

Tree Migration Detection Through Comparisons of Historic and Current Forest Inventories

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Abstract: *Changes in tree species distributions are a potential impact of climate change on forest ecosystems. The examination of tree species shifts in forests of the eastern United States largely has been limited to modeling activities with little empirical analysis of long-term forest inventory datasets. The goal of this study was to compare historic and current spatial distributions of tree species for sets of northern and southern tree species in the eastern United States using region-wide forest inventories. Based on the results of this study, no conclusions could be drawn about tree migration in the eastern United States. The technique of comparing outer ranges of tree species based on periodic forest inventories may be confounded by inconsistent forest inventory methods across time and space along with tree species identification measurement error. It is suggested that novel tree migration detection methods be developed based on contemporary forest inventories that are consistent across space and time.*

Keywords: Climate change, tree migration, forest inventory

Tree Species Migration

The world's climate is forecasted to change significantly over the next century due to a doubling of pre-industrial atmospheric carbon dioxide concentrations resulting in an increase in mean surface temperatures of 2 to 4.5 degrees C, more episodic precipitation events, and longer growing seasons (IPCC 2007). Climate is an important driver of forest ecosystem functions (Stenseth et al. 2002). Thus, changes in climate should change forest ecosystem attributes and functions.

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Fitness of trees is expected to be impacted by changes in absolute temperatures and the timing and/or magnitude of precipitation events (Saxe et al. 1998, Nabuurs et al. 2002, Sacks et al. 2007), along with a higher probability of catastrophic wildfires in regions of the United States (Westerling et al. 2006). These effects on individual tree fitness are forecasted to subsequently affect tree response to stress agents such as insects and disease (Volney and Fleming 2000; Logan et al. 2003). The culmination of climate change effects on forest ecosystems ultimately may be the migration of tree species (Opdam and Wascher 2004, Walther et al. 2002). There is evidence of past forest migration rates exceeding 50 km per century during episodes of climate change (Schwartz 1992, Noss 2001, Parmesan and Yohe 2003). Currently, forests may need to migrate one order of magnitude faster than in past migrations to adequately respond to current rates of warming (Schwartz 1992). However, modern day fragmentation of forest ecosystems may slow the movement of tree species, potentially reducing tree migration capacity by one order of magnitude (Schwartz et al. 2001, Davis and Shaw 2001, Walther et al. 2002, Opdam and Wascher 2004). Given the substantial implications of climate change impacts on tree species distributions within a relatively short period of time, the detection of tree species migration is critical.

Examination of tree species migration has mainly focused on investigating historic ranges during the past millennia (e.g., Davis and Shaw 2001, Malcolm et al. 2002, McLachlan et al. 2005, Pearson 2006) and simulating future tree species shifts (e.g., Schwartz et al. 2001, Iverson and Prasad 1998, Iverson et al. 1999, Malcolm et al. 2002, McCarty 2001, Iverson et al. 2008). These studies have been invaluable not only for raising awareness about climate change impacts on forest ecosystems, but also for highlighting knowledge gaps. However, holistic assessment of these climate change effect models continues to call for refinement of modeling techniques with little or no empirical validation of these models with current data (e.g., Botkin et al. 2007). Therefore, techniques need to be developed for validating extensive simulations of potential tree species shifts, which are based on poorly understood tree migration dynamics (Malcolm et al. 2002). Remote-sensing products and field-based forest inventories provide data for monitoring forest attributes across large regions. Unfortunately, remote-sensing products are not well suited for identifying individual tree species across large geographic extents, especially in the understory. The alternative is to use forest inventories to track geographic ranges of tree species over a period of decades.

Given the need to monitor the possible migration of tree species across the United States, the goal of this study was to compare tree locations for selected study species using both the oldest and most current digital forest inventories (stored in digital format) across states in the eastern United States. The study had three objectives: 1) for a selected list of northern tree species, compare the minimum latitude by species in year one (oldest inventory) and year two (most current inventory); 2) for a selected list of southern tree species, compare the maximum latitude by species in year one and year two; and 3) discuss the hurdles in using historic and annual forest inventories to monitor tree species migration.

Historic and Current Forest Inventories

During the 1930s, the U.S. Forest Service Forest Inventory and Analysis (FIA) program was charged by Congress to “make and keep current a comprehensive inventory and analysis of the present and prospective conditions of and requirements for the renewable resources of the forest and rangelands of the United States” (McSweeney-McNary Act of 1928) (Gillespie 1999, Frayer and Furnival 1999, Bechtold and Patterson 2005). During most of the 20th century, FIA was the primary source for information about the extent, condition, status, and trends of forest resources across all ownerships in the United States (Smith 2002). However, the national inventory of forest land was conducted only periodically, using sample designs and data management systems that varied by state and inventory period (Gillespie 1999). A variety of plot-level sample designs were used: fixed-radius to variable-radius, clusters of 4 to more than 10 sub-plots, and differing measurement protocols by individual variables (e.g., tree height or length). Additionally, remeasurement periods ranged from between 7 years to more than 20 years. The strategic-scale paradigm of varying sample designs, methods, and dates often confounded regional, cross-state forest resource analyses and digital data management -- two important aspects germane to 21st century analyses.

An annual forest inventory was initiated in 1999 by the FIA program. FIA now applies a nationally consistent sampling protocol using a quasi-systematic design covering all ownerships in the entire Nation (Bechtold and Patterson 2005). A three-phase inventory is now implemented, based on an array of hexagons assigned to separate interpenetrating, non-overlapping annual sampling panels (Bechtold and Patterson 2005). In phase 1, land area is stratified using aerial photography or classified satellite imagery to increase the precision of estimates using stratified estimation. Remotely sensed data may also be used to determine if plot locations have accessible forest land cover (Bechtold and Patterson 2005). In phase 2, permanent fixed-area plots are installed in each hexagon when field crews visit plot locations that have accessible forest land. Field crews collect data on more than 100 variables, including land ownership, forest type, tree species, tree size, tree condition, and other site attributes (e.g., slope, aspect, disturbance, land use) (Smith 2002, USDA Forest Service 2008). Plot intensity for phase 2 measurements is approximately one plot for every 2,428 ha of land (125,000 plots nationally). Briefly, the plot design for FIA inventory plots consists of four 7.2-m fixed-radius subplots spaced 36.6 m apart in a triangular arrangement with one subplot in the center. All trees with a diameter at breast height of at least 12.7 cm are inventoried on forested subplots. Within each subplot, a 2.07-m microplot offset 3.66 m from subplot center is established where all trees with a d.b.h. between 2.54 and 12.7 cm are inventoried.

Data and Methods

Two sets of 18 predominantly northern and southern tree species were selected based on species range maps developed by Little (1971); these sets

generally coincided with past species migration studies (Iverson and Prasad 1998) (Table 1).

Table 1: Common and Latin names of northern and southern tree species in the eastern United States used in this study

Northern Species		Southern Species	
Common Name	Latin	Common Name	Latin
Balsam Fir	<i>Abies balsamea</i>	Shortleaf Pine	<i>Pinus echinata</i>
Tamarack	<i>Larix laricina</i>	Slash Pine	<i>Pinus elliotii</i>
White Spruce	<i>Picea glauca</i>	Loblolly Pine	<i>Pinus taeda</i>
Black Spruce	<i>Picea mariana</i>	Baldcypress	<i>Taxodium distichum</i>
Red Pine	<i>Pinus resinosa</i>	Pignut Hickory	<i>Carya glabra</i>
Eastern White Pine	<i>Pinus strobus</i>	Flowering Dogwood	<i>Cornus florida</i>
Northern White - Cedar	<i>Thuja occidentalis</i>	American Holly	<i>Ilex opaca</i>
Eastern Hemlock	<i>Tsuga canadensis</i>	Sweetgum	<i>Liquidambar styraciflua</i>
Sugar Maple	<i>Acer saccharum</i>	Yellow-Poplar	<i>Liriodendron tulipifera</i>
Yellow Birch	<i>Betula alleghaniensis</i>	Southern Magnolia	<i>Magnolia grandiflora</i>
Paper Birch	<i>Betula papyrifera</i>	Sweetbay	<i>Magnolia virginiana</i>
Gray Birch	<i>Betula populifolia</i>	Red Mulberry	<i>Morus rubra</i>
Black Ash	<i>Fraxinus nigra</i>	American Sycamore	<i>Platanus occidentalis</i>
Balsam Poplar	<i>Populus balsamifera</i>	Southern Red Oak	<i>Quercus falcata</i>
Bigtooth Aspen	<i>Populus grandidentata</i>	Laurel Oak	<i>Quercus laurifolia</i>
Quaking Aspen	<i>Populus tremuloides</i>	Blackjack Oak	<i>Quercus marilandica</i>
Northern Pin Oak	<i>Quercus ellipsoidalis</i>	Water Oak	<i>Quercus nigra</i>
Northern Red Oak	<i>Quercus rubra</i>	Post Oak	<i>Quercus stellata</i>

The oldest forest inventory (year one) that was available in digital format was selected for each eastern state in the Nation (Table 2). The oldest inventories ranged in date from 1977 to 1995. For year two, the most recent annual inventory was selected because all eastern states currently have an FIA annual forest inventory (for more information, see USDA 2007). The most current forest inventories ranged in date from 2002 to 2005. All forest inventory data were taken entirely from FIA's national public database (FIADB 3.0) in 35 eastern states, so all plot latitudes are "fuzzed" as required by law. Because plot locations are perturbed in an unbiased direction not exceeding 1.67 km (typically within a 0.8-km radius of the actual plot location), estimates of maximum species latitudes should not be biased. Annual inventories for each state were first initiated between 1998 and 2003 and continued through 2006, so sample intensities may vary by state. Because FIA inventory is quasi-systematic with sample plots distributed across the geographic extent of each state, varying sample intensities will not bias assessment of tree species locations, but will only affect the precision of the estimates.

Table 2: Measurement years for FIA periodic forest inventories (Year 1) and annual forest inventories (Year 2) by eastern state used in this study

State	Year 1	Year 2	State	Year 1	Year 2
Alabama	1990	2004	Nebraska	1983	2005
Arkansas	1995	2005	New Hampshire	1983	2005
Connecticut	1985	2005	New Jersey	1987	2004
Delaware	1986	2004	New York	1993	2004
Florida	1987	2005	North Carolina	1984	2002
Georgia	1989	2004	North Dakota	1980	2005
Illinois	1985	2005	Ohio	1991	2004
Indiana	1986	2005	Pennsylvania	1989	2004
Iowa	1990	2005	Rhode Island	1985	2005
Kansas	1981	2005	South Carolina	1986	2005
Kentucky	1988	2004	South Dakota	1980	2005
Louisiana	1991	2005	Tennessee	1989	2004
Maine	1995	2003	Texas	1992	2005
Maryland	1986	2004	Vermont	1983	2005
Massachusetts	1985	2005	Virginia	1984	2004
Michigan	1980	2004	West Virginia	1989	2004
Minnesota	1977	2005	Wisconsin	1983	2004
Missouri	1989	2004			

Inventory Comparisons

Differences across minimum and maximum latitudes for northern and southern species between time one and time two indicated no obvious trends (Table 3). For northern species, 9 of 18 study species had higher minimum latitudes in time 2 than in time 1. The average degree difference between inventories for all northern species was 0.18 degrees farther south. Northern pin oak, black ash, and gray birch had some of the greatest shifts northward with their minimum latitude shifts at 2.5 degrees or more. For southern species, only 5 of the 18 study species had maximum latitudes farther north, but the average maximum northward latitude shift across all southern species was 0.02 degrees. Southern magnolia and laurel oak had the largest shifts northward in maximum latitude, with shifts of more than 2.4 degrees northward.

No species migration conclusions can be made given such inconsistent changes in maximum and minimum latitudes between forest inventories. Given that little ecological information can be gleaned from this exercise, perhaps methodologies should be critiqued. This study's technique of comparing maximum and minimum outliers of species ranges based partially on periodic forest inventories has revealed many confounding factors. The two overwhelming factors that complicate species migration detection using periodic data are inconsistent methods/measurement periods and reliance on outliers that may be measurement errors (e.g., species identification). First, only trees with a d.b.h. greater than 2.54 cm can be examined because seedlings were inventoried sporadically using inconsistent sampling methodologies in periodic inventories. Second, the latitudinal shift of mature and/or established trees may be a lagging indicator of climate change effects. Attempting to compare a periodic forest inventory from 1982 to an annual inventory conducted in 2000 may not provide a

sufficient period of time (only 18 years) to indicate the movement of trees with a d.b.h. greater than 2.54 cm.

Table 3: Maximum or minimum latitudes in times 1 and 2 by species in the eastern United States

Common Name	Northern			Common Name	Southern		
	Time 1 Min. Latitude (deg.)	Time 2 Min. Latitude (deg.)	Degree Diff. ^a		Time 1 Max. Latitude (deg.)	Time 2 Max. Latitude (deg.)	Degree Diff. ^a
Balsam Fir	43.12	42.06	1.06	Shortleaf Pine	40.53	40.06	0.47
Tamarack	39.94	40.66	-0.72	Slash Pine	34.06	34.55	-0.49
White Spruce	40.06	39.89	0.17	Loblolly Pine	39.8	39.09	0.71
Black Spruce	40.03	42.46	-2.43	Baldcypress	39.01	39.01	0.00
Red Pine	38.45	39.17	-0.72	Pignut Hickory	43.19	43.09	0.10
Eastern White Pine	35.11	31.49	3.62	Flowering Dogwood	45.96	43.99	1.97
Northern White-Cedar	42.79	41.35	1.44	American Holly	39.81	41.97	-2.16
Eastern Hemlock	34.19	34.34	-0.15	Sweetgum	41.49	40.14	1.35
Sugar Maple	31.47	29.11	2.36	Yellow-Poplar	42.95	42.39	0.56
Yellow Birch	35.17	34.53	0.64	Southern Magnolia	33.83	36.25	-2.42
Paper Birch	39.75	38.48	1.27	Sweetbay	39.17	39.51	-0.34
Gray Birch	38.46	40.96	-2.50	Red Mulberry	44.99	43.38	1.61
Black Ash	35.58	38.36	-2.78	American Sycamore	43.31	42.91	0.40
Balsam Poplar	39.37	35.54	3.83	Southern Red Oak	40.36	39.37	0.99
Bigtooth Aspen	37.28	36.44	0.84	Laurel Oak	34.22	39.14	-4.92
Quaking Aspen	38.78	40.51	-1.73	Blackjack Oak	41.01	40.36	0.65
Northern Pin Oak	38.54	41.1	-2.56	Water Oak	39.8	38.71	1.09
Northern Red Oak	31.25	31.69	-0.44	Post Oak	40.54	40.31	0.23

^aDegree Difference = Time 1 latitude – time 2 latitude

Furthermore, the oldest forest inventories (pre-1970s) are currently not digitized, disallowing comparisons to current inventories. Third, to examine tree species shifts across large geographic extents, multiple state inventories need to be used. Because inventories were periodic before 1999, comparing periodic to annual inventories would mean, for example, comparing a 1978 inventory to 2001 for one state while comparing a 1986 inventory to 1999 in an adjoining state. Fourth, FIA field crews attain measurement repeatability of only 95-98 percent for tree species identification (Pollard et al. 2006). Developing range maps based on maximum spatial distributions from periodic forest inventories places too much reliance on single observations that may be prone to measurement error. Fifth, even if some portions of periodic inventory plots were remeasured during the most recent annual inventory, sample protocols have changed. Hence, examining tree species migration over long periods of time in the eastern United States is almost completely confounded by changes in plot locations (sample intensities), plot sampling configurations/protocols, and non-matching periodic inventory dates from state to state. Overall, there appears to be many obstacles to using periodic forest inventories to monitor tree migration. Robust tree migration monitoring requires development of novel techniques, especially given the potentially profound impacts that such migration could have on the total environment and society as a whole.

Future Directions

Over thirty years ago, the overarching purpose of conducting forest inventories was state-level forest resource assessment (e.g., growing-stock volumes and forest-type distributions). The use of such data across state boundaries to monitor tree migration was not foreseen at that time and now is nearly precluded by a host of confounding factors. Although there may be some ways to avoid some of the confounding factors stemming from periodic inventories (e.g., conducting state-level monitoring of individual refugia), there is no statistically robust way forward to use periodic inventories to monitor species migrations along the eastern United States. Continued research is strongly suggested in this area. It is suggested that new indicators of tree species migration be developed using only annual forest inventory data (since 1999). These data are systematically balanced across the entire eastern United States using consistent sample protocols, digital database management, and thorough documentation. Perhaps comparing seedling to mature tree distributions by species may be a new indicator to consider. Nonetheless, high quality and consistent forest inventory across large-scales provides the best opportunity to monitor tree species migration for the foreseeable future.

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