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ORIGINAL ARTICLE

Modeling potential climate change impacts on the trees of the northeastern United States

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Abstract We evaluated 134 tree species from the eastern United States for potential response to several scenarios of climate change, and summarized those responses for nine northeastern United States. We modeled and mapped each species individually and show current and potential future distributions for two emission scenarios (A1fi [higher emission] and B1 [lower emission]) and three climate models: the Parallel Climate, the Hadley CM3, and the Geophysical Fluid Dynamics Laboratory model. Climate change could have large impacts on suitable habitat for tree species in this region, especially under a high emissions trajectory. Results indicate that while species with potentially increasing areas of suitable habitat in the Northeastern US substantially outnumber those with decreasing areas of habitat, there are key species that show diminishing habitat area: balsam fir (*Abies balsamea*), paper birch (*Betula papyrifera*), red spruce (*Picea rubens*), bigtooth and quaking aspen (*Populus grandidentata* and *P. tremuloides*), and black cherry (*Prunus serotina*). From these results we identified the top 10 losers and gainers for each US state in the region by scenario and emissions trajectory. By combining individual species importance maps and developing assembly rules for various classes, we created maps of potential forest types for the Northeast showing a general loss of the spruce–fir zone with advancing oak–hickory type. Further data, maps, and analysis can be found at http://www.nrs.fs.fed.us/atlas.

Keywords Climate change · Tree species distributions · Composition changes · Species shifts · Random forests · Parallel climate model (PCM) · Hadley · GFDL · CO_2 emissions · Northeastern United States

1 Introduction

Evidence continues to mount that climate change is already affecting an increasing number of species the world over (Fitter and Fitter 2002; Parmesan and Galbraith 2004; Wilson et al. 2004). Much attention has been focused on predicting the effects of future climatic

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change on ecological systems (e.g., Box et al. 1999; Iverson et al. 1999; Kirschbaum 2000; Joyce and Birdsey 2000; National Assessment Synthesis Team 2001; Yates et al. 2000; Hansen et al. 2001; Guisan and Thuiller 2005; Lovejoy and Hannah 2005; Ibanez et al. 2006; Thuiller et al. 2006). A recent study on the boreal forests of Siberia, Canada, and Alaska reported that many aspects of forest change are now occurring as predicted in models: a northern and upslope migration of certain trees, dieback of certain species, and increased outbreaks of insects and fire (Soja et al. 2006). Both the projected increases of atmospheric carbon dioxide (CO_2) concentration and changes in temperature and precipitation patterns alter ecosystem functions, species interactions, population biology, and plant distribution (Melillo et al. 1990; Kirschbaum 2000). Although much uncertainty remains in these predictions and observations, convergence of paleoecological evidence (Davis and Zabinski 1992; DeHayes et al. 2000) and modeling (Kirilenko et al. 2000) indicates that tree species eventually will undergo radical changes in distribution.

An earlier investigation of the impacts from climate change on the northeastern United States (NE) that was prepared for the National Assessment revealed that northeastern forest types move generally to the north, especially with the harsher Canadian Climate Centre model (Barron 2001).

It is clear that changes in distribution will occur independently among species so that the various species that combine to form a community will come together in different combinations under climate change (Webb and Bartlein 1992). Because of this individualistic nature of species combinations, it is important to evaluate potential changes in tree species individually rather than predetermined groups of species or forest types. We used an updated statistical approach to model changes in habitat for 134 individual tree species that are found in the eastern United States. We extracted data pertinent to the northeastern US and then group the species into forest types to allow comparison mapping to current forest types.

2 Background

Our group has been statistically modeling potential change in habitat for common tree species in the eastern United States. We initially developed the DISTRIB model around regression tree analysis, a procedure of recursive partitioning, to predict the potential future habitat, at the scale of the county, for 80 tree species (Iverson and Prasad 1998; Iverson et al. 1999; Prasad and Iverson 1999). In the current effort, we again focus on the eastern United States for the modeling but have made a series of improvements that increase our confidence in the outcomes: (1) the models run at a finer scale of resolution (20×20 km rather than at the county scale); (2) newer Forest Inventory and Analysis (FIA) data are used; (3) estimates of soil and land use are updated; (4) analysis of model behavior and fit are improved; (5) an additional 54 species are modeled; and (6) an improved modeling tool, Random Forests, is used to develop the models (Iverson et al. 2004a; Prasad et al. 2006). We also run the models with three new climate scenarios with two emission trajectories each (see Hayhoe et al. 2006). This work is based on current empirical relationships between organism and environment and assumes a near equilibrium between the two. For this analysis we must build the models on the largest portion of the species range as possible. Currently, forest inventory data allow species-by-species analysis only in the United States within North America. The dataset for the eastern United States is the most complete, so our work is centered on this region. For reporting on this NE assessment, we simply clip out the results from the eastern United States outputs.

3 Methods

We first present the overall methodological steps for this effort, and then provide more detail in the paragraphs following. We selected 134 species which met the criterion of at least 50 cells of recorded presence within the eastern United States from forest inventory data generated by the United States Department of Agriculture (USDA) Forest Service's FIA unit.

First, *Model and Data Preparation* included: (a) Create 20×20 km grid of eastern United States (east of 100th meridian); (b) Calculate importance value (IV) by plot from FIA data (based on number of stems and basal area); (c) Summarize importance value by 20×20 km cell; (d) Prepare predictor variables from source data; and (e) Calculate weighted averages for each predictor variable by cell. Second, *Model Runs* included (a) Run Regression Tree Analysis (RTA) to estimate IV from predictors; (b) Run Bagging Trees (BT) to evaluate stability of 30 individual runs of RTA; (c) Run Random Forests (RF) to create current estimates of IV from 1,000 perturbated trees; and (d) Run RF using future scenarios of climate to estimate future IV (suitable habitat). Third, *Generating Outputs* included: (a) Compare actual (FIA data) maps to predicted current maps; (b) Evaluate relative importance of variables using outputs from RF and BT; (c) Assess stability and reliability of model by calculating an R^2 equivalent, a Fuzzy Kappa, and measures of variability among multiple trees derived from BT; (d) Assess variable relationships, scale of influence, and location of predictors with RTA tree diagrams and maps; (e) Map outputs of RF for current and potential future suitable habitats; and (f) Assess potential changes in suitable habitat under various general circulation model scenarios.

3.1 Model and data preparation

More than 100,000 FIA plots, made up of nearly 3 million trees in the eastern United States, constituted the data source for this effort. Importance values for 134 tree species were calculated based equally on the relative number of stems and the relative basal area in each plot (Iverson and Prasad 1998). The plot data were averaged to yield IV estimates for each 20×20 km cell for each species. Species were included if they were native and had at least 50 cells of occupancy in the eastern United States. As a result, several rare species are included. Other data, including 4 land-use, 1 fragmentation, 7 climate, 5 elevation, 9 soil classes, and 12 soil property variables, were obtained from various agencies and data clearinghouses to provide the 38 predictor variables (Table 1). For current and future climate, we used late-century data created and described by Hayhoe et al. (2006), from three general circulation model outputs: the HadleyCM3 model, the Geophysical Fluid Dynamics Laboratory (GFDL) model, and the Parallel Climate Model (PCM). We used the data for two emission scenarios: the A1fi (high emissions continue) and the B1 (significant conservation and reduction of CO_2 emissions) (Nakićenović et al. 2000). We averaged the three models for each emission scenario to yield an average high (hereafter GCM3_hi) and average low (GCM3_lo) emission set of climate predictors. Although we analyzed all eight scenarios, we used these two averages plus the PCM B1 (coolest scenario, hereafter PCM_lo) and HadleyCM3 A1fi (warmest scenario, hereafter HAD_hi) to represent the averages and extremes of possible outcomes from the climate analysis. Average climate data for each of these four scenarios show that all scenarios are warmer and wetter by 2100 (Table 2).

3.2 Modeling

Three statistical processes were performed in this effort: Regression Tree Analysis (RTA), Bagging (BT), and Random Forests (RF). These techniques have been described in detail

Table 1 Variables used to predict current and future tree species habitat

Variables used			
Climate			
TAVG	Mean annual temperature (°C)	PPTMAYSEP	Mean May–September precipitation (mm)
TJAN	Mean January temperature (°C)		
TJUL	Mean July temperature (°C)	JULJANDIFF	Mean difference between July and January Temperature (°C)
TMAYSEP	Mean May–September temperature (°C)		
PPT	Annual precipitation (mm)		
Elevation			
ELV_CV	Elevation coefficient of variation	ELV_MEAN	Average elevation (m)
		ELV_MIN	Minimum elevation (m)
ELV_MAX	Maximum elevation (m)	ELV_RANGE	Range of elevation (m)
Soil class			
ALFISOL	Alfisol (%)	INCEPTSOL	Inceptisol (%)
ARIDISOL	Aridisol (%)	MOLLISOL	Mollisol (%)
ENTISOL	Entisol (%)	SPODOSOL	Spodosol (%)
HISTOSOL	Histosol (%)	ULTISOL	Ultisol (%)
VERTISOL	Vertisol (%)		
Soil property			
BD	Soil bulk density (g/cm^3)	ORD	Potential soil productivity, (m^3 of timber/ha)
CLAY	Percent clay (<0.002 mm size)		
KFFACT	Soil erodibility factor, rock fragment free	PERM	Soil permeability rate (cm/h)
NO10	Percent soil passing sieve no. 10 (coarse)	PH	Soil pH
		ROCKDEP	Depth to bedrock (cm)
NO200	Percent soil passing sieve no. 200 (fine)	SLOPE	Soil slope (%) of a soil component
OM	Organic matter content (% by weight)	TAWC	Total available water capacity (cm, to 152 cm)
Land use and fragmentation			
AGRICULT	Cropland (%)	NONFOREST	Nonforest land (%)
FOREST	Forest land (%)	WATER	Water (%)
FRAG	Fragmentation index (Riitters et al. 2002)		

elsewhere (Prasad et al. 2006). Suffice it to say that we use them together to the best advantage of each tool, allowing for excellent model results and a method to assess the reliability of the models. The BT procedure produces 30 independent regression trees, using a bootstrapping method with 2/3 of the data used to build each tree (Breiman 1996). The RF is a new data-mining technique that produces accurate predictions that do not overfit the data (Breiman 2001), by random sampling of 2/3 of the observations and less than half of the predictors in each tree. Large numbers of trees (1,000 in our case) are grown (hence a “forest” of trees) and averaged to yield powerful predictions.

Although we are pleased with the capabilities of RF to empirically model species habitats now and into the future, we also recognize that there are certainly limitations to this or any modeling approach. We cannot include changes in land use, land cover, and land

Table 2 Current and predicted mean climate for four future scenarios

Variable	Current	HAD_hi	PCM_lo	GCM3_hi	GCM3_lo
PPT, mm	1,081	1,260	1,193	1,210	1,204
PPTMAYSEP, mm	491	526	535	496	520
TJAN, C	−6	0	−4	−1	−3
TJUL, C	20	28	22	26	23
JULJANDIFF, C	26	28	26	27	26
TMAYSEP, C	17	24	19	23	20
TAVG, C	7	14	9	13	10

management out 100 years, nor disturbances like pests, pathogens, natural disasters, and other human activities. Also, unpredictable invasions, for example, Dutch elm disease, chestnut blight, or the emerald ash borer which is ravaging the ash trees in the midwestern US (Iverson et al. 2007) could result in marked departures from any model predictions.

3.3 Model reliability assessment

We produced a reliability rating for each species model because not all models represent reality to the same degree. We use the R^2 value as a primary indicator but also combine this with three additional indicators – a Fuzzy Kappa (FuzKap) variable based on a cell-by-cell comparison between the actual FIA map and the modeled current map (Hagen-Zanker et al. 2006), and two variables based on the variability among the 30 outcomes. With a stable model, the deviance explained would vary little across trees; an unstable model would yield trees explaining varying degrees of deviance. The CVbag variable considers the amount and consistency of contribution of the top five variables by calculating the coefficient of variation among the 30 trees of the sums of the product of their importance scores and a constant related to their rank (i.e., top variable=5, 5th variable=1). The Top5IV variable scores a comparison between the top five RF variables vs the top five variables of each of the 30 BT outputs, with a 1 indicating that all five variables match the order exactly between RF and a bagging output. Conversely, a zero indicates a completely different set of top five variables.

The final model reliability score was calculated as the average ($R^2\times2$, CVbag, Top5IV, FuzKap) with a double weight for R^2. We arbitrarily classed these as green (reliable, score>0.5), amber (moderately reliable, score >0.3 and <0.5), and red (poor reliability, score <0.3), and are indicated as such on the species maps we produce. We also calculated the portion of the current range that is within the United States (based on Little 1971, 1977) because if the species is primarily a Canadian species, there will be less confidence in the model as well. These also were coded green (>67% in US), amber (33% to 67%) and red (<33% in US).

3.4 Analysis

With 134 species, 3 scenarios, 2 emission pathways, and multiple ways to analyze the data, we select a subset that allows an overview of potential impacts of climate change on the northeastern US forests.

3.4.1 Percent occupancy and change in percentage of the nine northeastern states occupied

This tabulation allows a quick assessment of the species that likely would have gains or losses in the *area* of suitable habitat. We divided it into species gaining at least 10% new suitable habitat in the northeast, species gaining 2% to 10%, no change (±2%), and species losing 2% to 10% or >10% of the area.

3.4.2 Species importance values weighted by area

This statistic incorporates both area and the relative abundance of each species, so it is a better indicator of suitable habitat gains or losses. Because all cells occupy the same area (400 km^2), it is simply a sum of the IV values for all pixels in the area of interest. A species may gain aerial extent but become so minor that the overall importance of the species is diminished within the study area. In this case, we took the ratio of future to present modeled condition to calculate change: a value <1 indicates a decrease in area-weighted importance and a value >1 indicates an increase.

3.4.3 Analysis of dominants, gainers, and losers by state

We used area-weighted importance values to assess species dominance in the region and by selected states. We reported the species with values for the eastern US, the northeastern US, and each state in the Northeast. The top 10 gainers and top 10 losers for each spatial unit also were identified.

3.4.4 Species-level maps

We produced a page of maps for each species with six maps per page: the FIA estimate of current distribution of abundance, the modeled current map, and scenarios of PCM_lo, GCM3_lo, GCM3_hi, HAD_hi. These maps captured the range of possible future conditions according to the models we used.

3.4.5 Forest-type maps

To create our estimates of forest-type maps, we compiled the list of species that make up each of the Forest Service's forest types (Miles et al. 2001) and then combined individual species importance values so that they fell into one or more of these types. In certain cases, e.g., oak–pine, we developed percentage rules to adjust the scores. The Northeast was then clipped out from the resulting maps.

4 Results and discussion

4.1 Model reliability assessment

In general, we found high model reliability scores for the most important species in each state. If the data were abundant, the models usually were reliable according to our rating scheme. Most of the species undergoing the most significant reduction in habitat importance were also in the green zone, while many of the species experiencing a rapid increase in suitable habitat had a lower reliability rating (often due to the need to build the models from fewer samples).

According to our rating scheme, 31 species are in the red (poor reliability) zone, 49 are in the amber (medium reliable) zone, and 55 are in the green (good reliability) zone (Table

8 in the Appendix). We marked these reliability colors on the maps of suitable habitat to help ensure that model reliability is considered when one is viewing the results. Many of the poor-reliability species are small ranged, that is, the model may have failed to capture the underlying drivers and spatial pattern. This phenomenon was identified and analyzed with respect to forecasting extinctions by Schwartz et al. (2006). There also are 13 species in the red zone due to the low proportion of their current range existing within the eastern US, and another 8 in the amber zone. We did not detect a relationship between the percentage for the eastern US and the model reliability score (Table 8 in the Appendix).

4.2 Estimates and changes in area of suitable habitat

The region that comprises the northeastern US states is extremely diverse with respect to tree diversity; it contains most of the 134 species used in this study: 98 species according to FIA data. In addition, based on our models of current conditions, 24 extra species are predicted to have suitable habitat to occur within the northeastern US. Although these species are modeled as rare, the model shows suitable habitat for these species, whether or not the species exists. Because FIA plots are spaced at roughly every 1,000 to 2,250 ha of forest (depending on the state), some species might have been missed by the sampling. However, 14 of the 24 species also fall into the amber or red zones of model reliability, so they might have been modeled as present due to model error. In any case, the high species diversity currently found in the region provides an excellent base to evaluate potential changes to trees under climate change.

RF model outputs yielded estimates of percentage of the area covered for each of 134 species, as modeled for the current time, and for year 2100 according to the four scenarios discussed previously (Table 3, Table 9 in the Appendix). For all scenarios, we estimate that three times more species have increases than decreases in suitable habitat in the northeastern US (Table 3). This might be expected because of the large number of species occupying the southern half of the United States (often with climatic pressure to move north) and a lesser number across the northern tier. According to this assessment using the HAD_hi scenario (the harshest), 26 species are inclined to have a reduced habitat (by at least 2% of the northeastern area) and 84 species may have an increase in habitat by year 2100 (Table 3). For the PCM_lo scenario (least harsh) 22 species would have reduced habitat and 62 would have an increase. Note that 72 of the 134 species bound Canada, so a full assessment of the potential change in suitable habitat is not possible, i.e., only habitat within the United States was analyzed. Our data show that, of the decreasing species, most bound Canada; many of these species would find additional suitable habitat in Canada (Mc Kenney et al. 2001). Most of the increasing species do not yet reach the Canadian boundary because they are more southern in nature. In either case, the northward shifting of habitat is responsible for these patterns of predicted gains and losses.

Calculating the numbers of species that may have suitable habitat entering or leaving the region is further complicated because of the difference between FIA-determined and model-determined species counts, issues related to model reliability and precision, and the rareness of certain species. For example, the small amounts of newly available habitat for some species could be due to model reliability issues or reflect actual gains in habitat. If we consider the 36 species not currently found in the region's FIA plots, our modeling indicates that 11 could have suitable habitat (with at least 1% of the region's area) under the PCM_lo scenario and 22 could have newly available suitable habitat under the HAD_hi scenario (Table 4, Table 9 in the Appendix). However, our models indicate that 20 of 22 species already have suitable habitat at a low level either in reality or as model error, so it is

Table 3 Summary of the number of species with decreasing or increasing suitable habitat (percent of northeastern area) for each climate scenario

Number of species by percentage change class					
Scenario	Decrease >10%	Decrease 2–10%	No change%	Increase 2–10%	Increase >10%
PCM_lo	10	12	50	24	38
GCM3_lo	14	10	45	24	41
GCM3_hi	13	9	45	24	43
HAD_hi	16	10	34	20	54

not surprising that their habitat is expanding in the region under climate change. Also important is that reliability is medium to poor for 6 of 11 new species under PCM_lo and 10 of 22 new species under HAD_hi (Table 4). Species that could have a sizeable amount of newly suitable habitat include *Quercus nigra* (water oak), *Q. lyrata* (overcup oak), *Q. shumardii* (Shumard oak), *Q. falcata* var. *pagodifolia* (cherrybark oak), *P. palustris* (longleaf pine), *P. elliottii* (slash pine), *Celtis laevigata* (sugarberry), *Carya illinoiensis* (pecan), *Taxodium distichum* (baldcypress), and *Ulmus crassifolia* (cedar elm) (Table 4). Even if suitable habitat is present, it remains to be seen whether the species can migrate there and successfully become established.

Our models indicate that no species has suitable habitat removed from the region under any scenario, though the following species would have severely diminished habitat, especially under the harsher scenarios (Table 9 in the Appendix): *Picea mariana* (black spruce), *Acer spicatum* (mountain maple), *Juglans cinerea* (butternut), *Magnolia acuminata* (cucumbertree), and *Sorbus americana* (American mountain-ash).

4.3 Species importance values weighted by area

An analysis that simultaneously includes both species area and species importance perhaps yields a better indicator of potential change in overall species habitat under various scenarios of climate change. To evaluate, we used the ratios of future to current so that values around 1 (0.9 to 1.1) were “no change,” values <0.9 were decreases (in two classes of 0.5 to 0.9 and <0.5), and values >1.1 were increases (in two classes of 1.1 to 2 and >2) under each scenario (Table 10 in the Appendix). Averaged across all scenarios, 73 species showed increases, 54 showed decreases, and 7 had no change (Table 5). We calculated the same ratios after disallowing 50 species that occurred in 20 or less cells within the nine state region (<2% of the northeastern United States), because these species showed much wider variability. For the 84 more common species, 47 showed increases, 31 showed decreases, and 6 had no change (Table 5). Some of the hardest-hit species under this evaluation include relatively common northern species such as *Betula papyrifera* (paper birch), *Populus tremuloides* (quaking aspen), *P. grandidentata* (bigtooth aspen), *Abies balsamea* (balsam fir), *Thuja occidentalis* (northern white-cedar), *Acer pensylvanicum* (striped maple), *Fagus grandifolia* (American beech), *Picea rubens* (red spruce), *Acer saccharum* (sugar maple), and *Prunus serotina* (black cherry). Species showing increases of importance values area include *Quercus stellata* (post oak), *Pinus echinata* (shortleaf pine), *P. taeda* (loblolly pine), *Cercis canadensis* (eastern redbud), *Celtis occidentalis* (hackberry), *Carya cordiformis* (bitternut hickory), *Liquidambar styraciflua* (sweetgum), *Juniperus virginiana* (eastern redcedar), *Populus deltoides* (eastern cottonwood), *Oxydendrum arboretum* (sourwood), and *Platanus occidentalis* (sycamore).

Table 4 Species with suitable habitat entering the northeastern United States for various scenarios of climate change

Common name	Scientific name	Reliability	Percent suitable habitat				
			Modeled current[a]	PCM _lo[b]	GCM3_lo[c]	GCM3_hi[d]	HAD_hi[e]
Sand pine	*Pinus clausa*	Medium	0.6	*1.8*	2.5	2.4	2.6
Slash pine	*Pinus elliottii*	Good	0.7	*1.9*	1.6	4.4	12.2
Longleaf pine	*Pinus palustris*	Good	1	*5*	3.9	4.2	12.6
Pond pine	*Pinus serotina*	Good	0.4	*1.8*	3.1	3.6	4.3
Baldcypress	*Taxodium distichum*	Medium	3.3	*8.8*	10.9	12.6	15.5
Pondcypress	*Taxodium distichum* var. *nutans*	Good	0.3	0.2	0.2	0.2	1.3
Water hickory	*Carya aquatica*	Medium	1.1	0.5	0.6	1.2	2.5
Pecan	*Carya illinoensis*	Poor	0.3	0.8	*4*	34.8	64.1
Black hickory	*Carya texana*	Good	0.3	*12.3*	28.5	80.4	98
Sugarberry	*Celtis laevigata*	Medium	1.5	*3.8*	10.1	60.2	82.8
Swamp tupelo	*Nyssa sylvatica* var. *biflora*	Good	1.2	*4.7*	4.6	5.3	8.6
Redbay	*Persea borbonia*	Good	0.2	0.6	0.3	0.1	*3.2*
Wild plum	*Prunus americana*	Poor	0	0	0	0.7	*11*
Cherrybark oak	*Quercus falcata* var. *pagodifolia*	Medium	0.9	*2.9*	3.7	14.2	20.8
Turkey oak	*Quercus laevis*	Medium	0.7	*2.2*	1.9	2.2	4.9
Laurel oak	*Quercus laurifolia*	Good	0.2	0.5	0.5	*3.2*	6.6
Overcup oak	*Quercus lyrata*	Good	2.1	0.9	1.4	*5.6*	7.4
Water oak	*Quercus nigra*	Medium	0.5	*3.2*	4.6	20.1	42.7
Nuttall oak	*Quercus nuttallii*	Good	0.6	0.2	0.2	*1.1*	4.9
Shumard oak	*Quercus shumardii*	Good	0	0.1	0.3	*27.7*	57.2
Dwarf post oak	*Quercus stellata* var. *margaretta*	Good	0.2	0.2	0.2	0.7	*2.3*
Cedar elm	*Ulmus crassifolia*	Poor	0.1	0	1	*37.2*	66.5

None of the species were found in Forest Inventory and Analysis plots but most had some presence in the models of current suitable habitat. Those numbers in italics could have at least 1% of the area with suitable habitat by the end of this century given the models' reliability classes: poor (red zone), medium (amber zone), and good (green zone, as indicated on maps).

[a] Modeled current=% occupancy, modeled currently to be present in the NE.

[b] PCM_lo=% occupancy under PCM low emissions.

[c] GCM3_lo=% occupancy under average GCM low emissions.

[d] GCM3_hi=% occupancy under average GCM high emissions.

[e] HAD_hi=% occupancy under Hadley high emissions.

4.4 Analysis of dominants, gainers, and losers by state

In this analysis, we identify the dominant species in the eastern United States, Northeast, and selected states within the Northeast. We then evaluate what our models suggest with respect to the primary losers and gainers of suitable habitat according to each scenario. Twenty-eight species are required to rank the top 10 for each state and region, including the eastern United States (Table 6). New Jersey has the most different species list as compared to the Northeast regional top 10, with only 3 species in common. In contrast, New York has

Table 5 Potential species changes in area weighted importance value for habitat suitability

Number of species					
Future:current ratio					
Scenario	<0.5	0.5–0.9	0.9–1.1	1.1–2	> 2
For all 134 species studied					
PCM_lo	29	23	13	29	40
GCM3_lo	28	25	8	24	49
GCM3_hi	38	16	6	12	62
HAD_hi	41	10	2	12	69
For the 84 species in 20 or more 20×20 km cells					
PCM_lo	9	17	10	27	21
GCM3_lo	10	19	7	18	30
GCM3_hi	21	11	6	10	37
HAD_hi	25	8	1	10	40

A future:current ratio below 1 indicates a loss, while a value above 1 indicates a gain.

9 of the 10 dominant species in the Northeast. The top two species in New York and the Northeast are red maple (*A. rubrum*) and sugar maple (*A. saccharum*). Red maple is by far the most dominant species. These maples dominate the top 10 lists for all northeastern US states except Maine, which is dominated by balsam fir (*Abies balsamea*). These species are followed by white ash (*Fraxinus americana*), American beech (*Fagus grandifolia*), and black cherry (*Prunus serotina*) (Table 6).

We also tabulated the area-weighted importance value data for each state, as exemplified by New York (Table 7), and tabulated for several other states (Tables 11–13 in the Appendix). We present the dominant species but also the primary gainers and losers of suitable habitat according to our models. For all states, the hotter models resulting from high-emission scenarios show more extreme losses or gains in importance of suitable habitat. In most states, the suitable habitat for sugar maple (*Acer saccharum*) and red maple (*Acer rubrum*) would decline, but the fact that they are so common now indicates that these species likely would be reduced only in importance. Species of lesser current importance in New York and the other states with a projected loss of most of their habitat according to the hotter scenarios are quaking aspen (*Populus tremuloides*), yellow birch (*Betula alleghaniensis*), balsam fir (*Abies balsamea*) and red spruce (*Picea rubens*) (Table 7). Species with a high possibility of dramatic increases in New York include several oak species, eastern redcedar (*Juniperus virginiana*), hackberry (*Celtis occidentalis*), honeylocust (*Gleditsia triacanthos*), red mulberry (*Morus rubra*), shortleaf pine (*Pinus echinata*), common persimmon (*Diospyros virginiana*), and winged elm (*Ulmus alata*) (Table 7). Most models agree as to what species would lose substantial habitat, but the high-emission scenarios tended to predict different species with big gains in suitable habitat as compared to the low-emission scenarios (Table 7). A 69-year record for the Black Rock Forest in New York has shown invasions by *Ailanthus altissima*, *Catalpa bignonioides*, *Crataegus crus-galli*, *Morus rubra*, *Populus alba*, *Populus deltoides*, and *Ulmus rubra*, with losses of *Juglans nigra*, *Picea mariana*, *Quercus palustris*, and *Ulmus americana* (Bill Schuster, personal communication). Most of these species that were modeled are changing as predicted by our models.

In New Hampshire and Vermont (Tables 11 and 12 in the Appendix), the suitable habitat for red maple (*Acer rubrum*), increases slightly under PCM_lo but is greatly diminished under high-emission scenarios. The same is true for sugar maple (*Acer saccharum*) in Connecticut (Table 13 in the Appendix). It seems this is a clear distinction of low vs high

Table 6 Area-weighted importance values for the top 10 species by region and state as calculated from Forest Inventory and Analysis data; italicized data indicate top 10 statuses for the eastern United States (EUS), the nine northeastern (NE) US states, or an individual US state

Scientific name	EUS	NE	CT	ME	MA	NH	NJ	NY	PA	RI	VT
Acer rubrum	55,147	17,793	921	2,483	1,504	1,300	1,041	3,916	5,048	317	852
Acer saccharum	31,134	9,640	284	1,131	271	589	151	3,946	1,949	5	*1,314*
Fraxinus americana	20,366	7,519	186	359	*250*	249	*416*	3,467	2,203	34	323
Fagus grandifolia	14,152	*7,218*	73	*1,204*	237	447	111	*2,658*	1,821	7	*601*
Prunus serotina	22,835	6,732	177	139	*210*	146	178	*1,985*	3,584	21	199
Abies balsamea	10,528	*5,865*	0	*3,958*	8	*687*	0	532	0	0	*680*
Pinus strobus	9,982	*5,608*	222	1,087	861	982	30	*1,137*	565	*170*	*554*
Tsuga canadensis	6,976	*4,999*	150	839	407	614	64	*1,369*	928	15	*613*
Quercus rubra	21,482	4,694	287	390	*471*	402	217	*935*	1,714	*96*	155
Betula alleghaniensis	4,771	*3,244*	84	*1,026*	132	*427*	20	*805*	276	17	*457*
Picea rubens	3,102	2,961	6	*1,744*	28	*349*	2	471	18	1	*342*
Betula lenta	4,610	2,740	*251*	18	*204*	116	156	486	*1,372*	*42*	94
Betula papyrifera	7,477	2,323	31	*1,191*	84	*401*	4	233	49	1	*329*
Quercus alba	31,212	2,235	*124*	21	179	64	*330*	291	*1,027*	62	19
Quercus prinus	9,811	2,143	45	0	27	4	*203*	270	*1,566*	11	11
Quercus stellata	9,811	2,143	45	0	27	4	*203*	270	*1,566*	11	11
Thuja occidentalis	4,936	1,781	0	*1,341*	1	15	0	250	0	0	174
Quercus velutina	17,853	1,667	*163*	23	*251*	63	*218*	140	672	*88*	6
Ulmus americana	31,133	1,547	47	64	61	43	56	*839*	346	13	72
Sassafras albidum	8,771	1,180	22	0	23	3	150	59	856	*26*	0
Liriodendron tulipferfia	15,495	1,065	22	0	2	0	180	62	698	2	0
Nyssa sylvatica	12,417	974	11	0	17	2	193	45	590	13	0
Pinus rigida	1,571	889	14	17	114	17	*536*	43	127	19	2
Quercus coccinea	5,496	881	77	0	119	13	135	97	323	*81*	1
Carya glabra	9,951	774	94	0	60	12	71	191	301	*21*	7
Liquidambar styraciflua	32,335	515	0	0	0	0	*186*	4	82	0	0
Fraxinus pennsylvanica	20,660	398	1	7	7	7	2	245	103	2	18
Pinus taeda	52,284	134	0	0	0	0	2	0	2	0	0

EUS: eastern United States, *NE*: northeastern United States, *CT*: Connecticut, *ME*: Maine, *NH*: New Hampshire, *NJ*: New Jersey, *NY*: New York, *PA*: Pennsylvania, *RI*–Rhode Island, *VT*: Vermont.

emissions in the northeastern United States – the maples are largely spared from massive decline under the low-emission scenarios.

4.5 Species-level maps

We prepared maps for each species based on FIA, current model, HAD_hi, GCM3_hi, GCM3_lo, PCM_lo that also reflect our estimate of model reliability (Fig. 1). Maps for all 134 species are available from our website http://www.nrs.fs.fed.us/atlas. We include here an example species of large economic value (sugar maple, Fig. 1a), and a northern species losing considerable habitat (balsam fir, Fig. 1b).

4.6 Forest-type maps

By combining individual species importance maps and developing quantitative rules for establishing the dominant forest type in a particular cell, we created maps of forest types for the northeastern United States (Fig. 2). We find that in future, only PCM_lo (the least harsh

Table 7 Species in New York with the potential for substantial (top 10) losses (italic) or gains (bold) in suitable habitat based on area-weighted importance value; differences expressed as percentages

Common name	Scientific name	CurMod	dif_PCM_lo	dif_GCM3_lo	dif_GCM3_hi	dif_HAD_hi
Red maple	*Acer rubrum*	**4,319**	−2.6	*−10.8*	*−46.2*	*−57.7*
Sugar maple	*Acer saccharum*	**3,913**	*−21.2*	*−26.5*	*−55.9*	*−69.8*
White ash	*Fraxinus americana*	**3,216**	*−7.3*	*−16.5*	*−53.7*	*−62.1*
American beech	*Fagus grandifolia*	**2,587**	*−27.7*	*−40.6*	*−66.3*	*−71.4*
Black cherry	*Prunus serotina*	**1,976**	6.9	−4.4	*−59.2*	*−67.6*
Eastern hemlock	*Tsuga canadensis*	**1,478**	*−15.2*	*−25.0*	*−50.9*	*−54.2*
Eastern white pine	*Pinus strobus*	**1,332**	*−20.3*	*−22.0*	*−47.8*	*−58.5*
Northern red oak	*Quercus rubra*	**1,154**	26.5	33.6	20.8	5.9
Quaking aspen	*Populus tremuloides*	**899**	*−58.8*	*−72.0*	*−91.9*	*−92.7*
American elm	*Ulmus americana*	**861**	17.9	38.3	60.3	58.2
Yellow birch	*Betula alleghaniensis*	846	*−30.3*	*−48.1*	*−66.5*	*−66.0*
Balsam fir	*Abies balsamea*	738	*−40.5*	*−53.0*	*−68.7*	*−69.1*
White oak	*Quercus alba*	556	**84.9**	129.0	251.8	230.0
Red spruce	*Picea rubens*	497	*−54.7*	*−59.8*	−63.6	−59.6
Black oak	*Quercus velutina*	359	**98.9**	147.6	391.6	419.5
Chestnut oak	*Quercus prinus*	316	**142.7**	161.1	148.1	120.9
Post oak	*Quercus stellata*	316	**142.7**	161.1	148.1	120.9
Black ash	*Fraxinus nigra*	257	*−71.6*	−74.7	−81.7	−79.4
Eastern redcedar	*Juniperus virginiana*	177	**246.3**	436.2	907.9	952.0
Sassafras	*Sassafras albidum*	146	**182.2**	226.7	374.0	386.3
Flowering dogwood	*Cornus florida*	140	**420.0**	590.0	779.3	740.0
Yellow-poplar	*Liriodendron tuliperfia*	119	**235.3**	301.7	342.9	313.4
Black walnut	*Juglans nigra*	105	**298.1**	414.3	494.3	438.1
Hackberry	*Celtis occidentalis*	40	410.0	**910.0**	1,840.0	2030.0
Honeylocust	*Gleditsia triacanthos*	16	718.8	1,356.3	**4,393.8**	5,481.3
Red mulberry	*Morus rubra*	8	1,787.5	3,650.0	**10,262.5**	13,900.0
Blackjack oak	*Quercus marilandica*	6	633.3	1,483.3	**13,583.3**	19,183.3
Shortleaf pine	*Pinus echinata*	6	383.3	1,033.3	11383.3	**18,283.3**
Common persimmon	*Diospyros virginiana*	5	1,200.0	3,120.0	**1,5240.0**	18,020.0
Winged elm	*Ulmus alata*	1	3,800.0	7,800.0	**7,6300.0**	14,2700.0

scenario) retains spruce–fir habitat while the oak–hickory type gains significant habitat in all scenarios and especially under the high emission scenarios. Note that these maps reflect habitat suitability and not where the species may end up any time within the next 100 years. Forest and land management (or non-management) also have much to do with final outcomes. For example, these days most oaks and hickories have difficulty regenerating, e.g., Sutherland and Hutchinson (2003), so that oak–hickory expansions may not actually materialize (Iverson et al. 2004b; Carmel and Flather 2006). In contrast, a primary species

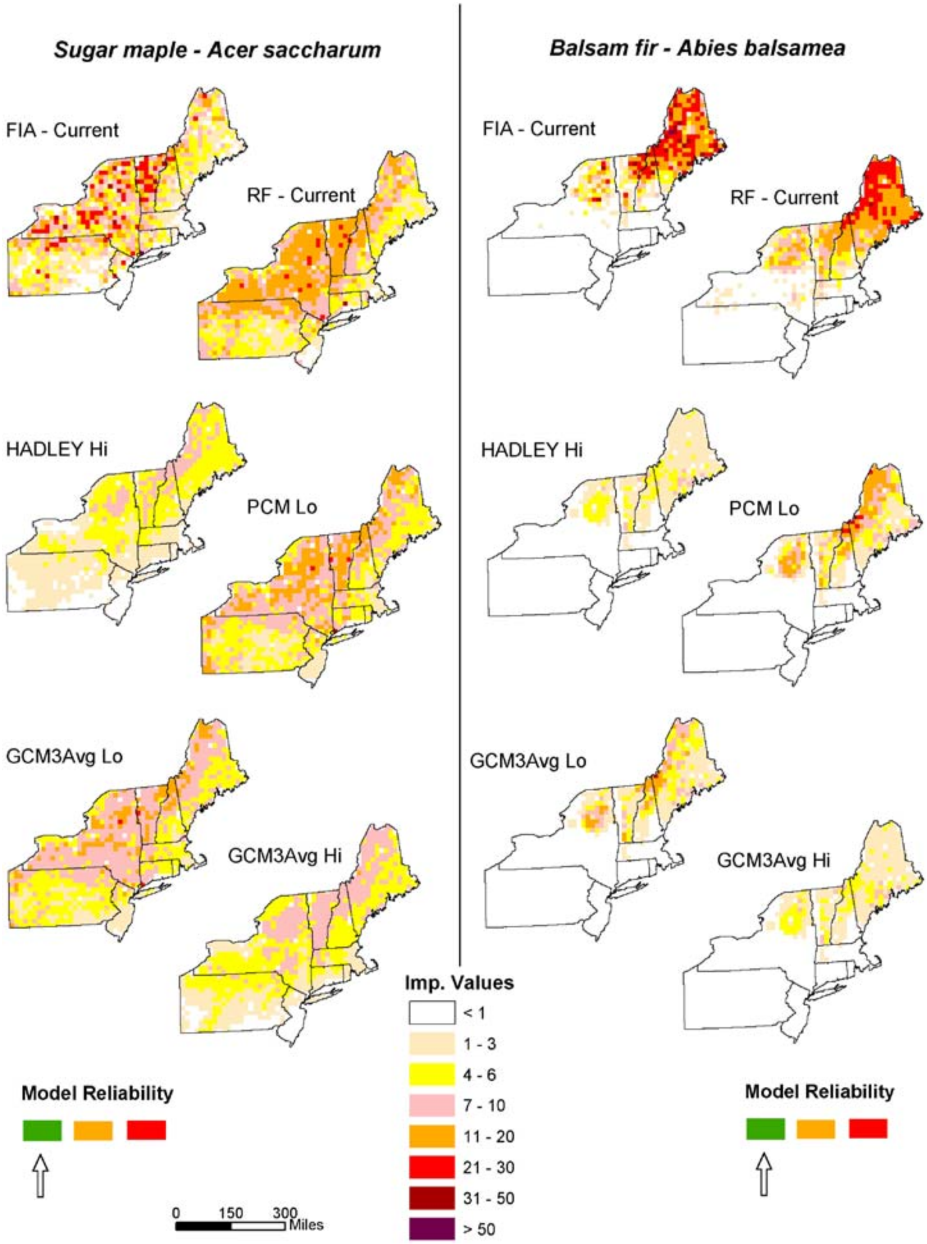

Fig. 1 Maps of suitable habitat for **a** sugar maple (*Acer saccharum*) and **b** balsam fir (*Abies balsamea*) under current and potential future scenarios of climate change according to the Random Forests analysis. Importance values are based on species basal area and number of stems as determined by US Forest Service Forest Inventory and Analysis units. *Arrow* reflects the reliability level of the model where *red* is poor, *orange* is medium, and *green* is good

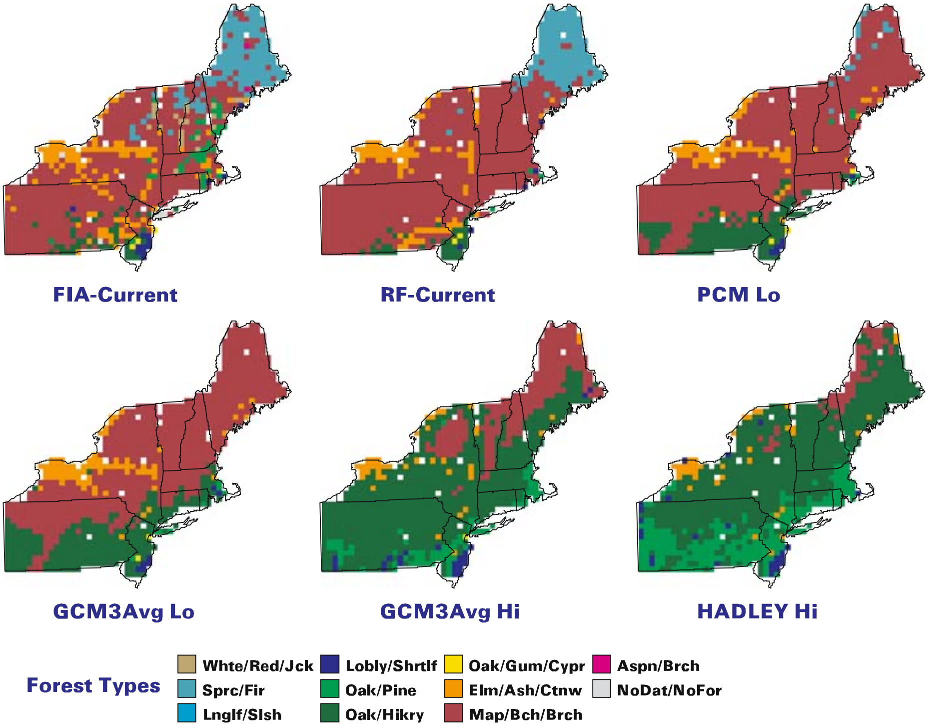

Fig. 2 Forest-type maps for the northeastern United States based on combining individual species maps of importance

currently replacing oaks, red maple, is presently flourishing in most environments under closed canopies resulting from little or no forest management (Sutherland and Hutchinson 2003); it seems plausible that the maple–beech–birch type will persist.

5 Conclusions

We show that forests of the northeastern United States are likely to undergo radical changes as the climate changes. Although we cannot put an exact timeline to the potential changes outlined here, suitable habitat will diminish for most of the currently important species: sugar maple (*Acer saccharum*), red maple (*Acer rubrum*), black cherry (*Prunus serotina*), balsam fir (*Abies balsamea*), red spruce (*Picea rubens*), yellow birch (*Betula alleghaniensis*), quaking aspen (*Populus tremuloides*), eastern white pine *(Pinus strobus)*, eastern hemlock (*Tsuga canadensis*), American beech (*Fagus grandifolia*), and white ash (*Fraxinus americana*). The models thus suggest a retreat of the spruce–fir zone as seen in the past (DeHayes et al. 2000). The extent of these changes depends largely on the emission scenario selected by humans over the next century–changes would be much less dramatic if humans follow a low-emissions pathway. The species listed as potential losers currently provide most of the region's commercial and tourism value. We have not addressed the potential economic impact of such changes but they are likely to be substantial.

Coupled with the reduced habitat for these species are the pests and diseases, e.g., the hemlock wooly adelgid on hemlock (Paradis et al. 2007) and emerald ash borer on ash

(Poland and McCullough 2006; Iverson et al. 2007), spruce budworm, pine bark beetle, white pine blister rust, beech bark disease, maple decline, spruce/fir decline (cited in Ayers and Lombardero 2000) that are threatening several of the same species. Thus the compositional changes could be accelerated. Warming also tends to accelerate the rate of insect development and facilitate range expansions of pests and diseases listed above. When climate change produces a mismatch between mature trees and the habitat upon which it is living, there can be increased vulnerability to pests and pathogens (Ayers and Lombardero 2000). Invasive plants also are likely to spread under climate change as niches open, because the invaders are adapted to wider conditions and rapid colonization and growth after disturbance and elevated CO_2 (Williamson 1999; Weltzin et al. 2003). Of course, other human-derived disturbances associated with changes in land use and land cover have had and will continue to have profound impacts on the species composition (Foster and Aber 2004).

Beyond the disturbances associated with insects and disease, a changing climate will increase the potential for other disturbances. Climatic effects such as increases in wind and ice damage, hurricane intensity, heavy precipitation events, drought in the later parts of the growing season, flooding during the growing season, and warmer winter and summer temperatures (Hayhoe et al. 2006) can increase stress on species, leading to further changes. An analysis of 806 northern temperate trees and shrubs showed that few species can tolerate more than one of the following stresses: shade, drought, or waterlogging (Niinemets and Valladares 2006). Climate change will modify the proportions of these stresses, e.g., increases in both drought and waterlogging potential, again leading to changes in species composition. Finally, wildfire is liable to increase under climate change, at least in some portions of the country (McKenzie et al. 2004). Fire could have a substantial effect on hastening species changes that are undergoing shifts in their habitat suitability, especially in places like the uninterrupted forests in Maine and the New Jersey pine barrens.

Concurrently, some species will likely increase substantially in habitat. These include several oaks (red, white, black, and chestnut), sweet birch, and silver maple. Increased habitat for oak could indicate an increased commercial and wildlife resource, but oaks are currently undergoing a regeneration crisis in the absence of fire or other agents that can partially open the canopy (Loftis and McGee 1993; Iverson et al. 2004b). It is possible that some of the disturbances mentioned may open the canopy sufficiently to enhance the probability of oak regeneration. Additional research on this topic is needed.

Another series of species may enter the Northeast from the south, including fairly common species such as longleaf pine, slash pine, and sugarberry, as well as uncommon species such as sand and pond pine and cherrybark, turkey, laurel, overcup, and Shumard's oak. Our models show that species with increasing suitable habitat outnumber those with decreasing habitat. This trend can be explained by the nature of the geography associated with the ranges of tree species. In the northeastern United States, there is much territory south but none north (because we cannot model Canada with FIA data). However, the pressures (backed by paleo and ever increasing present-day data) are for the species to migrate northward; so it is logical that many southern species, especially ones driven largely by climate (particularly temperature), would gain suitable habitat or grow inside the Northeast.

It is important to understand that we do not here model potential species ranges by the year 2100, only the suitable habitat related to each species. We would not expect the changes presented here to be realized by 2100 unless the disturbance agents cited exert a profound acceleration effect on the changes. We would expect that it is more likely that disturbance agents would hasten declines to a greater degree than they would accelerate the prominence of new species entering the region; however, if the species already is present (like some of the common oaks), they may increase in importance as the competitors decrease. Trees generally live a long time and migrate slowly so that great lag times would need to be considered to determine actual estimated ranges. We have attempted to do this for several species in other work using a companion model (SHIFT). We found that the lag times and fragmented nature of the remaining forests greatly slow migration rates. We estimated that, for five species, less than 15% of the suitable habitat would have a 1 in 50 chance of being colonized within 100 years (Iverson et al. 2004c).

An evaluation of the top 10 potential losers and gainers of potential suitable habitat for each of the states allows more specific generalizations about possible trends. For example in New York, habitat for red maple (*Acer rubrum*) and sugar maple (*Acer saccharum*) would decline substantially but not disappear, while most of the habitat is projected to disappear for quaking aspen (*Populus tremuloides*), yellow birch (*Betula alleghaniensis*), balsam fir (*Abies balsamea*), and red spruce (*Picea rubens*), according to the hotter scenarios. Species with a high possibility of dramatic increases include several oak species, eastern redcedar (*Juniperus virginiana*), hackberry (*Celtis occidentalis*), honeylocust (*Gleditsia triacanthos*), red mulberry (*Morus rubra*), shortleaf pine (*Pinus echinata*), common persimmon (*Diospyros virginiana*), and winged elm (*Ulmus alata*).

We also prepared forest-type maps according to decision rules applied to average species composition and importance within each 20×20 km cell. In this analysis, the habitat for the spruce–fir type is eliminated under each of the high-emission scenarios; some habitat is retained in the PCM_lo emission scenario. The models also reflect an increase in oak–hickory habitat and a decrease in maple–beech–birch habitat, especially under the high emission scenarios.

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Appendix

Table 8 Model reliability assessment scores, percentage of range in the eastern United States, and the top two variables defining the model. Mod Rel >0.5 green (good reliability), Mod Rel 0.3–0.5 amber (medium), Mod Rel <0.3 red (poor)

Species	EastUS %	R2_RF	CVBag	Top5VI	FuzKap	ModRel	RF_vi1	RF_vi2
Abies balsamea	13.8	0.79	0.94	0.51	0.72	0.75	tmaysep	tjul
Acer barbatum	100.0	0.09	0.76	0.42	0.23	0.32	ppt	pptmaysep
Acer negundo	67.5	0.16	0.81	0.37	0.22	0.34	Elv_mean	Elv_min
Acer nigrum	91.9	−0.06	0.58	0.43	0.15	0.21	ppt	NO200
Acer pensylvanicum	59.8	0.5	0.91	0.56	0.63	0.62	Elv_rang	tjul
Acer rubrum	81.3	0.61	0.96	0.64	0.49	0.66	MOLLISOL	tjul
Acer saccharinum	93.3	0.11	0.79	0.41	0.23	0.33	ppt	Elv_mean
Acer saccharum	73.4	0.49	0.95	0.59	0.46	0.59	tjul	ORD
Acer spicatum	34.2	0.45	0.85	0.45	0.56	0.55	tmaysep	tjul
Aesculus glabra	100.0	−0.03	0.72	0.32	0.24	0.25	ppt	pptmaysep
Aesculus octandra	100.0	0.18	0.79	0.5	0.49	0.43	SLOPE	Elv_mean
Alnus glutinosa	82.6	0.22	0.36	0.47	0.63	0.38	Elv_rang	Elv_Cv
Asimina triloba	99.3	0.03	0.47	0.31	0.37	0.24	Elv_Cv	Elv_min

Table 8 (continued)

Species	EastUS %	R2_RF	CVBag	Top5VI	FuzKap	ModRel	RF_vi1	RF_vi2
Betula alleghaniensis	58.7	0.65	0.94	0.51	0.70	0.69	tjul	tmaysep
Betula lenta	99.3	0.52	0.89	0.57	0.60	0.62	Elv_rang	INCEPTIS
Betula nigra	100.0	0.03	0.31	0.32	0.24	0.19	Elv_mean	Elv_max
Betula papyrifera	9.5	0.69	0.93	0.59	0.69	0.72	tmaysep	tavg
Betula populifolla	95.8	0.24	0.74	0.3	0.56	0.41	Elv_mean	Elv_min
Bumelia lanuginosa	95.6	−0.01	0.55	0.34	0.13	0.20	Elv_Cv	AGRICULT
Carpinus caroliniana	93.5	0.18	0.85	0.41	0.39	0.40	ppt	ORD
Carya aquatica	100.0	0.18	0.53	0.36	0.36	0.32	MOLLISOL	ppt
Carya cordiformis	96.4	0.07	0.61	0.32	0.38	0.29	pptmaysep	ppt
Carya glabra	99.7	0.4	0.93	0.49	0.52	0.55	ppt	ULTISOL
Carya illinoensis	99.5	0.02	0.67	0.32	0.24	0.26	ppt	AGRICULT
Carya laciniosa	99.9	−0.01	0.59	0.36	0.12	0.21	AWC	ppt
Carya ovata	96.0	0.22	0.82	0.38	0.41	0.41	pptmaysep	ppt
Carya texana	100.0	0.49	0.88	0.49	0.59	0.59	NO10	ppt
Carya tomentosa	99.7	0.38	0.94	0.46	0.51	0.53	ppt	ULTISOL
Castanea dentata	97.1	0.15	0.78	0.43	0.30	0.36	Elv_max	Elv_rang
Catalpa speciosa	100.0	−0.01	0.36	0.28	0.04	0.13	Elv_min	Elv_mean
Celtis laevigata	97.6	0.32	0.77	0.49	0.38	0.46	INCEPTIS	ORD
Celtis occidentalis	94.4	0.27	0.87	0.46	0.37	0.45	pptmaysep	NO200
Cercis canadensis	98.6	0.14	0.57	0.55	0.48	0.37	pptmaysep	ppt
Chamaecyparis thyoides	100.0	0.11	0.58	0.33	0.27	0.28	Elv_Cv	AGRICULT
Cornus florida	98.8	0.5	0.95	0.47	0.53	0.59	ULTISOL	FOREST
Diospyros virginiana	100.0	0.12	0.74	0.41	0.48	0.37	ppt	pptmaysep
Fagus grandifolia	83.4	0.51	0.93	0.61	0.52	0.61	AGRICULT	tjul
Fraxinus americana	86.9	0.41	0.91	0.5	0.47	0.54	juljandiff	ppt
Fraxinus nigra	45.4	0.33	0.84	0.52	0.56	0.51	HISTOSOL	ppt
Fraxinus pennsylvanica	70.4	0.1	0.83	0.32	0.24	0.32	ppt	pptmaysep
Fraxinus quadrangulata	99.8	0.14	0.67	0.26	0.23	0.29	Elv_rang	ALFISOL
Gleditsia aquatica	100.0	−0.06	0.40	0.37	0.17	0.16	Elv_Cv	Elv_min
Gleditsia triacanthos	99.9	0.04	0.65	0.3	0.32	0.27	pptmaysep	ppt
Gordonia lasianthus	100.0	0.24	0.77	0.39	0.48	0.42	pptmaysep	AGRICULT
Gymnocladus dioicus	99.8	0	0.62	0.39	0.32	0.27	NONFOR	AGRICULT
Halesia spp.	100.0	0.29	0.57	0.51	0.53	0.44	SLOPE	ppt
Ilex opaca	100.0	0.47	0.89	0.47	0.59	0.58	ULTISOL	Elv_mean
Juglans cinerea	90.7	0.05	0.38	0.29	0.22	0.20	Elv_Cv	AGRICULT
Juglans nigra	98.7	0.18	0.78	0.37	0.45	0.39	pptmaysep	Elv_max
Juniperus virginiana	95.4	0.19	0.76	0.28	0.32	0.35	ppt	Elv_rang
Larix laricina	12.2	0.39	0.85	0.4	0.59	0.52	HISTOSOL	tavg
Liquidambar styraciflua	100.0	0.68	0.97	0.53	0.62	0.70	ORD	ppt
Liriodendron tuliperfia	98.6	0.6	0.96	0.73	0.62	0.70	ULTISOL	tjul
Maclura pomifera	98.1	0.2	0.77	0.41	0.31	0.38	pptmaysep	ppt
Magnolia acuminata	99.6	0.36	0.89	0.52	0.61	0.55	SLOPE	Elv_rang
Magnolia grandiflora	100.0	0.15	0.83	0.37	0.43	0.39	pptmaysep	ppt
Magnolia macrophylla	100.0	0.09	0.55	0.46	0.20	0.28	ppt	pptmaysep

Table 8 (continued)

Species	EastUS %	R2_RF	CVBag	Top5VI	FuzKap	ModRel	RF_vi1	RF_vi2
Magnolia virginiana	100.0	0.33	0.74	0.48	0.62	0.50	pptmaysep	ppt
Morus rubra	99.0	0.05	0.75	0.35	0.25	0.29	ppt	pptmaysep
Nyssa aquatica	100.0	0.13	0.57	0.43	0.32	0.32	Elv_Cv	Elv_mean
Nyssa ogechee	100.0	0.64	0.91	0.52	0.62	0.67	KFFACT	pptmaysep
Nyssa sylvatica	99.0	0.15	0.62	0.28	0.42	0.33	ppt	ORD
Nyssa sylvatica var. *biflora*	99.7	0.47	0.95	0.56	0.60	0.61	ULTISOL	ppt
Ostrya virginiana	85.7	0.09	0.72	0.34	0.33	0.31	ppt	pptmaysep
Oxydendrum arboreum	100.0	0.63	0.94	0.76	0.66	0.72	juljandiff	ULTISOL
Persea borbonia	100.0	0.37	0.89	0.5	0.61	0.55	pptmaysep	KFFACT
Picea glauca	4.7	0.23	0.81	0.4	0.63	0.46	tmaysep	tjul
Picea mariana	7.0	0.69	0.90	0.48	0.65	0.68	tmaysep	tavg
Picea rubens	47.2	0.65	0.91	0.61	0.67	0.70	tjul	tmaysep
Pinus banksiana	7.9	0.43	0.87	0.5	0.50	0.55	NO200	ENTISOL
Pinus clausa	100.0	0.26	0.60	0.44	0.31	0.38	pptmaysep	ppt
Pinus echinata	100.0	0.6	0.86	0.46	0.55	0.61	ULTISOL	ppt
Pinus elliottii	100.0	0.64	0.93	0.62	0.56	0.68	KFFACT	pptmaysep
Pinus glabra	100.0	0.3	0.75	0.44	0.49	0.46	ppt	FOREST
Pinus palustris	100.0	0.45	0.92	0.63	0.54	0.60	pptmaysep	ppt
Pinus pungens	100.0	0.2	0.69	0.38	0.46	0.38	Elv_max	CLAY
Pinus resinosa	42.5	0.24	0.82	0.46	0.46	0.44	NO200	ppt
Pinus rigida	99.9	0.54	0.80	0.51	0.47	0.57	PERM	PH
Pinus serotina	100.0	0.43	0.80	0.45	0.52	0.53	pptmaysep	Elv_mean
Pinus strobus	55.1	0.44	0.91	0.63	0.53	0.59	Elv_min	CLAY
Pinus taeda	99.9	0.77	0.96	0.58	0.58	0.73	ORD	tjan
Pinus virginiana	100.0	0.54	0.92	0.53	0.54	0.61	ULTISOL	tjul
Planera aquatica	100.0	−0.06	0.55	0.35	0.15	0.19	Elv_Cv	Elv_rang
Platanus occidentallis	97.6	0.07	0.69	0.4	0.37	0.32	ppt	pptmaysep
Populus balsamifera	8.4	0.61	0.83	0.51	0.60	0.63	tjan	ppt
Populus deltoides	70.5	0.04	0.80	0.27	0.20	0.27	ppt	Elv_mean
Populus grandidentata	60.5	0.39	0.91	0.49	0.58	0.55	tjul	ppt
Populus tremuloides	15.6	0.74	0.92	0.53	0.61	0.71	tavg	tjan
Prunus americana	85.5	−0.03	0.44	0.29	0.11	0.16	Elv_mean	ppt
Prunus pensylvanica	20.3	0.13	0.69	0.44	0.39	0.36	pptmaysep	tmaysep
Prunus serotina	81.3	0.41	0.92	0.57	0.45	0.55	ppt	tjan
Prunus virginiana	28.7	−0.03	0.47	0.26	0.34	0.20	Elv_rang	ppt
Quercus alba	97.3	0.41	0.93	0.54	0.44	0.55	SLOPE	ppt
Quercus bicolor	97.1	0.05	0.75	0.25	0.23	0.27	Elv_mean	Elv_Cv
Quercus coccinea	99.8	0.39	0.89	0.48	0.62	0.55	ULTISOL	PERM
Quercus durandii	92.9	−0.1	0.41	0.35	0.02	0.12	ppt	pptmaysep
Quercus ellipsoidalis	99.2	0.34	0.75	0.44	0.44	0.46	pptmaysep	ENTISOL
Quercus falcata var. *falcata*	99.8	0.47	0.95	0.46	0.63	0.60	ORD	ppt
Quercus falcata var. *pagodifolia*	100.0	0.24	0.74	0.47	0.56	0.45	ppt	Elv_max
Quercus ilicifolia	99.3	0.02	0.54	0.27	0.22	0.21	PERM	AWC
Quercus imbricaria	100.0	0.27	0.84	0.3	0.49	0.43	ALFISOL	pptmaysep

Table 8 (continued)

Species	EastUS %	R2_RF	CVBag	Top5VI	FuzKap	ModRel	RF_vi1	RF_vi2
Quercus laevis	99.5	0.23	0.79	0.43	0.43	0.42	ppt	pptmaysep
Quercus laurifolia	99.5	0.47	0.77	0.42	0.48	0.52	AGRICULT	ppt
Quercus lyrata	99.9	0.44	0.92	0.51	0.62	0.58	KFFACT	pptmaysep
Quercus macrocarpa	76.9	0.2	0.50	0.39	0.37	0.33	pptmaysep	Elv_Cv
Quercus marilandica	99.9	0.18	0.87	0.53	0.37	0.43	juljandiff	ppt
Quercus michauxii	99.8	0.38	0.72	0.41	0.44	0.47	ppt	NO10
Quercus muehlenbergii	97.9	0.15	0.78	0.43	0.41	0.38	Elv_mean	Elv_max
Quercus nigra	99.8	0.25	0.78	0.42	0.47	0.43	NONFOR	pptmaysep
Quercus nuttallii	100.0	0.53	0.95	0.61	0.61	0.65	ORD	tjan
Quercus palustris	99.3	0.1	0.59	0.3	0.35	0.29	Elv_max	ppt
Quercus phellos	100.0	0.1	0.68	0.33	0.32	0.31	pptmaysep	Elv_mean
Quercus prinus	97.6	0.22	0.81	0.38	0.54	0.43	Elv_max	Elv_mean
Quercus rubra	82.0	0.61	0.93	0.6	0.59	0.67	Elv_rang	SLOPE
Quercus shumardii	99.9	0.38	0.91	0.52	0.48	0.53	tmaysep	ppt
Quercus stellata	98.2	−0.01	0.63	0.33	0.16	0.22	ppt	pptmaysep
Q.stellata var. *margaretta*	99.7	0.56	0.91	0.47	0.57	0.61	ppt	NO10
Quercus velutina	98.7	0.49	0.90	0.56	0.48	0.58	NO10	CLAY
Quercus virginiana	88.1	0.24	0.82	0.5	0.56	0.47	juljandiff	pptmaysep
Robinia pseudoacacia	100.0	0.04	0.56	0.22	0.34	0.24	Elv_mean	Elv_max
Salix amygdaloides	32.1	−0.06	0.08	0.38	0.01	0.07	ppt	pptmaysep
Salix nigra	99.8	−0.01	0.68	0.28	0.20	0.23	pptmaysep	ppt
Sassafras albidum	98.8	0.34	0.85	0.66	0.48	0.53	tjan	ppt
Sorbus americana	20.5	0.16	0.77	0.4	0.26	0.35	tmaysep	tjul
Taxodium distichum	100.0	0.17	0.65	0.42	0.42	0.37	VERITSOL	Elv_Cv
T. distichum var. *nutans*	100.0	0.4	0.80	0.41	0.53	0.51	pptmaysep	juljandiff
Thuja occidentalis	30.4	0.62	0.91	0.59	0.62	0.67	tmaysep	Elv_max
Tilia americana	84.5	0.2	0.84	0.36	0.44	0.41	ppt	pptmaysep
Tsuga canadensis	71.5	0.51	0.91	0.63	0.62	0.64	AGRICULT	tjul
Ulmus alata	100.0	0.34	0.78	0.56	0.54	0.51	ppt	pptmaysep
Ulmus americana	72.4	0.28	0.93	0.44	0.35	0.46	pptmaysep	ppt
Ulmus crassifolia	98.7	0.01	0.32	0.26	0.27	0.17	Elv_Cv	pptmaysep
Ulmus rubra	92.7	0.08	0.67	0.36	0.34	0.30	ppt	pptmaysep

Table 9 Percent occupancy of suitable habitat in the northeastern USA for 134 species under current (actual and modeled) and 4 potential future scenarios

Species	FIA	Current modeled	PCM_lo	GCM3_lo	GCM3_hi	HAD_hi	Canada
Abies balsamea	34.6	43.6	33.8[a]	33.3[b]	32.8[b]	32.9[b]	1
Acer barbatum	0	0	0	0	0	0.2	
Acer negundo	8.6	22.9	24.7	30.3[c]	44.3[d]	64.1[d]	1
Acer nigrum	0.8	1.1	0.6	0.2	0.1	0.1	1
Acer pensylvanicum	53	72.1	61.5[b]	57.4[b]	42.9[b]	38.8[b]	1

Table 9 (continued)

Species	FIA	Current modeled	PCM_lo	GCM3_lo	GCM3_hi	HAD_hi	Canada
Acer rubrum	97	100	100	100	100	100	1
Acer saccharinum	8	31.1	44.4[d]	63.6[d]	97.5[d]	98.8[d]	1
Acer saccharum	84.8	98.7	100	99.9	91.2[a]	83.4[b]	1
Acer spicatum	16.4	19.5	10.2[a]	6.8[b]	1.4[b]	1.3[b]	1
Aesculus glabra	0.1	0	3.9[b]	5[c]	0.7	1.7	
Aesculus octandra	0.3	0.9	0.6	0.4	0.6	0.6	
Alnus glutinosa	43.1	58.3	59.3	59.5	57	57.8	1
Asimina triloba	0.7	2.8	13.4[d]	16.3[d]	19.6[d]	19.7[d]	1
Betula alleghaniensis	68.6	80.7	69.9[b]	62.4[b]	53.1[b]	52.1[b]	1
Betula lenta	48.5	68	78.9[d]	77.4[c]	78.6[d]	72.4[c]	1
Betula nigra	0.9	1.3	1.4	1.8	7.2[c]	23.9	
Betula papyrifera	45.3	56.5	39.4[b]	34.3[b]	18.5[b]	15[b]	1
Betula populifolla	31.1	45.8	45	44	37.3[a]	37.7[a]	1
Bumelia lanuginosa	0	0	0	0	0.2	0.4	
Carpinus caroliniana	36.6	63.7	70[c]	77.7[d]	94.5[d]	99.3[d]	1
Carya aquatica	0	1.1	0.5	0.6	1.2	2.5	
Carya cordiformis	9.5	7.1	26.3[d]	46.7[d]	93.7[d]	99.4[d]	1
Carya glabra	29.7	56.1	78.9[d]	84.5[d]	99.4[d]	100[d]	1
Carya illinoensis	0	0.3	0.8	4[c]	34.8[d]	64.1[d]	
Carya laciniosa	0.9	0.2	1	5.8[c]	23.3[d]	26.4[d]	1
Carya ovata	17.9	29.1	53.6[d]	68.3[d]	94.7[d]	99.1[d]	1
Carya texana	0	0.3	12.3[d]	28.5[d]	80.4[d]	98[d]	
Carya tomentosa	22.7	48	65.5[d]	71.8[d]	92.7[d]	99.4[d]	1
Castanea dentata	9.9	4.2	6.6[c]	5.1	3.2	2.8	1
Catalpa speciosa	0.5	0.7	0.4	0.4	7[c]	20	
Celtis laevigata	0	1.5	3.8[c]	10.1[c]	60.2[d]	82.8[d]	
Celtis occidentalis	3.2	9.1	31.3[d]	52.8[d]	96[d]	98.5[d]	1
Cercis canadensis	1.5	5.2	32.7[d]	49.6[d]	81.6[d]	88.9[d]	
Chamaecyparis thyoides	2.2	5.7	4.1	4.1	3.8	3.6	
Cornus florida	24.5	40.7	76.5[d]	85.6[d]	99.8[d]	99.9[d]	1
Diospyros virginiana	0.7	2	20.2[d]	36.3[d]	87.1[d]	99.5[d]	
Fagus grandifolia	79.6	99.6	99.8	99.1	91.4[a]	88.3[b]	1
Fraxinus americana	84.9	97.1	100[c]	100[c]	100[c]	99.9[c]	1
Fraxinus nigra	19.9	37.4	24.3[b]	25.7[b]	15.8[b]	16.3[b]	1
Fraxinus pennsylvanica	12.2	24.5	26.3	29.9[c]	50[d]	78.5[d]	1
Fraxinus quadrangulata	0.1	0.2	0	0.1	0	0	1
Gleditsia aquatica	0	0	0	0	4.4[c]	10.4[d]	
Gleditsia triacanthos	0.9	2.8	16.1[d]	28.1[d]	80.5[d]	95.6[d]	1
Gordonia lasianthus	0	0.4	0.3	0.2	0.2	0.5	
Gymnocladus dioicus	0	0	0	0	0.3	5.2[c]	
Halesia spp.	0	0.1	0	0	0	0.1	
Ilex opaca	0.8	3.2	5.8[c]	7.9[c]	12.1[c]	14.3[d]	
Juglans cinerea	9.8	8.6	5.6[a]	4.4[a]	0.7[a]	0.5[a]	1
Juglans nigra	14.4	27.7	64.4[d]	79.2[d]	87.8[d]	79.4[d]	1
Juniperus virginiana	10.1	26.2	67.1[d]	82.3[d]	99.8[d]	100[d]	1
Larix laricina	12.3	18.9	13.5[a]	13.8[a]	10.7[a]	10.6[a]	1
Liquidambar styraciflua	2.3	9.6	24.5[d]	38.6[d]	77.5[d]	93.4[d]	
Liriodendron tuliperfia	24.5	39.9	70.5[d]	78.3[d]	97.2[d]	97.2[d]	1
Maclura pomifera	0.9	4	8.3[c]	15.1[d]	52.8[d]	82.7[d]	

Table 9 (continued)

Species	FIA	Current modeled	PCM_lo	GCM3_lo	GCM3_hi	HAD_hi	Canada
Magnolia acuminata	10.8	8.4	10.8[c]	8.9	4.8[a]	2.9[a]	1
Magnolia grandiflora	0	0	0	0	0	0.1	
Magnolia macrophylla	0	0	0	0	0	0	
Magnolia virginiana	0.7	2.9	4.8	4.3	3.5	9[c]	
Morus rubra	0.9	1.8	21.3[d]	46.8[d]	95.7[d]	98.3[d]	1
Nyssa aquatica	0.1	1	2.5	3.6[c]	5.5[c]	9.1[c]	
Nyssa ogechee	0	0	0	0	0	0	
Nyssa sylvatica	26.6	38.3	66.1[d]	72.7[d]	93.6[d]	99.3[d]	1
Nyssa sylvatica var. *biflora*	0	1.2	4.7[c]	4.6[c]	5.3[c]	8.6[c]	
Ostrya virginiana	60.4	90.4	96[c]	98.2[c]	99.2[c]	99.8[c]	1
Oxydendrum arboreum	0.3	2.1	7.8[c]	7.6[c]	10[c]	20.1[d]	
Persea borbonia	0	0.2	0.6	0.3	0.1	3.2[c]	
Picea glauca	21.3	32.2	25.2[a]	28.4[a]	17.6[b]	14.4[b]	1
Picea mariana	11.8	23.4	8.5[b]	6.3[b]	0.3[b]	0.2[b]	1
Picea rubens	38	42.7	37.6[a]	37.9[a]	36.7[a]	38.8[a]	1
Pinus banksiana	0.9	9.1	5.3[a]	6.9[a]	5.1[a]	12.4[c]	1
Pinus clausa	0	0.6	1.8	2.5	2.4	2.6[c]	
Pinus echinata	1.1	4	17.8[d]	30.1[d]	77.6[d]	97.4[d]	
Pinus elliottii	0	0.7	1.9	1.6	4.4[c]	12.2[d]	
Pinus glabra	0	0	0	0	0	0.1	
Pinus palustris	0	1	5[c]	3.9[c]	4.2[c]	12.6[d]	
Pinus pungens	0.7	0.2	0.2	0.4	0.8	0.9	
Pinus resinosa	16.9	41.2	30.9[b]	30.9[b]	31[b]	25.4[b]	1
Pinus rigida	14.7	18.8	21.4[c]	21.6[c]	20.4	19.1	1
Pinus serotina	0	0.4	1.8	3.1[c]	3.6[c]	4.3[c]	
Pinus strobus	67	95.5	90.6[a]	87[a]	73.4[b]	71.6[b]	1
Pinus taeda	0.1	6.3	14.1[c]	20.9[d]	54.6[d]	85.6[d]	
Pinus virginiana	5.6	18.7	30.3[d]	37.5[d]	66.7[d]	74.4[d]	
Planera aquatica	0	0.5	0.3	0.4	0.4	0.4	
Platanus occidentallis	6.6	13.4	36.1[d]	52.2[d]	90.5[d]	98[d]	1
Populus balsamifera	7.1	10.8	3.1[a]	2.9[a]	2.4[a]	1.7[a]	1
Populus deltoides	6.5	14.6	27.1[d]	39.7[d]	83.8[d]	97[d]	1
Populus grandidentata	50.1	84.9	71.3[b]	60.6[b]	27.6[b]	15.7[b]	1
Populus tremuloides	60.6	80.3	57.1[b]	44.4[b]	26.6[b]	20.9[b]	1
Prunus americana	0	0	0	0	0.7	11	1
Prunus pensylvanica	33.1	45.9	30.6[b]	28.3[b]	13.8[b]	8.8[b]	1
Prunus serotina	79.6	94.6	100[c]	100[c]	100[c]	99.8[c]	1
Prunus virginiana	20	32.4	18.7[b]	13.9[b]	6.5[b]	3.7[b]	1
Quercus alba	49.4	70.8	91.2[d]	97[d]	100[d]	100[d]	1
Quercus bicolor	4.3	7.4	8.5	8.2	7.3	9.1	1
Quercus coccinea	27.7	40.7	74.4[d]	80.2[d]	86.3[d]	87[d]	
Quercus durandii	0	0	0	0	0	0	
Quercus ellipsoidalis	0.3	1.3	1.1	2.2	3.1	13	1
Quercus falcata var. *falcata*	1.1	2.2	11.8[c]	19.7[d]	60.8[d]	83.1[d]	
Quercus falcata var. *pagodifolia*	0	0.9	2.9[c]	3.7[c]	14.2[d]	20.8[d]	
Quercus ilicifolia	5.5	9.1	12.7[c]	13.8[c]	12.9[c]	13.7[c]	
Quercus imbricaria	1.7	1.3	8.3[c]	17.2[d]	39.3[d]	42.2[d]	
Quercus laevis	0	0.7	2.2	1.9	2.2	4.9[c]	

Table 9 (continued)

Species	FIA	Current modeled	PCM_lo	GCM3_lo	GCM3_hi	HAD_hi	Canada
Quercus laurifolia	0	0.2	0.5	0.5	3.2[c]	6.6[c]	
Quercus lyrata	0	2.1	0.9	1.4	5.6[c]	7.4[c]	
Quercus macrocarpa	2.2	3.6	4.6	10.5[c]	53.2[d]	83.8[d]	1
Quercus marilandica	0.4	1.6	15.6[d]	29.6[d]	79.5[d]	97.7[d]	
Quercus michauxii	0.1	0	0.3	0.5	3.2[c]	5.9[c]	
Quercus muehlenbergii	0.8	1.1	16.2[d]	31.9[d]	75[d]	86.4[d]	1
Quercus nigra	0	0.5	3.2[c]	4.6[c]	20.1[d]	42.7[d]	
Quercus nuttallii	0	0.6	0.2	0.2	1.1	4.9[c]	
Quercus palustris	4.4	11.7	27.6[d]	30.8[d]	45.9[d]	53.5[d]	1
Quercus phellos	0.2	1.7	5.1[c]	7.3[c]	17.7[d]	34.7[d]	
Quercus prinus	32.3	56	75.5[d]	79.8[d]	88.3[d]	86.2[d]	1
Quercus rubra	69.9	86.2	98.9[d]	99.9[d]	98.5[d]	97.3[d]	1
Quercus shumardii	0	0	0.1	0.3	27.7[d]	57.2[d]	
Quercus stellata	1	3.4	21.6[d]	36.6[d]	85.7[d]	99.6[d]	
Quercus stellata var. *margaretta*	0	0.2	0.2	0.2	0.7	2.3[c]	
Quercus velutina	39.6	58.2	86[d]	93.4[d]	100[d]	100[d]	1
Quercus virginiana	0	0.1	0.3	0.3	0.3	0.4	
Robinia pseudoacacia	18.1	41.8	73.5[d]	81.7[d]	89.9[d]	86[d]	
Salix amygdaloides	0	0	0	0	0	0	1
Salix nigra	10.7	28.5	38.4[c]	50.5[d]	82.2[d]	89.4[d]	1
Sassafras albidum	29	45.7	75.6[d]	81.3[d]	99.4[d]	99.9[d]	1
Sorbus americana	6.8	3.2	1.1[a]	0.8[a]	0.3[a]	0.3[a]	1
Taxodium distichum	0	3.3	8.8[c]	10.9[c]	12.6[c]	15.5[d]	
Taxodium distichum var. *nutans*	0	0.3	0.2	0.2	0.2	1.3	
Thuja occidentalis	22	42.9	33[a]	32.7[b]	31.9[b]	32.3[b]	1
Tilia americana	42.9	63.1	68.4[c]	70.5[c]	70.2[c]	71.8[c]	1
Tsuga canadensis	69.9	89.1	85.2[a]	82[a]	78.2[b]	77.7[b]	1
Ulmus alata	0.2	0.3	14.9[d]	27[d]	78.6[d]	95.1[d]	
Ulmus americana	46.8	75.8	88.9[d]	95.6[d]	100[d]	100[d]	1
Ulmus crassifolia	0	0.1	0	1	37.2[d]	66.5[d]	
Ulmus rubra	16	30.3	55.9[d]	73.2[d]	96.3[d]	97[d]	1
Ulmus thomasii	0.7	0.7	2	2.7[c]	3.3[c]	3[c]	1

A ‘1’ under Canada indicates the species is also present in Canada.

[a] Decreasing species (2–10% loss).

[b] Decreasing species (>10% loss).

[c] Increasing species (2–10% gain).

[d] Increasing species (>10% gain).

Table 10 Weighted-area importance value scores and their potential gains or losses under four scenarios of climate change. Ratios pertain to future: current ratios

Species	CurMod	Ratio PCM_lo	Ratio GCM3_lo	Ratio GCM3_hi	Ratio HAD_hi
Abies balsamea	5,307	0.454[a]	0.330[a]	0.196[a]	0.189[a]
Acer barbatum	0	0[a]	0[a]	0[a]	0[a]
Acer negundo	386	1.150[b]	1.358[b]	1.995[b]	3.658[c]
Acer nigrum	11	0.545[d]	0.182[a]	0.091[a]	0.091[a]
Acer pensylvanicum	1,652	0.723[d]	0.593[d]	0.353[a]	0.298[a]
Acer rubrum	15,097	0.960	0.845[d]	0.517[d]	0.407[a]
Acer saccharinum	467	1.593[b]	2.602[c]	4.450[c]	5.266[c]
Acer saccharum	8,986	0.872[d]	0.816[d]	0.528[d]	0.373[a]
Acer spicatum	285	0.382[a]	0.249[a]	0.053[a]	0.049[a]
Aesculus glabra	0	0[a]	0[a]	0[a]	0[a]
Aesculus octandra	9	1	0.667[d]	0.889[d]	0.889[d]
Alnus glutinosa	858	1.054	0.984	0.815[d]	0.818[d]
Asimina triloba	38	4.368[c]	5[c]	5.947[c]	5.684[c]
Betula alleghaniensis	2,846	0.710[d]	0.562[d]	0.324[a]	0.326[a]
Betula lenta	2,198	1.148[b]	1.002	0.721[d]	0.615[d]
Betula nigra	18	0.889[d]	1.111[b]	4.278[c]	14[c]
Betula papyrifera	2,053	0.545[d]	0.466[a]	0.128[a]	0.078[a]
Betula populifolla	733	0.823[d]	0.772[d]	0.638[d]	0.637[d]
Bumelia lanuginosa	0	0[a]	0[a]	0[a]	0[a]
Carpinus caroliniana	951	1.082	1.179[b]	1.220[b]	1.266[b]
Carya aquatica	13	0.385[a]	0.462[a]	1	2[b]
Carya cordiformis	77	3.688[c]	6.506[c]	14.649[c]	18.935[c]
Carya glabra	908	1.790[b]	2.019[c]	2.175[c]	2.051[c]
Carya illinoensis	3	2.667[c]	14.333[c]	122.333[c]	227.667[c]
Carya laciniosa	2	5[c]	31[c]	122.0[c]	138[c]
Carya ovata	345	1.904[b]	2.638[c]	3.577[c]	3.713[c]
Carya texana	4	43.750[c]	149[c]	688.500[c]	920.750[c]
Carya tomentosa	662	1.675[b]	2.0[b]	2.790[c]	3.077[c]
Castanea dentata	46	1.609[b]	1.239[b]	0.804[d]	0.696[d]
Catalpa speciosa	9	0.889[d]	0.889[d]	8.556[c]	23.778[c]
Celtis laevigata	18	2.333[c]	6.556[c]	57.778[c]	96.778[c]
Celtis occidentalis	114	3.684[c]	7.114[c]	16.939[c]	20.202[c]
Cercis canadensis	54	7.278[c]	11.944[c]	21.759[c]	22.278[c]
Chamaecyparis thyoides	94	0.745[d]	0.713[d]	0.649[d]	0.596[d]
Cornus florida	882	2.507[c]	3.126[c]	3.786[c]	3.779[c]
Diospyros virginiana	28	11.500[c]	25.714[c]	87.571[c]	103.750[c]
Fagus grandifolia	6,535	0.750[d]	0.652[d]	0.399[a]	0.330[a]
Fraxinus americana	6,477	0.962	0.867[d]	0.582[d]	0.512[d]
Fraxinus nigra	548	0.518[d]	0.542[d]	0.352[a]	0.343[a]
Fraxinus pennsylvanica	402	0.995	1.157[b]	2.007[b]	2.873
Fraxinus quadrangulata	2	0[a]	0.500[d]	0[a]	0[a]
Gleditsia aquatica	0	0[a]	0[a]	0[a]	0[a]
Gleditsia triacanthos	31	7[c]	12.548[c]	51[c]	72.129[c]
Gordonia lasianthus	4	0.750[d]	0.500[d]	0.500[d]	1.250[b]
Gymnocladus dioicus	0	0[a]	0[a]	0[a]	0[a]
Halesia spp.	1	0[a]	0[a]	0[a]	1.000
Ilex opaca	60	2.117[c]	2.233[c]	2.500[c]	2.833[c]
Juglans cinerea	95	0.779[d]	0.589[d]	0.116[a]	0.074[a]

Table 10 (continued)

Species	CurMod	Ratio PCM_lo	Ratio GCM3_lo	Ratio GCM3_hi	Ratio HAD_hi
Juglans nigra	401	2.534[c]	3.142[c]	3.613[c]	3.494[c]
Juniperus virginiana	488	3.508[c]	5.408[c]	9.852[c]	10.832[c]
Larix laricina	277	0.596[d]	0.581[d]	0.408[a]	0.401[a]
Liquidambar styraciflua	313	2.751[c]	3.872[c]	7.805[c]	10.885[c]
Liriodendron tuliperfia	1,018	1.699[b]	1.607[b]	1.593[b]	1.560[b]
Maclura pomifera	51	1.980[b]	3.431[c]	11.725[c]	18.549[c]
Magnolia acuminata	88	1.307[b]	1.080	0.580[d]	0.352[a]
Magnolia grandiflora	0	0[a]	0[a]	0[a]	0[a]
Magnolia macrophylla	0	0[a]	0[a]	0[a]	0[a]
Magnolia virginiana	35	1.571[b]	1.400[b]	1.171[b]	3.686[c]
Morus rubra	20	14.100[c]	32.450[c]	110.850[c]	159.750[c]
Nyssa aquatica	11	2.636[c]	3.636[c]	5.455[c]	8.818[c]
Nyssa ogechee	0	0[a]	0[a]	0[a]	0[a]
Nyssa sylvatica	849	1.667[b]	1.744[b]	2.133[c]	2.325[c]
Nyssa sylvatica var. *biflora*	18	3.667[c]	3.500[c]	3.722[c]	8.444[c]
Ostrya virginiana	1,639	0.919	0.976	1.167[b]	1.442[b]
Oxydendrum arboreum	24	3.500[c]	3.583[c]	4.458[c]	8.833[c]
Persea borbonia	2	3[c]	1.500[b]	0.500[d]	18.500[c]
Picea glauca	570	0.540[d]	0.540[d]	0.330[a]	0.267[a]
Picea mariana	545	0.226[a]	0.138[a]	0.006[a]	0.004[a]
Picea rubens	2,702	0.476[a]	0.402[a]	0.345[a]	0.359[a]
Pinus banksiana	121	0.479[a]	0.645[d]	0.496[a]	1.256[b]
Pinus clausa	11	2.091[c]	2.909[c]	2.727[c]	2.818[c]
Pinus echinata	53	4.057[c]	10.434[c]	53.170[c]	78.358[c]
Pinus elliottii	12	1.833[b]	1.583[b]	5.583[c]	20.667[c]
Pinus glabra	0	0[a]	0[a]	0[a]	0[a]
Pinus palustris	15	4.133[c]	3.133[c]	3.867[c]	14.133[c]
Pinus pungens	2	1	2.000[b]	4[c]	4.500[c]
Pinus resinosa	532	0.806[d]	0.936	1.053	0.731[d]
Pinus rigida	646	0.955	0.943	0.907	0.881[d]
Pinus serotina	4	5.500[c]	9.250[c]	10.500[c]	13.250[c]
Pinus strobus	4,773	0.800[d]	0.739[d]	0.530[d]	0.383[a]
Pinus taeda	97	4.371[c]	6.773[c]	20.144[c]	38.876[c]
Pinus virginiana	301	1.339[b]	1.498[b]	2.661[c]	3.083[c]
Planera aquatica	7	0.429[a]	0.571[d]	0.571[d]	0.571[d]
Platanus occidentalis	154	2.727[c]	3.909[c]	6.649[c]	7.214[c]
Populus balsamifera	131	0.282[a]	0.229[a]	0.191[a]	0.137[a]
Populus deltoides	222	1.689[b]	2.685[c]	7.536[c]	10.360[c]
Populus grandidentata	1,175	0.849[d]	0.703[d]	0.278[a]	0.140[a]
Populus tremuloides	2,231	0.569[d]	0.487[a]	0.191[a]	0.119[a]
Prunus americana	0	0[a]	0[a]	0[a]	0[a]
Prunus pensylvanica	517	0.660[d]	0.602[d]	0.279[a]	0.178[a]
Prunus serotina	6,050	0.909	0.762[d]	0.476[a]	0.395[a]
Prunus virginiana	420	0.529[d]	0.362[a]	0.162[a]	0.093[a]
Quercus alba	2,276	1.652[b]	2.036[c]	2.688[c]	2.585[c]
Quercus bicolor	80	1.238[b]	1.175[b]	0.988	1.200[b]
Quercus coccinea	731	1.766[b]	1.948[b]	2.181[c]	1.796[b]
Quercus durandii	0	0[a]	0[a]	0[a]	0[a]
Quercus ellipsoidalis	14	0.786[d]	1.643[b]	2.286[c]	10.714[c]

Table 10 (continued)

Species	CurMod	Ratio PCM_lo	Ratio GCM3_lo	Ratio GCM3_hi	Ratio HAD_hi
Quercus falcata var. *falcata*	32	5.906[c]	10.281[c]	36.250[c]	52.063[c]
Quercus falcata var. *pagodifolia*	9	3.333[c]	4.333[c]	16.889[c]	24.889[c]
Quercus ilicifolia	122	1.623[b]	1.713[b]	1.623[b]	1.713[b]
Quercus imbricaria	14	6.357[c]	14.929[c]	31.071[c]	33.214[c]
Quercus laevis	10	2.900[c]	2.400[c]	2.700[c]	6.500[c]
Quercus laurifolia	2	2.500[c]	2.500[c]	16.500[c]	41[c]
Quercus lyrata	27	0.333[a]	0.556[d]	2.222[c]	2.963[c]
Quercus macrocarpa	45	1.222[b]	2.644[c]	13.667[c]	27.356[c]
Quercus marilandica	19	10.421[c]	27.158[c]	128.895[c]	178.105[c]
Quercus michauxii	0	0[a]	0[a]	0[a]	0[a]
Quercus muehlenbergii	12	15.083[c]	29.833[c]	70.917[c]	84.917[c]
Quercus nigra	7	7.857[c]	13.571[c]	72.571[c]	143.857[c]
Quercus nuttallii	6	0.333[a]	0.333[a]	1.833[b]	8.500[c]
Quercus palustris	147	2.388[c]	2.646[c]	3.558[c]	4.156[c]
Quercus phellos	20	2.750[c]	4.350[c]	12.350[c]	21.950[c]
Quercus prinus	2,002	1.363[b]	1.301[b]	1.181[b]	1.119[b]
Quercus rubra	4,091	1.176[b]	1.168[b]	1.044	0.914
Quercus shumardii	0	0[a]	0[a]	0[a]	0[a]
Quercus stellata	53	14.453[c]	37.321[c]	153.132[c]	205.868[c]
Quercus stellata var. *margaretta*	2	1	1	3.500[c]	12[c]
Quercus velutina	1,664	1.677[b]	2.159[c]	3.327[c]	3.377[c]
Quercus virginiana	2	1.500[b]	1.500[b]	1.500[b]	3[c]
Robinia pseudoacacia	720	1.490[b]	1.675[b]	2.174[c]	2.336[c]
Salix amygdaloides	0	0[a]	0[a]	0[a]	0[a]
Salix nigra	435	1.244[b]	1.605[b]	2.609[c]	3.110[c]
Sassafras albidum	1,105	1.655[b]	1.709[b]	1.966[b]	1.939[b]
Sorbus americana	33	0.333[a]	0.242[a]	0.091[a]	0.091[a]
Taxodium distichum	42	2.333[c]	3.000[c]	4.119[c]	5.571[c]
Taxodium distichum var. *nutans*	3	0.667[d]	0.667[d]	0.667[d]	4.667[c]
Thuja occidentalis	1,767	0.398[a]	0.356[a]	0.269[a]	0.252[a]
Tilia americana	830	0.966	0.980	0.976	1.127[b]
Tsuga canadensis	4,345	0.903	0.802[d]	0.536[d]	0.485[a]
Ulmus alata	3	85.667[c]	201[c]	986.333[c]	1,516.333[c]
Ulmus americana	1,718	1.203[b]	1.467[b]	1.991[b]	2.178[c]
Ulmus crassifolia	1	0[a]	10[c]	428[c]	761[c]
Ulmus rubra	484	1.655[b]	2.035[c]	2.523[c]	2.614[c]
Ulmus thomasii	7	3.429[c]	4.286[c]	5.143[c]	4.571[c]

TNRatio: "future : current ratio" for the scenario

[a] Potential losses (<0.5 times decrease).

[b] Potential gains (1.1–2.0-fold increase).

[c] Potential gains (>2.0-fold increase).

[d] Potential losses (0.5–0.9 times decrease).

Table 11 Species in New Hampshire with the potential for substantial (top 10) losses (in italics) or gains (in bold) in suitable habitat based on absolute area-weighted importance values differences expressed as percentages except those numbers followed by the letter 'a' indicate actual area-weighted importance values, since the initial value was zero

Common name	Scientific name	CurMod	dif_pcmlo	dif_gcm3lo	dif_gcm3hi	dif_hadhi
Red maple	*Acer rubrum*	**1,265**	7.2	4.3	*−36.2*	*−53.7*
Eastern white pine	*Pinus strobus*	**791**	*−22.1*	*−33.8*	*−48.9*	*−61.1*
Sugar maple	*Acer saccharum*	**711**	*−15.2*	*−19.7*	*−33.5*	*−45.9*
Balsam fir	*Abies balsamea*	**650**	*−45.4*	*−56.3*	*−76.8*	*−77.1*
American beech	*Fagus grandifolia*	**561**	*−20.9*	*−22.1*	*−52.0*	*−60.8*
Eastern hemlock	*Tsuga canadensis*	**554**	*−10.6*	*−17.0*	*−40.4*	*−46.4*
Northern red oak	*Quercus rubra*	**378**	30.7	**27.8**	1.1	−12.2
Yellow birch	*Betula alleghaniensis*	**375**	*−19.7*	*−32.0*	*−55.5*	*−54.7*
Red spruce	*Picea rubens*	**349**	*−37.5*	*−45.6*	*−55.9*	*−53.9*
Paper birch	*Betula papyrifera*	**334**	*−42.2*	*−53.3*	*−87.1*	*−92.2*
Quaking aspen	*Populus tremuloides*	191	*−30.4*	*−36.6*	*−70.2*	*−82.7*
Sweet birch	*Betula lenta*	110	**91.8**	**102.7**	58.2	25.5
Northern white-cedar	*Thuja occidentalis*	104	*−50.0*	*−48.1*	−48.1	−47.1
White oak	*Quercus alba*	75	**161.3**	**222.7**	**538.7**	**574.7**
Black oak	*Quercus velutina*	75	**161.3**	**202.7**	**396.0**	**452.0**
American elm	*Ulmus americana*	72	62.5	93.1	200.0	**280.6**
Silver maple	*Acer saccharinum*	25	216.0	**356.0**	**644.0**	712.0
Chestnut oak	*Quercus prinus*	25	**256.0**	**340.0**	**728.0**	716.0
Post oak	*Quercus stellata*	25	**256.0**	**340.0**	**728.0**	716.0
Pignut hickory	*Carya glabra*	20	**365.0**	**435.0**	725.0	655.0
Eastern redcedar	*Juniperus virginiana*	8	**875.0**	**1,587.5**	**4,350.0**	**5,462.5**
Sassafras	*Sassafras albidum*	7	685.7	885.7	**2,257.1**	2,614.3
Loblolly pine	*Pinus taeda*	6	0.0	133.3	983.3	**3,283.3**
Flowering dogwood	*Cornus florida*	1	**8,000.0**	**12,100.0**	**25,500.0**	**27,200.0**
Sweetgum	*Liquidambar styraciflua*	1	1,000.0	3,000.0	14,600.0	**26,700.0**
Red mulberry	*Morus rubra*	0	21a	56a	**176**a	**286a**
Common persimmon	*Diospyros virginiana*	0	3a	12a	**166**a	**234a**
Winged elm	*Ulmus alata*	0	0a	2a	**86a**	**239a**

Table 12 Species in Vermont with the potential for substantial (top 10) losses (in italics) or gains (in bold) in suitable habitat based on absolute area-weighted importance values; differences expressed as percentages

Common name	Scientific name	CurMod	dif_pcmlo	dif_gcm3lo	dif_gcm3hi	dif_hadhi
Sugar maple	*Acer saccharum*	**1,130**	*−18.3*	*−30.0*	*−47.8*	*−57.0*
Red maple	*Acer rubrum*	**1,010**	**7.0**	4.6	*−20.5*	*−42.0*
American beech	*Fagus grandifolia*	**681**	*−10.7*	*−22.0*	*−55.1*	*−63.1*
Balsam fir	*Abies balsamea*	**674**	*−51.0*	*−62.5*	*−75.1*	*−75.2*
Eastern hemlock	*Tsuga canadensis*	**548**	**10.8**	2.4	*−35.4*	*−42.2*
Eastern white pine	*Pinus strobus*	**523**	*−9.8*	*−20.1*	*−39.6*	*−54.3*
Yellow birch	*Betula alleghaniensis*	**425**	*−23.5*	*−37.4*	*−63.3*	*−62.6*
Red spruce	*Picea rubens*	**372**	*−42.5*	*−51.1*	*−58.1*	*−55.1*
White ash	*Fraxinus americana*	**362**	**22.9**	**22.1**	5.8	−2.8
Paper birch	*Betula papyrifera*	**306**	*−36.9*	*−49.0*	*−88.2*	*−94.4*
Black cherry	*Prunus serotina*	280	**21.8**	28.2	−1.1	−28.2
Quaking aspen	*Populus tremuloides*	248	*−27.0*	*−32.3*	*−77.4*	*−85.9*

Table 12 (continued)

Common name	Scientific name	CurMod	dif_pcmlo	dif_gcm3lo	dif_gcm3hi	dif_hadhi
Northern red oak	*Quercus rubra*	229	**55.0**	**71.6**	**74.7**	61.1
Striped maple	*Acer pensylvanicum*	197	−18.3	*−27.4*	−56.9	−64.5
Northern white-cedar	*Thuja occidentalis*	150	*−41.3*	*−34.7*	−38.7	−38.0
American elm	*Ulmus americana*	114	47.4	66.7	150.0	**200.0**
Sweet birch	*Betula lenta*	85	**114.1**	**132.9**	102.4	62.4
Black ash	*Fraxinus nigra*	80	*−52.5*	−43.8	−72.5	−76.3
White oak	*Quercus alba*	52	**178.8**	**303.8**	**750.0**	**919.2**
Black oak	*Quercus velutina*	37	**205.4**	**310.8**	**832.4**	**1,105.4**
Silver maple	*Acer saccharinum*	32	150.0	**268.8**	450.0	550.0
Chestnut oak	*Quercus prinus*	23	247.8	**482.6**	**1,013.0**	**969.6**
Post oak	*Quercus stellata*	23	247.8	**482.6**	**1,013.0**	**969.6**
Eastern redcedar	*Juniperus virginiana*	13	**615.4**	**992.3**	**3,030.8**	**3,700.0**
Eastern cottonwood	*Populus deltoides*	7	514.3	1,085.7	**2,457.1**	**3,071.4**
Flowering dogwood	*Cornus florida*	2	**3,050.0**	**5,750.0**	**14,150.0**	**15,450.0**
Hackberry	*Celtis occidentalis*	2	1,450.0	3,000.0	**9,150.0**	**12,350.0**
Red mulberry	*Morus rubra*	1	3,500.0	6,900.0	**24,200.0**	**33,200.0**

Table 13 Species in Connecticut with the potential for substantial (top 10) losses (in italics) or gains (in bold) in suitable habitat based on absolute area-weighted importance values; differences are expressed as percentages except those numbers followed by the letter ‘a’ indicate actual area-weighted importance values, since the initial value was zero

Common name	Scientific name	CurMod	dif_pcmlo	dif_gcm3lo	dif_gcm3hi	dif_hadhi
Red maple	*Acer rubrum*	**854**	*−20.1*	*−38.8*	*−70.7*	*−74.5*
Eastern white pine	*Pinus strobus*	**276**	*−43.1*	*−50.4*	*−66.7*	*−68.8*
Northern red oak	*Quercus rubra*	**269**	*−13.4*	*−26.4*	*−58.0*	*−58.7*
Sugar maple	*Acer saccharum*	**232**	**17.7**	9.9	*−47.8*	*−77.6*
Sweet birch	*Betula lenta*	**216**	*−6.5*	*−27.8*	*−48.1*	*−48.1*
White ash	*Fraxinus americana*	**207**	6.8	*−16.9*	*−55.1*	*−60.4*
Eastern hemlock	*Tsuga canadensis*	**182**	*−31.9*	*−43.4*	*−47.8*	*−45.1*
Black oak	*Quercus velutina*	**162**	9.3	16.7	43.2	9.3
White oak	*Quercus alba*	**141**	**40.4**	**76.6**	**85.1**	56.7
Black cherry	*Prunus serotina*	**139**	25.2	−0.7	*−31.7*	*−33.1*
American beech	*Fagus grandifolia*	113	−6.2	−8.0	*−37.2*	*−38.1*
Chestnut oak	*Quercus prinus*	67	**65.7**	62.7	13.4	11.9
Post oak	*Quercus stellata*	67	**65.7**	62.7	13.4	11.9
Eastern redcedar	*Juniperus virginiana*	57	**86.0**	**126.3**	**182.5**	**177.2**
Gray birch	*Betula populifolla*	44	*−27.3*	*−25.0*	−18.2	−13.6
Bigtooth aspen	*Populus grandidentata*	36	*−44.4*	*−77.8*	*−100.0*	*−100.0*
Yellow-poplar	*Liriodendron tuliperfia*	35	**137.1**	**160.0**	94.3	94.3
Paper birch	*Betula papyrifera*	35	*−82.9*	*−85.7*	−85.7	−85.7
Flowering dogwood	*Cornus florida*	34	**214.7**	**238.2**	**247.1**	**279.4**
Quaking aspen	*Populus tremuloides*	32	*−53.1*	*−84.4*	−100.0	−100.0
Silver maple	*Acer saccharinum*	9	388.9	**533.3**	866.7	**1,088.9**
Chokecherry	*Prunus virginiana*	7	*−100.0*	−100.0	−100.0	−100.0
Sweetgum	*Liquidambar styraciflua*	6	**1,533.3**	**2,150.0**	**3,450.0**	**3,783.3**
Black walnut	*Juglans nigra*	2	**2,300.0**	**2,400.0**	1,600.0	1,450.0

Table 13 (continued)

Common name	Scientific name	CurMod	dif_pcmlo	dif_gcm3lo	dif_gcm3hi	dif_hadhi
Loblolly pine	*Pinus taeda*	1	**3,900.0**	**6,400.0**	**20,700.0**	**36,000.0**
Virginia pine	*Pinus virginiana*	1	2,800.0	**4,600.0**	3,400.0	3,400.0
Winged elm	*Ulmus alata*	0	10a	33a	**151**a	**192a**
Common persimmon	*Diospyros virginiana*	0	26a	**67**a	**129a**	**127a**
Shortleaf pine	*Pinus echinata*	0	11a	30a	**138**a	**185a**
Southern red oak	*Quercus falcata* var. *falcata*	0	9a	23a	**82**a	**93a**
Blackjack oak	*Quercus marilandica*	0	9a	22a	**81**a	**112a**

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