, 2021). We used a model comparison approach to determine the best predictors of SPB infestation status (1: infested; and 0: uninfested) from eight factors related to SPB susceptibility in past work: pitch pine basal area (m^2/ha), pine basal area (white and pitch pine), proportional pitch pine basal area, proportional pine basal area, hardwood basal area, total stand basal area, soil texture (sand or loam), and the number of nearby previous year (2018) SPB spots determined from aerial surveys, defined as a group of six or more neighbouring trees infested by SPB within a radius of 690 m, or the approximate maximum dispersal distance of half of SPB individuals (Turchin & Thoeny, 1993). The *dredge* function (*MuMIn* package) was used to compare models based on Akaike's information criterion (AIC), and the two most parsimonious equivalent models (ΔAIC ≤2) were identified as candidates (Barton, 2020; Burnham & Anderson, 2004). Candidate models were further evaluated using McFadden's R^2, receiver operating characteristic (ROC) curves (60% of data used for training, 40% reserved for testing), and ten-fold cross-validation (repeated five times). The optimal model was selected based on model performance, ecological meaningfulness, and applicability to forest management decisions. The relative contribution of each predictor variable to the model was assessed using its odds ratio, equal to the exponent of regression coefficients or the factor by which odds of infestation changes given a one-unit increase in the predicator variable (Szumilas, 2010).

RESULTS

Stand conditions and candidate models

Uninfested stands exhibited significantly lower pitch pine basal area, pine basal area, proportional pitch pine basal area, and proportional pine basal area, and fewer previous year SPB spots nearby than reconstructed SPB-infested stands (Figure 2).

SPB infestation status was associated with stand basal area, soil texture, and previous year SPB spots based on the inclusion of these predictor variables in the top candidate model (SM for "stand model", Table 1). A competing candidate model (PM for "pitch pine" model, Table 1) also indicated that soil texture and previous year SPB spots were effective at approximating SPB infestation status, but it included pitch pine basal area instead of stand basal area. Odds ratios of all three continuous predictor variables used in these models (stand basal area, pitch pine basal area, and previous year SPB spots) were greater than 1, indicating a positive correlation with odds of SPB infestation. Previous year SPB spots exhibited the same odds ratio in both models (OR = 1.30), which was higher than the odds ratios of stand basal area in SM (OR = 1.07) and pitch pine basal area in PM (OR = 1.08). Estimates for the discrete variable (soil texture) indicated classification as sand (as opposed to loam) had the highest odds ratio in both models, but was higher in SM (OR = 5.49) than in PM (OR = 5.18).

TABLE 1 Predictor variables of the two candidate models; SM and PM

Predictor variables	SM					PM (HRM)				
	B	SE	z	p	OR	β	SE	z	p	OR
Intercept	−3.34	0.97	−3.43	0.001*	0.04	−3.03	0.92	−3.29	0.001*	0.05
Stand basal area (m^2/ha)	0.07	0.03	2.61	0.009*	1.07	—	—	—	—	—
Pitch pine basal area (m^2/ha)	—	—	—	—	—	0.08	0.03	2.39	0.017*	1.08
Soil type: sand	1.70	0.73	2.32	0.020*	5.49	1.65	0.73	2.25	0.024*	5.18
Previous year SPB spots ≤690 m	0.26	0.07	3.82	<0.001*	1.30	0.27	0.07	3.73	<0.001*	1.30

Note: β, regression coefficient; SE, standard error; z, z-value; *p*, *p*-value; OR, odds ratio. Significant *p*-values (*) are based on $\alpha = 0.05$. PM (in bold) was selected as the hazard rating model.

TABLE 2 Performance of two candidate models (SM and PM) based on ΔAIC, McFadden's R^2, AUC (area under ROC curve), and accuracy (from ten-fold cross-validation)

Candidate model	ΔAIC	McFadden's R^2	AUC	Accuracy
SM	0	0.401	0.883	0.814
PM (HRM)	1.956	0.387	0.846	0.805

Note: PM (in bold) was selected as the hazard rating model.

Model validation and selection

Model validation outcomes for the two candidate models indicated good model fit, with SM performing slightly better in all tests (Table 2). SM had a higher McFadden's pseudo R^2 (SM $R^2 = 0.401$, PM = 0.387) and slightly higher accuracies evidenced by ROC curves (SM AUC = 0.883, PM = 0.846; Table 2) and ten-fold cross-validations (SM overall accuracy = 0.814, PM = 0.805; Tables 2 and 3). Both models exhibited higher sensitivities than specificities (Table 3). Since performance of candidate models was comparable, PM (hereafter called hazard rating model or HRM) was selected over SM as the optimal model. This selection was justified for two primary reasons. First, unlike pitch pine basal area (used in HRM), total stand basal area (used in SM) did not significantly differ between infested and uninfested stands (Figure 2). Second, research has shown that SPB populations are highly dependent on the availability of host species: a factor that could not be distinguished in SM (Mason et al., 1985; Showalter & Turchin, 1993). The HRM predicts probability of SPB infestation (interpreted as hazard) using the following equation where PBA = pitch pine basal area (m^2/ha), SPB = number of previous year SPB spots within 690 m, and STF = soil texture factor (1.645 for sand and 0 for loam):

$$Hazard\ rating = \frac{1}{1 + \exp(-(-3.035 + PBA * 0.075 + SPB * 0.265 + STF))}$$

Thus, stand-level hazard rating increases with (1) increasing pitch pine basal area, (2) increasing number of previous year SPB spots nearby, and (3) on sandy soil (Figures 3 and 4).

DISCUSSION

Hazard rating model as a forest management tool

Statistically, predictions from the hazard rating model (HRM) correspond to the probability that a stand is infested given its pitch pine basal area, number of previous year SPB spots nearby, and soil texture. When interpreted as a forest management tool, however, model predictions do not correspond to "risk", or the actual probability of pest infestation (Hicks et al., 1987). Instead, model outputs correspond to "hazard ratings". Hazard ratings describe stand-level

TABLE 3 Accuracy estimates of two candidate models (SM and PM) from ten-fold cross-validation repeated five times

Candidate model	Confusion matrix				Accuracy assessment
		Reference			
	Predicted	Infested	Uninfested	Total	
SM	Infested	342	61	403	Overall accuracy = 0.814
	Uninfested	48	134	182	Sensitivity = 0.877
	Total	390	195	585	Specificity = 0.687
					Balanced accuracy = 0.782
PM (HRM)	Infested	338	62	400	Overall accuracy = 0.805
	Uninfested	52	133	185	Sensitivity = 0.867
	Total	390	195	585	Specificity = 0.682
					Balanced accuracy = 0.774

Note: PM (in bold) was selected as the hazard rating model.

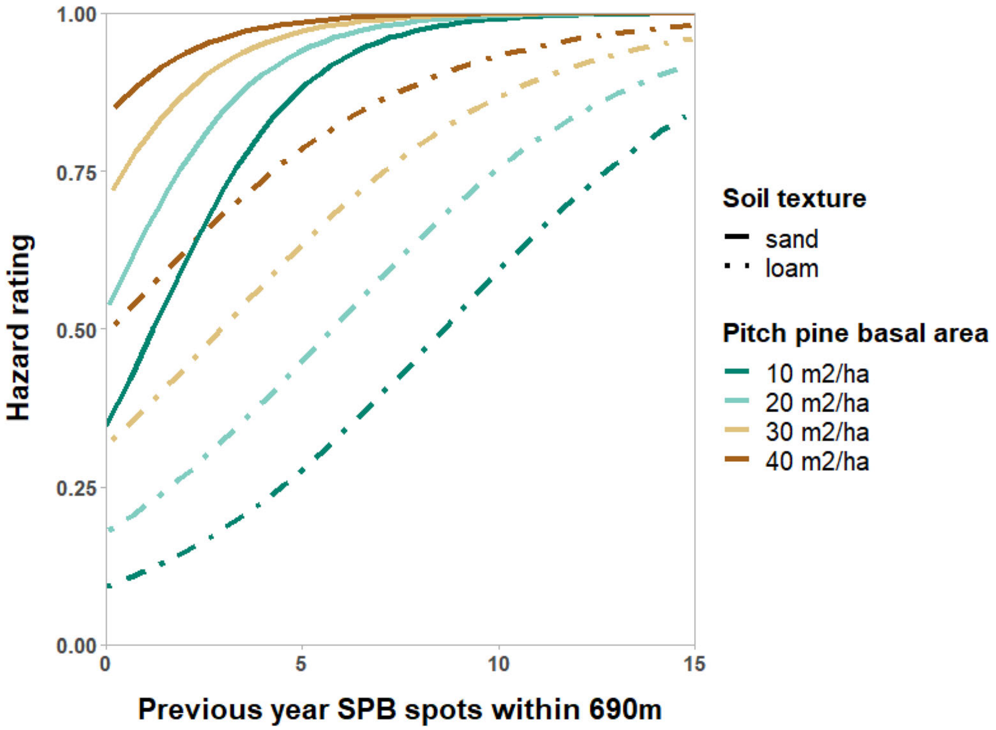

FIGURE 3 Southern pine beetle (SPB) hazard ratings predicted across increasing previous year SPB spots within 690 m (x-axis) by soil texture (line style) and pitch pine basal area (m^2/ha; line colour).

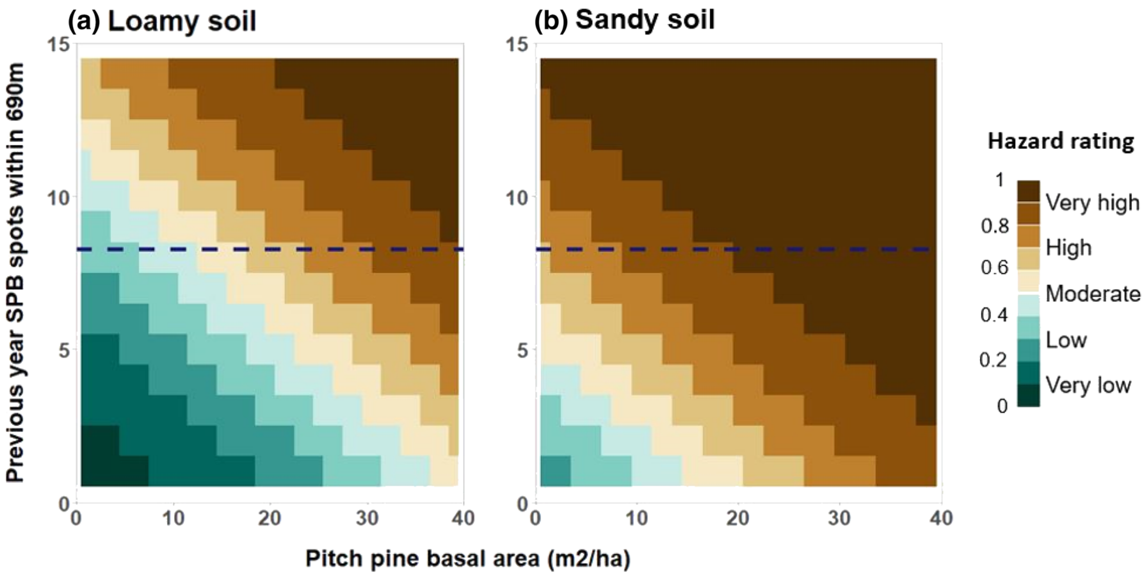

FIGURE 4 Stand-level southern pine beetle (SPB) hazard ratings across increasing pitch pine basal area (m^2/ha; x-axis) and previous year SPB spots within 690 m (y-axis) for loamy (a) and sandy (b) soils. The dashed line corresponds to the mean number of previous year SPB spots within 690 m of stands on Long Island, NY (8.27 spots).

susceptibility to infestation by analysing attributes that predispose a stand to infestation (Hicks et al., 1987). Ratings closer to zero indicate that a stand's conditions are not conducive to pest infestation (i.e., it is a low hazard stand), while values closer to one indicate that a stand's conditions are highly conducive to infestation (i.e., it is a high hazard stand). A high hazard stand that is isolated from SPB activity or in a period of low SPB population can therefore exist with little to no risk of attack and vice versa (Hicks et al., 1987). This means that, in addition to areas within the extent of SPB infestations, the HRM can be applied outside of the current range of SPB (where risk of infestation is currently low) to inform prevention management in regions that may experience future infestations and outbreaks.

Hazard rating predictors

Many stand conditions have been shown to impact SPB susceptibility in the south-eastern United States, with pine basal area being one of the most important and commonly cited (Krist Jr. et al., 2013; Kushmaul et al., 1979; Lorio Jr., 1978; Mason et al., 1985). This is consistent with our HRM, which indicates that stands with higher pitch pine basal areas are more susceptible to SPB. This relationship likely results from three factors: (1) trees in denser stands have lower vigour, growth, and defensive capabilities; (2) SPB populations (particularly at low levels) are strongly dependent on the availability and accessibility of hosts; and (3) airflow is not as disruptive to SPB aggregation pheromones in closed-canopy conditions (Brown et al., 1987; Lorio Jr. & Hodges, 1968; Lorio Jr. & Hodges, 1977; Mason et al., 1985; Showalter & Turchin, 1993; Thistle et al., 2004, 2011). For these reasons, past work in the south-eastern United States has recommended that stands with a density greater than 27.5 m^2/ha in basal area be reduced to less than 18.4 m^2/ha. Based on the predictions of our HRM, pitch pine basal areas less than 15 m^2/ha appeared to be less susceptible to SPB infestations. This lower density suggested for pitch pine systems likely reflects the historic woodland and barrens structure of these ecosystems relative to the highly stocked, economically important southern pine plantations where hazard ratings have previously been developed (Asaro et al., 2017; Krist Jr. et al., 2013; Mason et al., 1985).

Our inclusion of the number of previous year SPB spots nearby (i.e., risk) was used to account for stands that were SPB-infested not because they contained hazardous stand conditions, but because they were in close proximity to beetle source populations in neighbouring infested stands. This concept is often overlooked in studies, yet it can have drastic impacts on landscape-level vulnerability (Showalter & Turchin, 1993). When SPB populations are low, spots typically initiate in high hazard stands because they provide optimal habitat for beetles (Mason et al., 1985). As conditions become more favourable for SPB, spots increase in number and size and expand or proliferate into moderate or low hazard stands (Mason et al., 1985). Thus, by harbouring SPB populations and facilitating an initial infestation, the existence of high hazard stands increases the susceptibility of moderate and low hazard stands. Eliminating high hazard stands has been demonstrated to prevent future spot development and reduce landscape-scale susceptibility (Mason et al., 1985).

In areas such as Long Island where SPB is already present, the number of previous year SPB spots nearby can be determined using available survey data collected during annual state and federal aerial insect and disease surveys. The inclusion of this predictor in the HRM increases prediction accuracy by 10%, largely because it improves the model's ability to identify uninfested stands. However, regardless of whether previous year SPB activity is included in the model, the relationship between hazard and the other two predictors (pitch pine basal area and soil texture) remains the same. Therefore, if SPB is not yet present in an area or if SPB spot data are unavailable, pitch pine basal area and soil type alone can offer strong guidance for reducing stand hazard.

Site characteristics including slope, landform, and clay content have previously been incorporated into SPB hazard ratings (Mason et al., 1985). Our HRM indicates that odds of infestation are over five times as great for stands growing on sand than stands growing on loam. The strength of this variable is likely attributed to its ability to capture multiple factors that impact overall stand susceptibility. First, the variable could be capturing the effect of water stress on pitch pine's defensive capabilities. Pitch pines defend against SPB using resin to "pitch out" attacking beetles (Lorio Jr. & Hodges, 1977), but sustained resin flow is dependent on adequate oleoresin exudation pressure, which decreases beyond moderate levels of moisture stress (Lorio, 1986). Thus, better hydrated trees are better equipped to expel invading beetles, while trees under severe water stress have almost no defence capabilities (Lorio Jr. & Hodges, 1968; Lorio Jr. & Hodges, 1977; Thatcher, 1960). The greater water retention of loamy soil (Kurczewski & Boyle, 2000) may translate into less water stress and greater defensive capabilities in pitch pines growing on loamy soil than those growing on sandy soils.

The second explanation for lower hazard ratings on loamy sites is presumably related to the more mixed composition associated with pitch pine forest on these sites relative to more pure pine conditions on sandy soils. In particular, mesophytic communities, like oak-pitch pine forest or pitch pine-oak forest, tend to develop on sites with finer-grained, moderately permeable loamy soils (Jordan et al., 2003; Kurczewski & Boyle, 2000). These communities have greater hardwood dominance than xerophytic communities such as pitch pine-oak-heath woodlands or pitch pine-scrub oak barrens that grow on coarser-grained, sandy soils. This was reflected in our study in that loamy stands exhibited a lower percentage of pitch pine trees than sandy stands. Hardwoods have been suggested to impact SPB susceptibility through two mechanisms: they could promote infestation through direct competition with pines (Hicks, 1980) or, as nonhost species, they could interfere with beetle dispersal and host discovery to inhibit infestation (Belanger & Malac, 1980; Showalter & Turchin, 1993). Results of a 1993 study that investigated the interactive effects of pine and hardwood basal areas on SPB susceptibility supported the later mechanism (Showalter & Turchin, 1993). This implies that lower hazard ratings predicted for stands on loamy soil may be due to the presence of more hardwoods that disrupt infestation spread.

Management implications

In agreement with many hazard rating systems developed for the south-eastern United States, our HRM suggests that an effective way to reduce SPB susceptibility is to maintain open stand conditions and promote stand health by reducing pitch pine basal area. This can be accomplished through application of thinning and prescribed fire

(Brown et al., 1987; Clarke & Nowak, 2009; Nowak et al., 2015; Showalter & Turchin, 1993), processes that have shaped the pine barrens landscape for centuries. In the pine barrens of Long Island, Coastal Native American tribes likely managed with fire to promote oak as a food source (from mast), pine as a source of wood and resin for canoe building, and berry production from *Vaccinium* (Abrams & Nowacki, 2021; Kimmerer & Lake, 2001). In the 17–19th centuries, logging and land clearing by European colonizers caused frequent fires, which led to the expansion of pitch pine forests throughout Suffolk County (Kurczewski & Boyle, 2000). Fire suppression policies of the 1920s abruptly reduced the amount of fire in the north-east, thereby accelerating the conversion of pyrophilic pitch pine communities to closed-canopy, mesic forests through the process of mesophication (Nowacki & Abrams, 2008; Welch et al., 2000). Thus, in addition to SPB resilience, prescribed fire and thinning bring many benefits to north-eastern pitch pine barrens; they have proven effective in reducing the risk of severe crown fires and generating conditions that restore pitch pine dominance, ecosystem function, and habitat structure critical to regional biodiversity (Bried et al., 2011, 2014, 2015; Bried & Gifford, 2010; Gifford et al., 2010; Howard et al., 2011; Jordan et al., 2003).

CONCLUSION

Our HRM uses three variables accessible to land managers to predict stand-level SPB susceptibility. We found that stand hazard increases with (1) increasing pitch pine basal area, (2) increasing instances of previous year SPB spots nearby, and (3) sandy soil texture. Basal area reduction treatments such as thinning and prescribed burning have not only proven to be effective in achieving SPB resilience, but they have also been applied to achieve pine barrens conservation objectives. This clear alignment implies that north-eastern pitch pine barrens can be managed both to conserve historic ecological conditions and improve resilience to future threats.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data available on request from the authors.

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REFERENCES

Abrams, M.D. & Nowacki, G.J. (2021) Examining the heritage and legacy of indigenous land management in oak and pine forests of northeastern United States. *International Journal of Ecology and Environmental Sciences.*, 47(1), 27–36.

Adams, H.D., Guardiola-Claramonte, M., Barron-Gafford, G.A., Villegas, J. C., Breshears, D.D., Zou, C.B. et al. (2009) Temperature sensitivity of drought-induced tree mortality portends increased regional die-off under global-change-type drought. *Proceedings of the National Academy of Sciences of the United States of America*, 106(17), 7063–7066.

Asaro, C., Nowak, J.T. & Elledge, A. (2017) Why have southern pine beetle outbreaks declined in the southeastern U.S. with the expansion of intensive pine silviculture? A brief review of hypotheses. *Forest Ecology and Management*, 391, 338–348.

Ayres, M.P. & Lombardero, M.J. (2000) Assessing the consequences of global change for forest disturbance from herbivores and pathogens. *Science of The Total Environment*, 262(3), 263–286.

Barton, K. 2020. MuMIn: Multi-Model Inference. Available online at: https://CRAN.R-project.org/package=MuMIn.

Belanger, R.P. & Malac, B.F. (1980) *Silviculture can reduce losses from the southern pine beetle*. Washington, DC: Combined Forest Research and Development Program.

Berryman, A.A. (1986) *Forest insects: principles and practice of population management*. New York, USA: Penum Press. Available online at: https://books.google.com/books?id=DRHrBwAAQBAJ&pg=PA72&lpg=PA72&dq=pulse+eruptive+berryman&source=bl&ots=gwkYBn_8ty&sig=ACfU3U2AUGBDcXmB2EnwOQiXvCnJgPIPmQ&hl=en&sa=X&ved=2ahUKEwiOzvKTrZfnAhWomuAKHaW8BAUQ6AEwAHoECAcQAQ#v=onepage&q=pulse%20eruptive&f=false

Billings, R.F. & Pase, H.A.I. (1979) *A field guide for ground checking southern pine beetle spots*. Washington, DC: United States Department of Agriculture. Available online at: https://www.barkbeetles.org/spb/spbspts.cfm

Billings, R.F. & Upton, W.W. (2010) A methodology for assessing annual risk of southern pine beetle outbreaks across the southern region using pheromone traps. In: Pye, J.M., Rauscher, H.M., Sands, Y., Lee, D.C. & Beatty, J.S. tech. (eds.) *2010. Advances in threat assessment and their application to forest and rangeland management*. Gen. Tech. Rep. PNW-GTR-802. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest and Southern Research Stations. Available online at: https://www.fs.fed.us/pnw/pubs/gtr802/Vol1/pnw_gtr802vol1_billings01.pdf; last accessed November 7, 2019

Blanchard, B. & Ryan, R.L. (2007) Managing the wildland–urban Interface in the northeast: perceptions of fire risk and Hazard reduction strategies. *Northern Journal of Applied Forestry*, 24(3), 203–208.

Boon, S. (2012) Snow accumulation following forest disturbance. *Ecohydrology*, 5(3), 279–285.

Bried, J.T. & Gifford, N.A. (2010) Mowing and herbicide of scrub oaks in pine barrens: baseline data (New York). *Ecological Restoration*, 28(3), 245–248.

Bried, J.T., Gifford, N.A. & Robertson, K.M. (2015) Predicted crown fire risk adds incentive to restore open-canopy pine barrens at the wildland-urban Interface. *Journal of Sustainable Forestry*, 34, 147–167.

Bried, J.T., Langwig, K.E., Dewan, A.A. & Gifford, N.A. (2011) Habitat associations and survey effort for shrubland birds in an urban pine barrens preserve. *Landscape and Urban Planning*, 99(3–4), 218–225.

Bried, J.T., Patterson, W.A.I. & Gifford, N.A. (2014) Why pine barrens restoration should favor barrens over pine. *Restoration Ecology*, 22(4), 442–446.

Brown, M.W., Nebeker, T.E. & Honea, C.R. (1987) Thinning increases loblolly pine vigor and resistance to bark beetles. *Southern Journal of Applied Forestry*, 11(1), 28–31.

Burkhart, H.E., Haney, H.L., Jr., Newberry, J.D., Leuschner, W.A., Morris, C. L. & Reed, D.D. (1986) Evaluation of thinning for reduction of losses from southern pine beetle attack in loblolly pine stands. *Southern Journal of Applied Forestry*, 10(2), 105–108.

Burnham, K.P. & Anderson, D.R. (2004) Multimodel inference: understanding AIC and BIC in model selection. *Sociological Methods & Research*, 33(2), 261–304.

Carroll, A. L., S. W. Taylor, J. Régnière, and L. Safranyik. 2003. Effects of climate change on range expansion by the mountain pine beetle in British Columbia. Available online at: https://digitalcommons.usu.edu/barkbeetles/195/.

Clarke, S. R., and J. T. Nowak. 2009. *Southern Pine Beetle*. Forest Insect and Disease Leaflet 49, U.S. Department of Agriculture, U.S. Forest Service. Available online at: https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fsbdev2_042840.pdf; last accessed October 29, 2019.

Coulson, R.N. & Klepzig, K.D. (2011) Southern pine beetle II. In: *Southern pine beetle II, general technical report (GTR)*. Ashville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station, p. 512 Available online at: https://www.srs.fs.usda.gov/pubs/39017

Dale, V.H., Joyce, L.A., McNulty, S., Neilson, R.P., Ayres, M.P., Flannigan, M.D. et al. (2001) Climate change and Forest disturbances: climate change can affect forests by altering the frequency, intensity, duration, and timing of fire, drought, introduced species, insect and pathogen outbreaks, hurricanes, windstorms, ice storms, or landslides. *Bioscience*, 51(9), 723–734.

Deutsch, C.A., Tewksbury, J.J., Huey, R.B., Sheldon, K.S., Ghalambor, C.K., Haak, D.C. et al. (2008) Impacts of climate warming on terrestrial ectotherms across latitude. *Proceedings of the National Academy of Sciences of the United States of America*, 105, 6668–6672.

Dodds, K.J., Aoki, C.F., Arango-Velez, A., Cancelliere, J., D'Amato, A.W., DiGirolomo, M.F. et al. (2018) Expansion of southern pine beetle into northeastern forests: management and impact of a primary bark beetle in a new region. *Journal of Forestry*, 116(2), 178–191.

Dukes, J.S., Pontius, J., Orwig, D., Garnas, J.R., Rodgers, V.L., Brazee, N. et al. (2009) Responses of insect pests, pathogens, and invasive plant species to climate change in the forests of northeastern North America: what can we predict? *Canadian Journal of Forest Research*, 39(2), 231–248.

Gifford, N.A., Deppen, J.M. & Bried, J.T. (2010) Importance of an urban pine barrens for the conservation of early-successional shrubland birds. *Landscape and Urban Planning*, 94(1), 54–62.

Griffiths, M.E. & Orians, C.M. (2004) Salt spray effects on Forest succession in rare coastal sandplain heathlands: evidence from field surveys and Pinus rigida transplant experiments. *The Journal of the Torrey Botanical Society*, 131(1), 23–31.

Hain, F.P., Duehl, A.J., Gardner, M.J. & Payne, T.L. (2011) Natural history of the southern pine beetle. In: *Southern pine beetle II, general technical report (GTR)*. Ashville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station, pp. 13–24 Available online at: https://www.srs.fs.usda.gov/pubs/39017

Hassett, M., R. Cole, and K. Dodds. 2017. New York State Southern Pine Beetle Management Plan. New York State Department of Environmental Conservation. Available online at: https://www.dec.ny.gov/docs/lands_forests_pdf/spbplan2017.pdf; last accessed October 29, 2019.

Heuss, M., D'Amato, A.W. & Dodds, K.J. (2019) Northward expansion of southern pine beetle generates significant alterations to forest structure and composition of globally rare Pinus rigida forests. *Forest Ecology and Management*, 434, 119–130.

Hicke, J.A., Allen, C.D., Desai, A.R., Dietze, M.C., Hall, R.J., Hogg, E.H. et al. (2012) Effects of biotic disturbances on forest carbon cycling in the United States and Canada. *Global Change Biology*, 18(1), 7–34.

Hicks, R.R. (1980) Climate, site, and stand factors. In: *The southern pine beetle, USDA for. Serv. Tech. Bull. 1631*. Washington, DC: USDA Forest Service, pp. 55–68.

Hicks, R.R., Coster, J.E. & Mason, G.N. (1987) Forest insect hazard rating-applying a little-understood management tool using the southern pine beetle and the gypsy moth. *Journal of Forestry*, 85(20), 20–26.

Hicks, R.R., Howard, J.E., Watterston, K.G. & Coster, J.E. (1980) Rating forest stand susceptibility to southern pine beetle in East Texas. *Forest Ecology and Management*, 2, 269–283.

Holland, G. & Bruyère, C.L. (2014) Recent intense hurricane response to global climate change. *Climate Dynamics*, 42(3), 617–627.

Howard, L.F., Lee, T.D. & Eckert, R.T. (2011) Forest community composition and dynamics of the Ossipee Pine Barrens, New Hampshire. *Journal of the Torrey Botanical Society*, 138(4), 434–452.

Jactel, H., Koricheva, J. & Castagneyrol, B. (2019) Responses of forest insect pests to climate change: not so simple. *Current Opinion in Insect Science*, 35, 103–108.

Jepsen, J.U., Hagen, S.B., Ims, R.A. & Yoccoz, N.G. (2008) Climate change and outbreaks of the geometrids Operophtera brumata and Epirrita autumnata in subarctic birch forest: evidence of a recent outbreak range expansion. *Journal of Animal Ecology*, 77(2), 257–264.

Jordan, M.J., Patterson, W.A. & Windisch, A.G. (2003) Conceptual ecological models for the Long Island pitch pine barrens: implications for managing rare plant communities. *Forest Ecology and Management*, 185(1), 151–168.

Kimmerer, R.W. & Lake, F.K. (2001) The role of indigenous burning in land management. *Journal of Forestry*, 99(11), 36–41.

Krist, F.J., Jr., Ellenwood, J.R., Woods, M.E., McMahan, A.J., Cowardin, J.P., Ryerson, D.E. et al. (2014) *2013–2027 National Insect and disease Forest risk assessment. U.S. Department of Agriculture*. Fort Collins, Colorado: Forest Service, Forest Health Technology Enterprise Team.

Krist, F.J., Jr., McMahan, A.J., Cowardin, J.P. & Zweifler, M.O. (2013) *The 2013–2027 national insect and disease forest risk assessment: Risk Map Application (RMAP) Model Details*. Fort Collins, Colorado: U.S. Department of Agriculture, Forest Service, FHTET.

Kurczewski, F.E. & Boyle, H.F. (2000) Historical changes in the pine barrens of Central Suffolk County, New York. *Northeastern Naturalist*, 7(2), 95–112.

Kushmaul, R.J., Cain, M.D., Rowell, C.E. & Porterfield, R.L. (1979) Stand and site conditions related to southern pine beetle susceptibility. *Forest Science*, 25(4), 656–664.

Lesk, C., Coffel, E., D'Amato, A.W., Dodds, K. & Horton, R. (2017) Threats to north American forests from southern pine beetle with warming winters. *Nature Climate Change*, 7, 713–717.

Logan, J.A., Régnière, J. & Powell, J.A. (2003) Assessing the impacts of global warming on forest pest dynamics. *Frontiers in Ecology and the Environment*, 1(3), 130–137.

Lorio, P. L. Jr. 1978. Developing stand risk classes for the southern pine beetle. Research Paper SO-144, U.S. Department of Agriculture Forest Service, Southern Forest Experiment Station.

Lorio, p.L., Jr. & Hodges, J.D. (1968) Oleoresin exudation pressure and relative water content of inner bark as indicators of moisture stress in loblolly pines. *Forest Science*, 14(4), 392–398.

Lorio, P. L. Jr., John D. Hodges. 1977. Tree water status affects induced southern pine beetle attack and brood production. USDA Forest Service Research Paper SO-135.

Lorio, p.L. (1986) Growth-differentiation balance: a basis for understanding southern pine beetle-tree interactions. *Forest Ecology and Management*, 14(4), 259–273.

Mason, G.N., Lorio, p.L., Belanger, R.P. & Nettleton, W.A. (1985) *Rating the susceptibility of stands to southern pine beetle attack*. Washington, DC: Department of Agriculture, Forest Service Cooperative State Research Service. Available online at: https://books.google.com/books?hl=en&lr=&id=N2J8AAAAIAAJ&oi=fnd&pg=PA3&dq=Rating+the+susceptibility+of+stands+to+southern+pine+beetle+attack&ots=pt_XZJV3u-&sig=hTAoJVvd2nMZ8mC_GMfTPYHPhMA#v=onepage&q=Rating%20the%20susceptibility%20of%20stands%20to%20southern%20pine%20beetle%20attack&f=false

Mcshea, W.J., Healy, W.M., Devers, P., Fearer, T., Koch, F.H., Stauffer, D. et al. (2007) Forestry matters: decline of oaks will impact wildlife in hardwood forests. *The Journal of Wildlife Management*, 71(5), 1717–1728.

Nebeker, T.E. & Hodges, J.D. (1983) Influence of forestry practices on host-susceptibility to bark beetles. *Zeitschrift für Angewandte Entomologie*, 96(1–5), 194–208.

Niemelä, P., Chapin, F.S., Danell, K. & Bryant, J.P. (2001) Herbivory-mediated responses of selected boreal forests to climatic change. *Climatic Change*, 48(2), 427–440.

Nowacki, G.J. & Abrams, M.D. (2008) The demise of fire and "Mesophication" of forests in the eastern United States. *Bioscience*, 58(2), 123–138.

Nowak, J.T., Meeker, J.R., Coyle, R., Steiner, C.A. & Brownie, C. (2015) Southern pine beetle infestations in relation to Forest stand conditions, previous thinning, and prescribed burning: evaluation of the southern pine beetle prevention program. *Journal of Forestry*, 113(5), 454–462.

Parmesan, C. (2006) Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology, Evolution, and Systematics*, 37(1), 637–669.

Payne, T. L. 1980. Life history and habits. in *The Southern Pine Beetle*, US Department of Agriculture, Expanded Southern Pine Beetle Research and Application Program. Available online at: https://www.barkbeetles.org/spb/spbbook/Index.cfm.

Price, T.S., Doggett, C., Pye, J.M. & Smith, B. (2006) *A history of southern pine beetle outbreaks in the southeastern United States*. Macon, GA: Georgia Forestry Commission. Available online at: https://www.barkbeetles.org/spb/index.HTML

Pureswaran, D.S., Roques, A. & Battisti, A. (2018) Forest insects and climate change. *Current Forestry Reports*, 4(2), 35–50.

R Core Team. (2021) *R: a language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. Available online at: https://www.R-project.org/

Radeloff, V.C., Hammer, R.B., Stewart, S.I., Fried, J.S., Holcomb, S.S. & McKeefry, J.F. (2005) The wildland-urban interface in the United States. *Ecological Applications*, 15(3), 799–805.

Ryan, R.L. (2012) The influence of landscape preference and environmental education on public attitudes toward wildfire management in the northeast pine barrens (USA). *Landscape and Urban Planning*, 107(1), 55–68.

Showalter, T.D. & Turchin, P. (1993) Southern pine beetle infestation development: interaction between pine and hardwood basal areas. *Forest Science*, 39(2), 201–210.

Soil Survey Staff. n.d. Soil Survey Geographic (SSURGO) Database for Long Island, NY. Natural Resources Conservation Service, United States Department of Agriculture. Available online at: https://websoilsurvey.nrcs.usda.gov/; last accessed May 5, 2021.

Sullivan, B.T. (2011) Southern pine beetle behavior and semiochemistry. In: Coulson, R.N. & Klepzig, K.D. (ed.) *2011. Southern Pine Beetle II*. Gen. Tech. Rep. SRS-140. Asheville, NC: Department of Agriculture Forest Service, Southern Research Station, pp. 25–50 Available online at: https://www.srs.fs.usda.gov/pubs/gtr/gtr_srs140/gtr_srs140_025.pdf

Szumilas, M. (2010) Explaining odds ratios. *Journal of Canadian Academy of Child and Adolescent Psychiatry*, 19(3), 227–229.

Thatcher, R.C. (1960) *Bark beetles affecting southern pines: a review of current knowledge*. Pineville, LA: U.S. Department of Agriculture Forest Service, Southern Forest Experiment Station.

Thistle, H.W., Peterson, H., Allwine, G., Lamb, B., Strand, T., Holsten, E.H. et al. (2004) Surrogate pheromone plumes in three Forest trunk spaces: composite statistics and case studies. *Forest Science*, 50(5), 610–625.

Thistle, H.W., Strom, B., Strand, T., Lamb, B.K., Edburg, S., Allwine, G. et al. (2011) Atmospheric dispersion from a point source in four southern pine thinning scenarios: basic relationships and case studies. *Transactions of the ASABE*, 54(4), 1219–1236.

Tran, K., T. Ylioja, Billings F., J. Regniere, and M. Ayres P. 2007. Impact of minimum winter temperatures on the population dynamics of *Dendroctonus frontalis*. *Ecological Applications* 17(3):882–899.

Turchin, P. & Thoeny, W.T. (1993) Quantifying dispersal of southern pine beetles with mark-recapture experiments and a diffusion model. *Ecological Applications*, 3(1), 187–198.

Ungerer, M.J., Ayres, M.P. & Lombardero, M.J. (1999) Climate and the northern distribution limits of *Dendroctonus frontalis* Zimmermann (Coleoptera: Scolytidae). *Journal of Biogeography*, 26, 1133–1145.

Veblen, T.T., Hadley, K.S., Reid, M.S. & Rebertus, A.J. (1991) The response of subalpine forests to spruce beetle outbreak in Colorado. *Ecology*, 72(1), 213–231.

Weed, A.S., Ayres, M.P. & Hicke, J.A. (2013) Consequences of climate change for biotic disturbances in north American forests. *Ecological Monographs*, 83(4), 441–470.

Welch, N.T., Waldrop, T.A. & Buckner, E.R. (2000) Response of southern Appalachian table mountain pine (*Pinus pungens*) and pitch pine (*P. rigida*) stands to prescribed burning. *Forest Ecology and Management*, 136(1), 185–197.

Williams, D.W. & Liebhold, A.M. (2002) Climate change and the outbreak ranges of two north American bark beetles. *Agricultural and Forest Entomology*, 4(2), 87–99.

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