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Potential redistribution of tree species habitat under five climate change scenarios in the eastern US

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Abstract

Global climate change could have profound effects on the Earth's biota, including large redistributions of tree species and forest types. We used DISTRIB, a deterministic regression tree analysis model, to examine environmental drivers related to current forest-species distributions and then model potential suitable habitat under five climate change scenarios associated with a doubling of atmospheric CO_2. Potential shifts in suitable habitat for 76 common tree species in the eastern US were evaluated based on more than 100,000 plots and 33 environmental variables related to climate, soils, land use, and elevation. Regression tree analysis was used to devise prediction rules from current species–environment relationships. These rules were used to replicate the current distribution and predict the potential suitable habitat for more than 2100 counties east of the 100th meridian. The calculation of an importance value-weighted area score, averaged across the five climate scenarios, allowed comparison among species for their overall potential to be affected by climate change. When this score was averaged across all five climate scenarios, 34 tree species were projected to expand by at least 10%, while 31 species could decrease by at least 10%. Several species (*Populus tremuloides*, *P. grandidentata*, *Acer saccharum*, *Betula papyrifera*, *Thuja occidentalis*) could have their suitable habitat extirpated from US. Depending on the scenario, the optimum latitude of suitable habitat moved north more than 20 km for 38–47 species, including 8–27 species more than 200 km or into Canada. Although the five scenarios were in general agreement with respect to the overall tendencies in potential future suitable habitat, significant variations occurred in the amount of potential movement in many of the species. The five scenarios were ranked for their severity on potential tree habitat changes. Actual species redistributions, within the suitable habitat modeled here, will be controlled by migration rates through fragmented landscapes, as well as human manipulations.

Keywords: Climate change; Eastern US; Tree species migration; Regression tree analysis

1. Introduction

The world's climate has always been undergoing change, but there is reason to suspect that human activity is disrupting this dynamic process. It has been estimated that the composition of one-third of the earth's forests could change markedly due to climate changes associated with a doubling of atmospheric CO_2 (Melillo, 1999; Shriner and Street, 1998). Plant species are expected to shift in range and importance as the climate changes. In North America, studies of plants from the Holocene warming provide the best evidence that plant ranges do shift with climate, and that: (a) species generally have shifted northward (Delcourt and Delcourt, 1988); (b) species did not shift in unison, i.e. the rates and direction of migration differed among taxa and species assemblages did not

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remain the same (Davis, 1981; Webb III, 1992); (c) variations in competition and dispersal mechanisms seemed to have little influence on vegetation migration patterns or rates, i.e. historical data show little distinction in past migration patterns between trees with wind- or animal-dispersed propagules (Malanson, 1993).

Several approaches have been used to evaluate possible effects of climate change on vegetation. These include paleoecological models, mechanistic models including biogeochemical and biogeographical models, and statistical models. There are advantages and disadvantages of each. In each case, many assumptions are made and verification is impossible. In this paper, we take a statistical approach and evaluate possible effects of climate change on the distribution and abundance of specific species. Because statistical models are not driven by physiological mechanisms, e.g. changes in water-use efficiency or temperature sensitivity, they are unable to incorporate changes in competitive interactions or changes in these mechanisms. However, statistical approaches take advantage of known driving factors associated with current and historic species ranges, and extend those relationships into the future via climate change scenarios. Statistical models can also be generated for a large number of individual species with little extended effort associated with model parameterization. As such, these models can provide a suitability analysis for individual species, that is, potential future habitat locations can be mapped (assuming an equilibrium between environment and species that will be maintained). Species interactions and physiological adjustments then can be incorporated over time as research progresses (Box et al., 1993).

Several researchers have used such an approach. For example, Morse et al. (1993) evaluated more than 15,000 native vascular species from 194 sections of North America in assessing potential effects of a 3 °C rise in temperature. Assuming a species can be eliminated from an area where the "new" climate falls outside the current envelope, they estimated an eventual loss of 7–11% of North America's native plant species. Uncommon species with smaller ranges would be affected disproportionately. That study is the most extensive for species, but uses coarse analyses for geographic areas and climate variables.

Other studies are more intensive on a selected subset of species or geographic area. For example, in evaluating potential future changes for seven vegetative groups in eastern North America, Overpeck et al. (1991) found that the northern boundaries of all seven groups could shift by 100–1000 km. Bartlein et al. (1997), assessing possible range shifts for several species in Yellowstone National Park, predicted that the magnitude of the changes could exceed the ability of species to adjust their ranges. In their assessment of possible changes in distribution of 16 species in the western US, Thompson et al. (1998) reported that the range of 11 of these species could increase under a 2× CO_2 climate regime. Sykes et al. (1996) reported that their response surface models of climate (coldest month temperature and growing degree days) matched the actual distribution of 19 northern European tree species. Under a 2× CO_2 regime, they predicted a possible major reorganization of the dominant forest ecosystems of northern Europe. Likewise Hughes et al. (1996), working in Australia, found that many species of eucalyptus could have entire present-day populations exposed to temperature and rainfall patterns that do not now exist. Huntley et al. (1995) used a three-way climate response surface to model the present and future distributions of eight species in Europe. Using envelope analysis to evaluate the potential fate of 124 woody species native to Florida, Box et al. (1999) concluded that many of these species could be extirpated from the state.

For this paper, we used DISTRIB, a deterministic regression tree analysis model, to examine environmental drivers related to current forest-species distributions. We then model possible future distributions of suitable habitat for 76 common tree species, under five climate change scenarios associated with a doubling of atmospheric CO_2. We derive an index to evaluate potential species changes that can provide an overall ranking among species. We further analyze relative differences among the five scenarios for some attributes of the potential future species assemblages.

2. Methods

It has been demonstrated that environmental factors, modified by disturbance and competitive processes, generally control the overall range and abundance of tree species (Woodward, 1987). For this study we used these relationships to generate statistical models that can spatially replicate the current range and importance values (IV) for each of the common species. Then, the climate was changed according to five general circulation models (GCM), and the potential future suitable habitat and importance values were predicted with the models. The overall methodology to build the models and project future suitable habitat follows that described in Iverson and Prasad (1998), although the individual models were refined slightly for this paper. We also extend the earlier work by modeling the species for potential changes in suitable habitat according to five, instead of two, global circulation model outputs of future climate at about the year 2100. We further calculate an IV-weighted area score for each species and scenario, and when averaged across scenarios, produce a rank-ordered table of potential impacts of climate change on 76 species. Finally, we compare among the five scenarios relative to current conditions, for individual species and all species collectively, the potential effects on percent area occupied, percent change in area, percent change in importance value, and shift in optimum latitude.

2.1. Data preparation

The primary data source for this study was the USDA Forest Service's Forest Inventory and Analysis (FIA) unit. The data were from the Eastwide Database that comprises more than 100,000 plots and records for nearly three million trees in 37 states (Hansen et al., 1992). We had data only for US, even though many species' ranges extend (or will extend) into Canada. The data were summarized for individual forest plots to create general importance values for each species as: where x is a particular species on a plot, BA is basal area, and NS is number of stems (summed for overstory and understory trees). In monotypic stands, the IV could reach a maximum of 200. Only species found in at least 100 counties (of the 2124 total possible) were modeled (see Iverson et al., 1996). Plots were averaged to yield a species IV score for each county.

$$IV(x) = \frac{100BA(x)}{BA(\text{all species})} + \frac{100NS(x)}{NS(\text{all species})}$$

We used 33 variables at the county-level for land east of the 100th meridian (Iverson and Prasad, 1998). Climate variables included monthly means of precipitation, temperature, and potential evapotranspiration (PET), for current condition and five climate scenarios. From these, we generated data on annual means for temperature and precipitation, mean monthly PET values, and derived two attributes based on their physiological importance to tree growth for this region: July–August ratio of precipitation to PET (the time most prone to drought stress), and May–September (i.e. growing season) mean temperature.

Fourteen soil variables were used in the models, including water-holding capacity, cation exchange capacity, pH, permeability, bulk density, K-factor, organic content, depth to bedrock, slope, potential productivity, clay content, and three texture indicators. We acquired the data from STATSGO, the State Soil Geographic Database (USDA, Soil Conservation Service, 1991), and processed them to county-level statistics (Iverson et al., 1996). Other data on soils (percent of county in each of four soil associations) and land use (percent of county in forest, grazing, crops, or disturbed) were obtained from the GEOECOLOGY databases of the Oak Ridge National Laboratories (Olson et al., 1980). Elevation data for each county were obtained from the US Geological Survey's (1990) Digital Elevation Files scaled at 1:250,000; these were processed to identify the county's maximum and minimum elevation along with a coefficient of variation. A measure of landscape fragmentation (edge density) was calculated, by county, from a forest classification from 1 km AVHRR data (Evans and Zhu, 1993).

2.2. DISTRIB

We generated individual-species models with DISTRIB, a statistical model that predicts the abundance and distribution of most of the common tree species in the eastern US (Iverson and Prasad, 1998). At a continental scale, different variables may drive species abundances within different portions of the ranges. Thus, the preferred statistical technique is one that is flexible enough to capture these spatial variations in driving variables. Regression tree analysis (RTA), also known as classification and regression trees, is well suited for this purpose. RTA is based on recursive sampling of the data to form prediction rules. RTA uses the recursive partitioning approach and a single variable to split a dataset. It then splits the remaining data into increasingly smaller, homogeneous subsets until a termination is reached (Clark and Pergibon, 1992). Variables (e.g. climate) that operate at larger scales usually split the data early in the model, while variables that influence the response variable at more local scales operate closer to the terminal nodes of the regression trees. For each species, a tree diagram is created and an importance value is predicted for each county depending on the path through a particular set of branches that each county follows according to its environmental variables.

2.3. Climate scenarios

The DISTRIB model uses equilibrium 2× CO_2 conditions to predict potential future suitable habitat. DISTRIB by itself assumes that the species will be able to colonize all suitable sites; migration into the suitable habitat is assumed. No real-time component exists in the DISTRIB model, though predictions from the Intergovernmental Panel on Climate Change (Houghton et al., 1996) show that, if CO_2 emissions were maintained at 1994 levels, the 2× CO_2 level could be reached by the end of the 21st century. Obviously, the typical longevity of trees and the presence of refugia will create large lag times, especially for the southern range limit (Loehle, 1996).

Five climate models were used to evaluate possible future species distributions: (1) Geophysical Fluid Dynamics Laboratory (GFDL) (Wetherald and Manabe, 1988), (2) Goddard Institute of Space Studies (GISS) (Hansen et al., 1988), (3) United Kingdom Meteorological Office (UKMO) (Wilson and Mitchell, 1987), (4) Hadley Center for Climate Prediction and Research (Hadley) (Mitchell et al., 1995), and (5) Canadian Climate Center (CCC) (Laprise et al., 1998). The Hadley and CCC models are transient scenarios; for these, 30-year climatic averages were estimated for the period 2071–2100 (Neilson, personal communication). These scenarios provide a good range of possible outcomes in equilibrium climate at 2× CO_2 (Table 1). Hadley has the least severe change in temperatures, especially January temperature, while UKMO predicts a large change in January temperature. Also, UKMO and Hadley predict significant increases in precipitation, while the others predict little change (Table 1). Data of current climate and outputs from the GFDL and GISS scenarios were acquired in 10 km × 10 km format (US Environmental Protection Agency, 1993). The Hadley, CCC, and UKMO data were obtained in 0.5° × 0.5° format from the USDA Forest Service Laboratory in Corvallis, OR (Neilson and Drapek, personal communication). In all cases, gridded climate data were converted to county averages via weighted averaging in the geographic information system. Importantly, the Hadley, CCC, and UKMO data sets had relatively higher calculated PET values than those of current, GFDL, and GISS (Table 1), i.e. the PET values from the former three scenarios were calculated using a slightly different model which resulted in higher than expected mean values (Neilson, personal communication). Thus, for the 31 species that use PET or the ratio of precipitation

Table 1
Area-weighted averages for the eastern US of each climate variable in the DISTRIB models, current climate, and five climate change scenarios (2× CO_2 equilibrium runs)[a]

Model	JANT (°C)	JULT (°C)	AVGT (°C)	MAYSEPT (°C)	PPT (mm)	PET (mm per month)	JARPPET
Current	−1.7	23.5	11.6	20.6	1043	65	1.06
GISS	3.2	27.0	16.1	24.6	1068	104	0.79
GFDL	3.1	30.7	17.0	26.5	999	139	0.30
Hadley	−0.8	25.9	14.3	23.3	1285	179	0.50
UKMO	6.5	30.2	19.1	27.6	1159	267	0.28
CCC	4.9	28.5	17.2	26.0	1083	216	0.26

[a] AVGT: mean annual temperature; JANT: mean January temperature; JULT: mean July temperature; PPT: annual precipitation; PET: potential evapotranspiration; MAYSEPT: mean May–September temperature; JARPPET: July–August ratio of precipitation to PET.

Table 2
Possible percent change in IV-weighted area score, by species and averaged for five climate change scenarios[a]

Species	IV-weighted area score	
	% Change	FIA (×1000)
Populus grandidentata Michx.[b]	−99.5	3.1
Acer saccharum Marsh.[b]	−98.5	23.1
Thuja occidentalis L.	−97.9	4.0
Abies balsamea (L.) Mill.[c]	−96.0	8.5
Populus tremuloides Michx.	−94.5	16.1
Pinus resinosa Ait.	−93.4	2.6
Betula papyrifera Marsh.	−90.0	6.1
Fagus grandifolia Ehrh.[b]	−85.7	9.1
Betula alleghaniensis Britton	−83.3	3.2
Tilia americana L.[b]	−73.1	7.7
Acer pensylvanicum L.	−71.5	1.9
Crataegus sp.[c]	−65.5	5.6
Fraxinus nigra Marsh.	−65.3	4.0
Acer rubrum L.[c]	−62.9	36.6
Pinus virginiana Mill.[c]	−59.0	4.2
Prunus serotina Ehrh.[b]	−53.0	14.5
Carya glabra (Mill.) Sweet[c]	−50.0	1.8
Ulmus rubra Muhl.	−46.6	7.3
Fraxinus americana L.	−46.3	14.3
Tsuga canadensis (L.) Carr.	−41.6	4.2
Quercus rubra L.	−41.4	14.5
Sassafras albidum (Nutt.) Nees[c]	−35.8	6.0
Ostrya virginiana (Mill.) K. Koch[c]	−32.0	7.1
Quercus macrocarpa Michx.	−30.0	12.6
Populus deltoides Bartr. ex Marsh.	−22.1	11.8
Betula lenta L.	−18.9	2.2
Nyssa aquatica L.[c]	−17.9	1.7
Ilex opaca Ait.	−16.2	1.9
Quercus coccinea Muenchh.	−15.4	3.8
Ulmus americana L.[c]	−14.9	23.4
Acer negundo L.	−14.6	13.5
Oxydendrum arboreum (L.) DC.	−8.5	3.3
Quercus alba L.[b]	−8.2	22.4
Acer saccharinum L.	−4.2	6.5
Platanus occidentalis L.	0.4	2.7
Salix nigra Marsh.	1.8	4.2
Robinia pseudoacacia L.	2.2	3.2
Quercus prinus L.	3.5	6.7
Liriodendron tulipifera L.[c]	3.9	8.9
Juniperus virginiana L.	4.4	8.5
Quercus velutina Lam.[c]	6.7	12.5
Carya cordiformis (Wangenh.) K. Kock	6.8	2.8
Pinus strobus L.[c]	11.1	6.1
Cercis canadensis L.	12.5	2.2
Taxodium distichum (L.) Rich. var. *distichum*[c]	13.4	2.6
Quercus falcata var. *pagodaefolia* Ell.	14.2	1.6
Pinus echinata Mill.	14.6	8.8
Cornus florida L.	17.6	11.8
Carya ovata (Mill.) K. Kock	20.5	5.0
Nyssa sylvatica var. *biflora* (Walt.) Sarg.	20.7	4.6
Liquidambar styraciflua L.	21.8	20.7

Table 2 (*Continued*)

Species	IV-weighted area score	
	% Change	FIA (×1000)
Carpinus caroliniana Walt.[c]	24.1	4.8
Fraxinus pennsylvanica Marsh.	28.6	21.3
Quercus palustris Muenchh.	31.9	1.4
Nyssa sylvatica Marsh. var. *sylvatica*	37.9	8.4
Juglans nigra L.	38.9	6.3
Pinus elliottii Engelm.	39.8	12.6
Quercus muehlenbergii Engelm.	41.6	1.8
Quercus laurifolia Michx.	47.0	3.5
Celtis occidentalis L.[c]	54.1	10.9
Pinus taeda L.	54.2	33.1
Morus rubra L.	61.7	3.6
Quercus nigra L.	64.2	7.9
Gleditsia triacanthos L.	76.6	3.6
Magnolia virginiana L.[c]	101.8	2.5
Diospyros virginiana L.[c]	115.7	2.7
Quercus phellos L.[c]	118.9	2.4
Quercus falcata Michx. var. *falcata*	134.6	5.6
Pinus palustris Mill.[c]	137.8	4.3
Maclura pomifera (Raf.) Schneid.[c]	181.3	3.7
Carya tomentosa (poir.) Nutt.[b]	208.9	1.7
Quercus marilandica Muenchh.[c]	212.2	2.7
Celtis laevigata Willd.	362.4	3.0
Ulmus alata Michx.[c]	410.6	4.8
Taxodium distichum var. *nutans* (Ait.) Sweet[c]	425.1	2.7
Quercus stellata Wangenh.[b]	445.6	10.7

[a] FIA (×1000) indicates the current score of IV × area (in km^2), summed for all counties in which the species is present. Species nomenclature follows that of Burns and Honkala (1990a,b).

[b] Indicates the species is influenced by PET higher in the model such that a significant number of counties are affected. See Section 2 for explanation.

[c] Indicate a species is influenced by PET in the regression tree analysis model, but only for a few counties locally.

to PET, errors could occur for Hadley, CCC, or UKMO potential species outcomes due to higher calculated PET values (these species are flagged in Table 2). However, we report the model outcomes here because of the consistent response across all scenarios and, except for eight species, the PET-related variable comes out low in the binary regression tree, and thus would affect few counties. Even for the eight species with PET variables factoring higher in the regression tree (also flagged in Table 2), there is consistency across all five climate scenarios such that the models are reliable.

2.4. Analysis of potential outcomes

The output from DISTRIB is the average importance value for each species, for each county, and for each climate scenario. An additional outcome was the predicted current (PRD) distribution, based on the DISTRIB model running on current climate. Five metrics were calculated: (1) an estimate of total area occupied, in km^2, as the sum of the area for each county with an importance value above a minimum level; (2) the potential change in area by scenario; (3) the potential change in average IV for occupied counties, by scenario; (4) an IV-weighted area score, calculated as the sum of area × IV for each county; and (5) the latitudinal optimum, or the east–west line that captures the highest average levels of importance values for a species. The IV-weighted area score gives an overall value with respect to IV and area. Because this metric combines the effects of potential change in area and importance value, it might be the best overall statistic to show potential species changes at the scale of the eastern US. When averaged across the five scenarios, this score was also the single most important variable to evaluate and compare potential effects among species. The latitudinal optimum was calculated by first dividing the eastern US study area into 10 km × 10 km grids, summing the IVs for each of 277 rows (= 2770 km from south to north), calculating relative IV values by dividing the sum by total area in the row, and calculating the mean of the interquartile range using box plot capabilities in S-PLUS (Statistical Sciences, 1993). This mean was deemed the "optimum" latitude range for the species. We assume that the optimum latitude is roughly equivalent to the ecological optimum, and that optimum condition of the environmental drivers results in the highest average importance values for a species.

3. Results

3.1. Potential changes in area and importance value

According to the FIA data, percent area occupied by each species ranges from 7.4% area occupied by *Taxodium distichum* var. *nutans* to 80.2% for *Prunus serotina* (Table 3). The 70% of the species occupied 40% or less of the eastern US for both the actual FIA data and the modeled, or predicted current (PRD) data (Fig. 1).

For most species there tends to be agreement among the five scenarios for area and importance value changes (Table 4). The climate change scenarios tend to even out the distribution compared to actual and PRD data, with fewer species in the 20–40% class and more species in the 40–60 and 80–100% classes (Fig. 1).

The potential changes in area and IV are divided into five classes representing gain, loss, or no change (Table 4). Only in several instances do species shift in sign (negative to positive or vice versa) among the five scenarios: area for *Carya glabra*, and importance values for *Betula alleghaniensis*, *Ostrya virginiana*, and *Quercus macrocarpa*. Species that show opposite effects (positive and negative) for area and importance value include *Carya tomentosa*, *Celtis laevigata*, *Fagus grandifolia*, *Fraxinus nigra*, *Pinus virginiana*, *Quercus meuhlenbergii*, *Quercus nigra*, and *Robinia pseudoacacia* (Table 4).

Depending on scenario, about 27–31% of the species are predicted to lose at least 10% in area, while another 33–43% could record a gain of 10% or more, according to DISTRIB (Fig. 2). Hadley had the fewest species in either extreme class (>50% loss or >50% gain). For changes in importance value, 43–52% of the species recorded at least a 10% loss, while 32–37% species would be expected to gain at least 10% (Fig. 3). GISS and Hadley recorded the fewest species in the extreme classes.

3.2. Potential changes in IV-weighted area score

Average IV-weighted area scores are presented in order from largest average loss to largest average gain (Table 2). Seven species could decline by 90% or more: *Populus grandidentata*, *Acer saccharum*, *Thuja occidentalis*, *Abies balsamea*, *Populus tremuloides*, *Pinus resinosa*, and *Betula papyrifera* (Table 2). An additional 24 species could decline by at least 10%. In contrast, 34 species could increase in IV-weighted area score under the average of the five scenarios (Table 2). Of these, 12 species could see at least a 100% gain: *Magnolia virginiana*, *Diospyros virginiana*, *Quercus phellos*, *Q. falcata* var. *falcata*, *Pinus palustris*, *Maclura pomifera*, *C. tomentosa*, *Quercus marilandica*, *C. laevigata*, *Ulmus alata*, *T. distichum* var. *nutans*, and *Quercus stellata*.

For the most part, species showing maximum gain or loss in area weighted average are low in areal extent, importance value, or both. As a result, their percentage gains or losses are large. The initial (FIA) scores of the IV-weighted area score, given in Table 2, generally are lower for the species predicted to encounter extreme percentage changes.

3.3. Potential shifts in optimum latitude

The potential shift in optimum latitude for each species is presented in Table 5. The optimum latitude for *P. grandidentata*, *P. tremuloides*, *B. papyrifera*, *P. resinosa*, *A. balsamea*, and *A. saccharum* potentially moves north of the US border for at least three scenarios. Only *T. occidentalis* moved north into Canada in all five scenarios (Table 5). Other species that could move great distances northward include *C. laevigata* (250–530 km), *D. virginiana* (180–380 km), *P. virginiana* (90–440 km), *Platanus occidentalis*

Table 3
Percent land area of the eastern US occupied by species for current (FIA), modeled current (PRD), and five scenarios of climate change[a]

Species	FIA	PRD	GISS	GFDL	HAD	UKMO	CCC
Abies balsamea	13.4	11.3	0.3	0.0	3.7	0.0	0.0
Acer negundo	45.6	34.5	34.5	34.5	34.5	34.5	34.5
Acer pensylvanicum	14.6	10.6	7.6	6.8	7.9	5.8	7.6
Acer rubrum	74.9	77.6	77.6	77.6	77.6	77.6	77.6
Acer saccharinum	29.6	24.1	25.1	22.9	27.2	27.0	25.7
Acer saccharum	49.3	46.9	5.5	0.1	0.0	0.0	0.0
Betula alleghaniensis	22.7	19.9	6.5	0.0	9.3	0.7	1.7
Betula lenta	12.4	10.4	10.4	10.4	10.4	10.4	10.4
Betula papyrifera	19.9	17.4	3.3	0.0	8.0	0.0	0.0
Carpinus caroliniana	54.5	67.7	68.5	72.3	66.8	74.6	69.7
Carya cordiformis	26.9	22.3	24.0	21.3	27.7	26.5	26.6
Carya glabra	14.2	12.6	7.3	6.6	15.9	11.2	12.1
Carya ovata	26.4	21.3	23.2	19.5	28.3	26.3	26.9
Carya tomentosa	15.2	10.4	26.5	47.8	47.8	47.8	47.8
Celtis laevigata	16.0	12.3	52.0	94.3	39.1	81.9	61.3
Celtis occidentalis	33.3	38.9	41.8	41.8	41.8	41.8	41.8
Cercis canadensis	29.8	25.7	28.4	35.7	32.0	23.5	28.3
Cornus florida	55.2	63.9	84.2	84.6	76.5	93.0	92.7
Crataegus sp.	44.1	93.1	90.3	87.9	78.0	95.3	94.1
Diospyros virginiana	40.3	44.7	65.4	67.7	61.1	80.0	74.2
Fagus grandifolia	48.9	40.7	7.0	4.0	3.8	3.8	3.8
Fraxinus americana	59.5	62.1	41.6	41.3	53.2	24.3	35.3
Fraxinus nigra	20.7	24.4	10.4	9.7	7.5	6.0	6.3
Fraxinus pennsylvanica	60.7	100.0	100.0	100.0	100.0	100.0	100.0
Gleditsia triacanthos	27.3	19.4	27.3	26.7	27.5	26.7	27.4
Ilex opaca	22.4	23.5	24.6	25.6	24.0	26.5	24.3
Juglans nigra	41.4	50.5	48.5	45.2	53.9	50.5	50.5
Juniperus virginiana	36.4	33.7	31.5	31.6	32.4	28.5	29.1
Liquidambar styraciflua	39.9	36.4	53.7	53.9	41.0	74.4	60.6
Liriodendron tulipifera	40.4	40.1	44.9	46.6	54.9	54.6	57.5
Maclura pomifera	14.4	12.1	19.3	22.4	17.9	24.2	21.0
Magnolia virginiana	17.8	27.7	43.3	42.5	32.4	68.1	53.5
Morus rubra	28.5	16.8	17.2	16.8	18.3	18.2	18.0
Nyssa aquatica	12.2	16.8	16.8	16.8	16.7	16.7	16.7
Nyssa biflora	16.8	10.6	11.1	11.1	10.7	11.0	10.9
Nyssa sylvatica	49.2	53.3	53.9	53.4	61.4	57.7	60.2
Ostrya virginiana	61.6	62.4	49.1	47.1	56.2	41.9	43.8
Oxydendrum arboreum	23.0	29.0	33.5	33.7	33.7	33.7	33.5
Pinus echinata	31.7	24.5	32.6	34.0	29.0	38.3	34.7
Pinus elliottii	14.6	11.6	19.9	19.5	13.9	27.7	23.9
Pinus palustris	14.9	15.9	28.4	23.8	16.1	38.8	29.6
Pinus resinosa	19.9	25.3	2.9	0.0	8.2	0.0	0.0
Pinus strobus	30.4	31.6	14.1	11.8	16.6	11.8	11.8
Pinus taeda	31.3	31.4	49.5	49.5	36.3	72.4	57.4
Pinus virginiana	15.9	12.1	5.5	1.5	6.6	3.4	2.8
Platanus occidentalis	41.1	70.1	87.6	87.5	80.2	93.3	94.6
Populus deltoides	26.8	32.2	31.1	33.7	29.9	30.2	30.8
Populus grandidentata	28.0	25.1	0.8	0.0	0.0	0.0	0.0
Populus tremuloides	26.4	25.1	4.6	0.0	9.3	0.0	0.8
Prunus serotina	80.2	96.9	99.4	100.0	100.0	100.0	100.0
Quercus falcata var. *pagodaefolia*	20.9	21.1	22.2	23.0	23.3	23.4	23.0
Quercus falcata var. *falcata*	37.3	45.8	73.5	73.8	56.9	86.6	79.9
Quercus alba	72.7	100.0	100.0	100.0	100.0	100.0	100.0

Table 3 (*Continued*)

Species	FIA	PRD	GISS	GFDL	HAD	UKMO	CCC
Quercus coccinea	33.2	37.5	42.7	46.5	40.0	46.3	44.3
Quercus laurifolia	20.1	20.2	36.7	36.4	26.2	56.3	47.2
Quercus macrocarpa	26.9	28.9	27.3	28.0	17.2	20.3	20.0
Quercus marilandica	24.9	29.2	58.5	69.8	48.2	80.3	63.8
Quercus muehlenbergii	19.2	20.5	18.4	16.9	20.2	17.1	17.9
Quercus nigra	31.1	30.9	58.7	67.2	47.8	83.6	66.2
Quercus palustris	13.0	8.3	9.6	9.0	14.1	12.8	13.3
Quercus phellos	25.2	26.3	52.5	58.4	41.2	69.2	57.4
Quercus prinus	23.6	28.0	29.4	29.7	28.4	29.7	29.7
Quercus rubra	65.6	63.3	42.0	41.2	54.5	21.2	35.8
Quercus stellata	41.4	46.5	63.0	73.6	72.7	72.9	72.9
Quercus velutina	58.2	52.9	44.3	37.6	62.6	24.7	38.5
Robinia pseudoacacia	26.3	23.8	28.4	28.5	26.8	30.6	31.0
Salix nigra	25.0	24.7	24.7	24.7	24.7	24.7	24.7
Sassafras albidum	46.1	39.6	47.2	40.2	45.5	42.1	48.7
Taxodium distichum var. *nutans*	7.4	8.8	16.8	15.1	10.3	26.4	20.9
Taxodium distichum var. *distichum*	18.2	20.8	20.8	20.8	20.7	20.7	20.7
Thuja occidentalis	11.7	12.9	0.0	0.0	1.5	0.0	0.0
Tilia americana	45.7	45.6	24.9	22.6	29.1	12.4	17.9
Tsuga canadensis	19.9	21.5	18.5	18.4	17.7	18.4	18.4
Ulmus alata	23.5	21.6	63.6	93.0	53.7	85.7	69.5
Ulmus americana	70.2	100.0	100.0	100.0	100.0	100.0	100.0
Ulmus rubra	50.6	57.9	57.9	57.9	57.9	57.9	57.9

[a] GISS: Goddard Institute of Space Studies; GFDL: Geophysical Fluid Dynamics Laboratory; HAD: Hadley Center for Climate Prediction and Research; UKMO: United Kingdom Meteorological Office, and CCC: Canadian Climate Center.

(170–240 km), *Quercus falcata* var. *falcata* (80–470 km), *Q. marilandica* (60–410 km), *Q. nigra* (170–340 km), *Q. phellos* (120–380 km), *Q. velutina* (100–400 km), and *U. alata* (190–530 km).

Five species move south in optimum latitude in all five scenarios: *Acer rubrum*, *Crataegus* sp., *F. grandifolia*, *Juniperus virginiana*, and *P. serotina* (Table 5). *F. grandifolia* (210–280 km) could be reduced in area

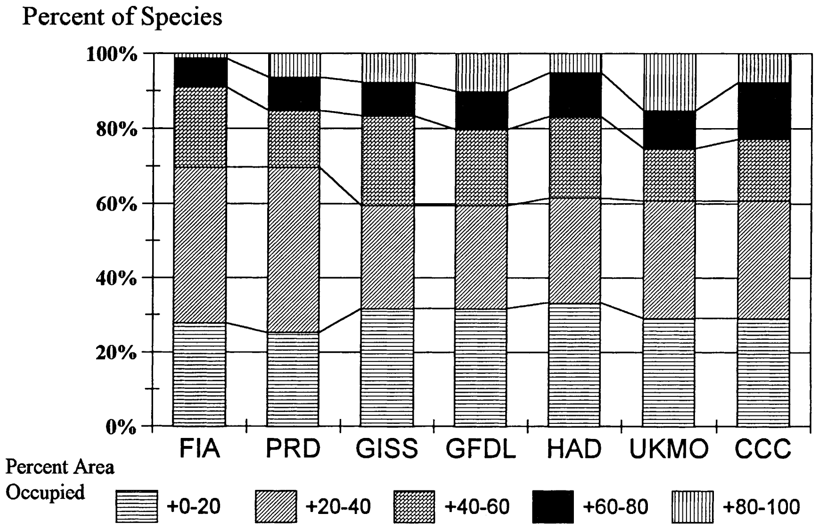

Fig. 1. Percent of land area occupied by percent of species and climate change scenario. Scenario abbreviations are found in Table 3.

Table 4
Potential changes, by species and climate change scenario for area and importance value[a]

Species	Area change					Importance value change				
	GISS	GFDL	HAD	UKMO	CCC	GISS	GFDL	HAD	UKMO	CCC
Abies balsamea	− −	− −	− −	− −	− −	− −	− −	−	− −	− −
Acer negundo	0	0	0	0	0	−	−	−	−	−
Acer pensylvanicum	−	−	−	−	−	− −	− −	−	− −	− −
Acer rubrum	0	0	0	0	0	−	− −	− −	− −	− −
Acer saccharinum	0	0	+	+	0	0	0	0	0	0
Acer saccharum	− −	− −	− −	− −	− −	−	−	− −	− −	− −
Betula alleghaniensis	− −	− −	− −	− −	− −	0	− −	+	+	+
Betula lenta	0	0	0	0	0	−	−	0	0	−
Betula papyrifera	− −	− −	− −	− −	− −	−	− −	−	− −	− −
Carpinus caroliniana	0	0	0	+	0	+	+	+	+	+
Carya cordiformis	0	0	+	+	+	0	0	−	0	−
Carya glabra	−	−	+	−	0	−	− −	−	−	−
Carya ovata	0	0	+	+	+	0	0	0	0	0
Carya tomentosa	+ +	+ +	+ +	+ +	+ +	−	−	−	−	−
Celtis laevigata	+ +	+ +	+ +	+ +	+ +	−	0	−	−	−
Celtis occidentalis	0	0	0	0	0	+	+	+	+	+
Cercis canadensis	+	+	+	0	+	0	0	0	+	0
Cornus florida	+	+	+	+	+	−	−	−	−	−
Crataegus sp.	0	0	−	0	0	− −	− −	− −	− −	− −
Diospyros virginiana	+	+ +	+	+ +	+ +	+	+	+	+	+
Fagus grandifolia	− −	− −	− −	− −	− −	+	+	+	+	+
Fraxinus americana	−	−	−	− −	−	−	−	0	−	−
Fraxinus nigra	− −	− −	− −	− −	− −	+	+	+	+ +	+ +
Fraxinus pennsylvanica	0	0	0	0	0	+	+	+	+	+
Gleditsia triacanthos	+	+	+	+	+	+	+	+	+	+
Ilex opaca	0	0	0	+	0	−	−	−	−	−
Juglans nigra	0	−	0	0	0	+	+	+	+	+
Juniperus virginiana	0	0	0	−	−	+	+	+	+	+
Liquidambar styraciflua	+	+	+	+ +	+ +	−	−	0	−	−
Liriodendron tulipifera	+	+	+	+	+	−	−	−	−	−
Maclura pomifera	+ +	+ +	+	+ +	+ +	+ +	+ +	+ +	+ +	+ +
Magnolia virginiana	+ +	+ +	+	+ +	+ +	+	0	+	+	0
Morus rubra	0	0	0	0	0	+	+	+ +	+ +	+ +
Nyssa aquatica	0	0	0	0	0	−	−	−	−	−
Nyssa sylvatica var. *biflora*	0	0	0	0	0	+	+	+	+	+
Nyssa sylvatica var. *sylvatica*	0	0	+	0	+	+	0	+	+	+
Ostrya virginiana	−	−	−	−	−	−	−	+	−	−
Oxydendrum arboreum	+	+	+	+	+	−	−	−	−	−
Pinus echinata	+	+	+	+ +	+	−	−	0	−	−
Pinus elliottii	+ +	+ +	+	+ +	+ +	−	−	−	−	−
Pinus palustris	+ +	+	0	+ +	+ +	+	+	+ +	+ +	+
Pinus resinosa	− −	− −	− −	− −	− −	−	− −	−	− −	− −
Pinus strobus	− −	− −	−	− −	− −	+ +	+ +	+ +	+ +	+ +
Pinus taeda	+ +	+ +	+	+ +	+ +	0	0	0	−	0
Pinus virginiana	− −	− −	−	− −	− −	+	+	+	+	+
Platanus occidentalis	+	+	+	+	+	−	−	0	−	−
Populus deltoides	0	0	0	0	0	0	0	−	−	−
Populus grandidentata	− −	− −	− −	− −	− −	−	− −	− −	− −	− −
Populus tremuloides	− −	− −	− −	− −	− −	−	− −	−	− −	− −
Prunus serotina	0	0	0	0	0	− −	− −	− −	− −	− −
Quercus falcata var. *pagodaefolia*	0	0	+	+	0	0	0	0	0	0

Table 4 (*Continued*)

Species	Area change					Importance value change				
	GISS	GFDL	HAD	UKMO	CCC	GISS	GFDL	HAD	UKMO	CCC
Quercus falcata var. *falcata*	+ +	+ +	+	+ +	+ +	+	+	+	+ +	+ +
Quercus alba	0	0	0	0	0	−	−	0	−	−
Quercus coccinea	+	+	0	+	+	−	− −	−	− −	−
Quercus laurifolia	+ +	+ +	+	+ +	+ +	−	−	0	−	−
Quercus macrocarpa	0	0	−	−	−	−	−	+	0	0
Quercus marilandica	+ +	+ +	+ +	+ +	+ +	+ +	+ +	+ +	+ +	+ +
Quercus muehlenbergii	−	−	0	−	−	+ +	+ +	+	+ +	+ +
Quercus nigra	+ +	+ +	+ +	+ +	+ +	−	−	−	−	−
Quercus palustris	+	0	+ +	+ +	+ +	0	0	0	0	0
Quercus phellos	+ +	+ +	+ +	+ +	+ +	0	0	0	0	0
Quercus prinus	0	0	0	0	0	0	0	−	0	0
Quercus rubra	−	−	−	− −	−	0	−	0	0	−
Quercus stellata	+	+ +	+ +	+ +	+ +	+ +	+ +	+ +	+ +	+ +
Quercus velutina	−	−	+	− −	−	+	+ +	+ +	+	+
Robinia pseudoacacia	+	+	+	+	+	−	−	−	−	−
Salix nigra	0	0	0	0	0	0	0	0	0	0
Sassafras albidum	+	0	+	0	+	−	− −	−	− −	− −
Taxodium distichum var. *nutans*	+ +	+ +	+	+ +	+ +	+ +	+ +	+	+ +	+ +
Taxodium distichum var. *distichum*	0	0	0	0	0	+	+	0	0	0
Thuja occidentalis	− −	− −	− −	− −	− −	− −	− −	−	− −	− −
Tilia americana	−	− −	−	− −	− −	−	−	− −	−	−
Tsuga canadensis	−	−	−	−	−	−	−	−	−	−
Ulmus alata	+ +	+ +	+ +	+ +	+ +	+	+ +	+	+	+ +
Ulmus americana	0	0	0	0	0	0	0	−	−	−
Ulmus rubra	0	0	0	0	0	−	− −	−	− −	− −

[a] Scenario abbreviations are defined in Table 3 ((0) no change (−10 to +10% change); (+) 10–50% gain; (++) >50% gain; (−) 10–50% loss; (− −) >50% loss).

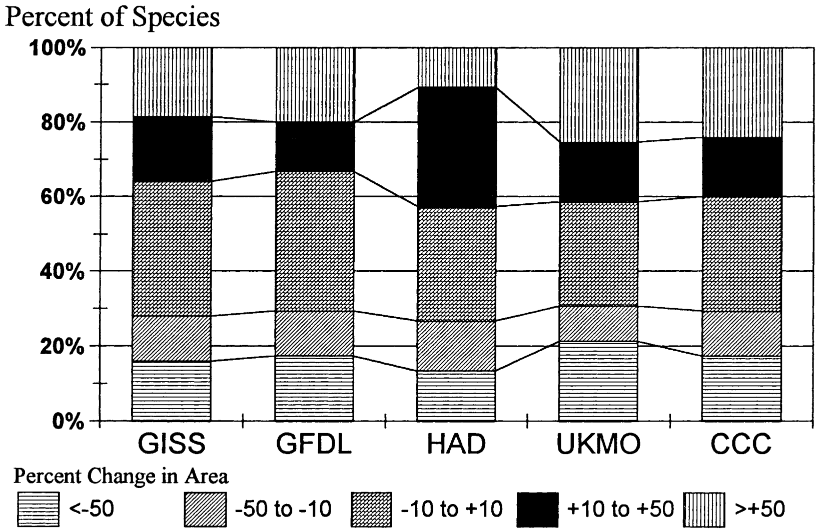

Fig. 2. Potential change in area, by percent of species and climate change scenario. Scenario abbreviations are found in Table 3.

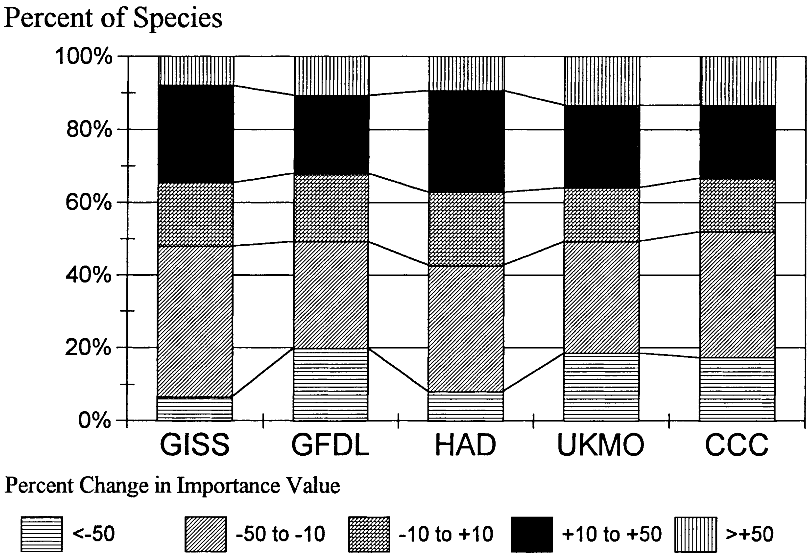

Fig. 3. Potential change in importance value, by percent of species and climate change scenario. Scenario abbreviations are found in Table 3.

by more than 90%, with the new distribution, only in the southern Appalachians. *A. rubrum* (200–230 km) shows little change in area but a large change in average IV. It currently occupies much of the eastern US, with higher IV values to the north. After climate change, the estimated IV values would be higher along the more southern Ohio and Mississippi River Valleys relative to its current prominence in northern locations.

Hadley was the least severe with respect to a potential shift in optimum latitude. About 41% of the species did not change (<20 km N or S), 30 species could move >100 km north, five species could move >200 km, and three species (*A. saccharum*,

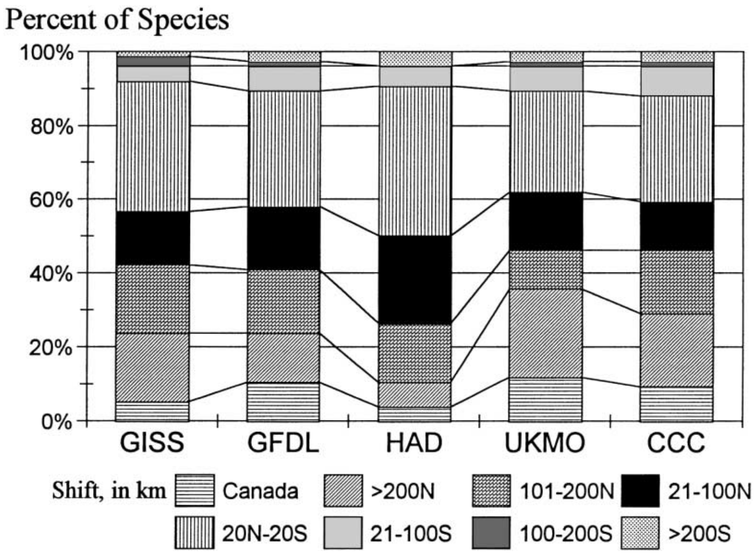

Fig. 4. Summary of potential movement of optimum latitude, by percent of species and climate change scenario. Scenario abbreviations are found in Table 3.

Table 5
Potential movement of the latitudinal optimum (in km)[a]

Species	Original optimum latitude	GISS	GFDL	HAD	UKMO	CCC
Abies balsamea	196	Canada	Canada	100N	Canada	Canada
Acer negundo	152	0N	0N	0N	0N	0N
Acer pensylvanicum	172	70N	50N	60S	60S	70N
Acer rubrum	147	200S	230S	220S	220S	230S
Acer saccharinum	159	10S	10N	10N	10N	10N
Acer saccharum	166	270N	Canada	Canada	Canada	Canada
Betula alleghaniensis	169	300N	Canada	290N	Canada	370N
Betula lenta	171	10N	10N	10N	10N	10N
Betula papyrifera	200	Canada	Canada	60N	Canada	Canada
Carpinus caroliniana	127	20S	50S	0N	0N	40S
Carya cordiformis	163	0N	0N	0N	0N	0N
Carya glabra	159	30S	30S	160N	140N	140N
Carya ovata	157	0N	0N	0N	0N	0N
Carya tomentosa	144	160N	130N	130N	130N	130N
Celtis laevigata	95	290N	530N	250N	530N	310N
Celtis occidentalis	160	0N	0N	0N	0N	0N
Cercis canadensis	143	330N	350N	220N	300N	340N
Cornus florida	121	200N	200N	80N	200N	200N
Crataegus sp.	154	110S	160S	310S	40S	40S
Diospyros virginiana	105	250N	260N	180N	380N	370N
Fagus grandifolia	163	210S	280S	280S	280S	280S
Fraxinus americana	168	60N	60N	30S	60N	60N
Fraxinus nigra	193	30N	30N	110N	Canada	0N
Fraxinus pennsylvanica	151	10N	10N	10N	10N	10N
Gleditsia triacanthos	154	0N	0N	0N	0N	0N
Ilex opaca	105	10N	90N	10S	200N	10N
Juglans nigra	156	0N	0N	0N	0N	0N
Juniperus virginiana	156	10S	10S	10S	10S	10S
Liquidambar styraciflua	116	0N	40N	10S	100N	30N
Liriodendron tulipifera	120	20N	20N	240N	170N	220N
Maclura pomifera	145	30N	30N	40N	30N	30N
Magnolia virginiana	97	70N	100N	10N	260N	110N
Morus rubra	168	0N	0N	0N	0N	0N
Nyssa aquatica	99	0N	0N	20N	20N	10N
Nyssa sylvatica var. *biflora*	98	80N	80N	10S	150N	70N
Nyssa sylvatica var. *sylvatica*	114	0N	0N	80N	60N	80N
Ostrya virginiana	156	160S	80S	0N	160S	200S
Oxydendrum arboreum	110	130N	110N	30N	90N	130N
Pinus echinata	104	180N	190N	20N	50N	200N
Pinus elliottii	78	140N	180N	60N	320N	180N
Pinus palustris	89	120N	200N	10N	370N	150N
Pinus resinosa	191	Canada	Canada	70N	Canada	Canada
Pinus strobus	157	10S	10S	0N	10S	10S
Pinus taeda	105	40N	130N	10S	200N	90N
Pinus virginiana	128	160N	230N	90N	440N	280N
Platanus occidentalis	127	240N	220N	170N	240N	240N
Populus deltoides	159	0N	0N	0N	0N	0N
Populus grandidentata	179	290N	Canada	Canada	Canada	Canada
Populus tremuloides	179	270N	Canada	250N	Canada	Canada
Prunus serotina	156	40S	40S	50S	50S	50S
Quercus facata var. *pagodaefolia*	101	120N	150N	90N	100N	130N
Quercus falcata var. *falcata*	104	220N	180N	80N	470N	340N

Table 5 (*Continued*)

Species	Original optimum latitude	GISS	GFDL	HAD	UKMO	CCC
Quercus alba	154	20N	20N	20N	10N	20N
Quercus coccinea	138	140N	30N	80N	40N	120N
Quercus laurifolia	83	140N	170N	70N	370N	210N
Quercus macrocarpa	182	10N	10N	10N	10N	10N
Quercus marilandica	115	150N	360N	60N	410N	210N
Quercus muehlenbergii	143	210N	230N	110N	210N	210N
Quercus nigra	92	220N	280N	170N	340N	270N
Quercus palustris	154	60N	40N	190N	190N	190N
Quercus phellos	100	250N	280N	120N	380N	270N
Quercus prinus	144	20N	20N	10N	30N	30N
Quercus rubra	167	60N	140N	40N	280N	170N
Quercus stellata	112	110N	100N	100N	100N	110N
Quercus velutina	153	180N	190N	100N	400N	290N
Robinia pseudoacacia	153	50N	50N	50N	50N	50N
Salix nigra	169	0N	0N	0N	0N	0N
Sassafras albidum	143	100N	90N	130N	50N	90N
Taxodium distichum var. *nutans*	91	30S	30S	0N	20N	60S
Taxodium distichum var. *distichum*	108	10N	10N	30S	30S	10N
Thuja occidentalis	195	Canada	Canada	Canada	Canada	Canada
Tilia americana	171	210N	150N	200N	260N	60S
Tsuga canadensis	161	0N	0N	0N	0N	0N
Ulmus alata	102	280N	530N	190N	480N	260N
Ulmus americana	153	0N	0N	0N	0N	0N
Ulmus rubra	156	0N	0N	0N	0N	0N

[a] "Canada" refers to the optimum latitude moving north of the border of the US; in this case, the actual distance of potential change of suitable habitat is indeterminable. Original optimum latitude refers to the row number of 10 km strips, from 1 at southern Florida to 277 in northern Minnesota (see text). Scenario abbreviations are defined in Table 3.

P. grandidentata, and *T. occidentalis*) could migrate into Canada (Table 5, Fig. 4). UKMO was the most severe scenario—47% of the species could move >100 km north, with 18 species moving more than 200 km and nine species' habitats moving into Canada. GISS was most closely aligned with Hadley, and GFDL and CCC were similar to UKMO in the overall impact on species distributions (Table 5, Fig. 4).

4. Discussion

4.1. Regression tree analysis models

Regression tree analysis has proven to be valuable in improving our understanding of species–environment relations. Variables important at the continental scale are distinguishable from more local variables when the tree diagrams are examined. Tree diagrams and maps depicting variable influences spatially are available for each species (Iverson et al., 1999a; Prasad and Iverson, 1999). These data show that different variables are correlated with the different range boundaries. For example, January temperatures often limit northern boundaries while western boundaries are influenced more by moisture gradients. At these regional scales, overall vegetation patterns depend primarily on general climatic patterns (Woodward, 1987; Neilson, 1995; Box et al., 1999). However, at local scales, we and other researchers have found that vegetation patterns rely more on edaphic and topographic variables (Ertsen et al., 1995; Iverson et al., 1997a). There are limitations to the methodology, however. Regression tree analysis is a statistical model that by nature is unable to incorporate many biological attributes (e.g. species interactions, physiological changes associated with higher CO_2 or temperature, dispersal characteristics) that will be important in the new species assemblages accompanying climate change.

There is general agreement between the current distribution of species importance and the modeled current distribution (FIA versus PRD data in Table 3). For a few widely dispersed, generalist species (*Fraxinus pennsylvanica*, *P. serotina*, *Quercus alba*, and *Ulmus americana*), the DISTRIB models were less able to accurately estimate area in that they predicted a small importance value over 100% of the study area, both now and in the future. Still, based on the IV-weighted area scores, the models fit the current FIA data reasonably well even for those species, and thus are reasonable for overall climate change assessments.

Although it is not possible to validate these models (Rastetter, 1996), the potential outcomes presented here are reasonable, particularly as these outcomes converge with those using other approaches (e.g. VEMAP members, 1995). The few studies of eastern North American species generally agree with these outputs. For example, Jacobson and Dieffenbacker-Krall (1995) predicted that *Pinus strobus* would be favored under climate warming while spruce–fir species would decrease. We found that the IV-weighted area score for *P. strobus* increases by 11% while that for *A. balsamea* decreases by 96% (Table 2). Flannigan and Woodward (1994) predicted that *P. resinosa* would migrate 600–800 km to the northeast but with an increase in volume per unit area. We projected that *P. resinosa* could have its optimum latitude move into Canada (Table 5). Overpeck et al. (1991) predicted similar trends for the northern pines but also large increases in oak abundance in the northern Great Lakes and New England. We projected northward shifts in optimum latitude for each of 15 oak species evaluated; several species could move more than 200 km northward (Table 5). Joyce et al. (1990) and Overpeck et al. (1991) predicted a large northward expansion among southern pines, and this result is also reported in our study.

We present in this paper the shift in potential suitable habitat for 76 species that could accompany climate change. The actual redistribution of species into the suitable habitat is dependent on several other factors. During the Holocene, species tended to respond to climate change in an equilibrium condition as migrations were occurring over thousands of years and over a relatively uninterrupted landscape; species tended to move approximately 50 km per century (Schwartz, 1992). However, the climate is projected to change at a much faster rate under climate change scenarios presented here. As a result, many species may be susceptible to expiration (Solomon and Kirilenko, 1997). Further, in today's fragmented and human-dominated landscapes, for some native species there are fewer individuals producing fewer propagules and fewer sites for these propagules to colonize. Thousands of exotic species potentially are better suited for colonizing or invading sites that otherwise may have been suitable for migrating tree species (Vitousek et al., 1996). For example, 899 of 3208 vascular taxa (28%) of the Illinois flora are nonnative (Iverson et al., 1997b). Many of these are woody species (167 taxa) and potentially long-term competitors to native trees. Thus, competition, dispersal ability, and nonequilibrium responses may be critical in determining the new species assemblages (Davis et al., 1998). Our approach (in a concurrent project) to estimating the actual redistributions into the suitable habitat is to model migration rates through a cellular automata model, SHIFT (Schwartz, 1992; Iverson et al., 1999b). It uses habitat quality and species abundance near the range boundary to model the migration of species across fragmented habitats. By intersecting the outputs from DISTRIB with those of SHIFT, we can estimate both the natural barriers to suitable new habitat and the colonization probability within that new habitat over 100 years.

4.2. Potential changes in suitable habitat

Results from these models show potentially great changes in the habitat for tree flora of the US during climate change. Some species could suffer severe reduction in the IV-weighted area score. Economically important species such as *A. saccharum*, *A. balsamea*, *P. tremuloides*, and *P. resinosa* could be reduced by more than 90% in the eastern US (Table 2). Other economically or ecologically important species that could be significantly reduced (>40%) are *Tilia americana*, *P. serotina*, *C. glabra*, *Fraxinus americana*, *Tsuga canadensis*, and *Quercus rubra*. Although not predicted to change in area, *A. rubrum* could be reduced in importance, which would reverse the current trend in which *A. rubrum* flourishes over much of the study area (Abrams, 1998). In contrast, several other economically and ecologically important species could flourish under hotter and perhaps drier conditions accompanying a climate change. Seven of 15 species of oak (*Quercus*) would increase in IV-weighted area score by more than 40% (Table 2). *Pinus taeda* and *P. palustris*, two economically important southern pine species are also projected to expand greatly in suitable habitat.

4.3. Comparison of global change scenarios

On the basis of the results of these model experiments, the severity of the five climate change scenarios with respect to tree-distribution shifts appears to be:

$$\text{UKMO} > \text{CCC} > \text{GFDL} > \text{GISS} \gg \text{Hadley}$$

This observation is taken primarily from Table 5 and Fig. 4, which show the potential shift in optimum latitude by species. The number of species with their latitudinal optimum potentially moving >200 km north or into Canada is 27 for UKMO, 22 for CCC, 18 for GFDL and GISS, and eight for Hadley. The number of species exhibiting essentially no movement north or south is highest for Hadley (31), while 21–27 species did so under the other scenarios. Hadley is considered "moderate" for the eastern US, i.e. it is much wetter and cooler than the others (though significantly warmer and wetter than current conditions, Table 1).

Overall, there is considerable agreement among scenarios in the trends for most of the 76 species, especially with regards to sign (Table 4). The ordering of IV-weighted area scores in Table 2 changes only slightly among scenarios, implying that the average ranking presented here is realistic.

5. Conclusions

Our results show that suitable habitat for eastern US tree species will fluctuate greatly with climate change. Of the 76 species evaluated here, potential habitat would increase >10% for 33–43 species and decrease >10% for 27–31 species, depending on the climate change scenario. We have presented here a ranked listing of species according to potential climate change effects. Such large changes would also have significant effects on other components or users of the forest. As forest-species and assemblages shift, so do the associated flora and fauna. Further, conditions would likely favor invasive species to gain importance in the changing forests because many are adapted to disturbance.

For most of the potential habitat changes described, it matters little as to which climate change scenario is evaluated; overall tendencies in area and importance value are similar. Larger differences in potential movement of habitat exist, however. Of the scenarios evaluated, the Hadley scenario imparts the least, and the UKMO and CCC scenarios the greatest impacts on movement of potential suitable habitat.

We emphasize that the results presented here are for potential changes in suitable habitat, not actual distributions. The actual distributions will be determined by migration rates and various measures humans take to intervene. This framework of potential future suitable habitat, however, can be the starting place for future research on how biological factors interact to produce the species assemblages though these next decades of climate change.

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