ADAPTING OAK MANAGEMENT IN AN AGE OF ONGOING MESOPHICATION BUT WARMING CLIMATE

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Abstract—Rising temperatures and variable precipitation events leading to droughts and floods will likely increase in frequency. We present climate models with bracketed scenarios of daily temperature and precipitation from 1980 to 2099 showing increasing heat and drought for much of the country throughout this century. We then model and map potential changes in suitable habitat for ~130 tree species (10 x 10 km to 20 x 20 km) in the Eastern United States. Potential adaptability to changing climate was evaluated by literature assessment of biological and disturbance traits. Overall, trends show many species with shrinking habitat suitability but also several drought-tolerant species (especially oaks) with increased habitat. However, current oak regeneration is often poor - hence management assistance is needed to ensure an ongoing, thriving oak component. Long-term research in Ohio has shown that prescribed fire and thinning can provide a successful path for oak regeneration, depending on the moisture regime within the landscape. These data-informed models of oak regeneration highlight potential sites for oak regeneration across a 17-county region in southeastern Ohio. Silvicultural treatments promoting future increasers (e.g., oak) and finding refugia for decreasers can then be devised as a means to adapt to the changing climate.

INTRODUCTION

Oaks (*Quercus* spp.) have long been a foundational genus across much of Eastern United States (Hanberry and Nowacki 2016), but oak regeneration has been shown to be a problem across its distribution for many decades, and this problem continues to grow despite research and management attempts to decelerate it (Hutchinson and others 2012, Johnson and others 2009, Loftis 2004). Trends in Ohio, for instance, show a leveling out of oak volume, especially white oak (*Q. alba*), which is being harvested at a rate exceeding growth, as compared to a rapid rise in the maples (*Acer* spp.), which are increasing at a rate that is nearly four times their harvest rate (Widmann and others 2014). This is due to 'mesophication' of the landscape because of closed overstory canopies with insufficient light reaching the forest floor for adequate oak regeneration (Nowacki and Abrams 2008). Oaks provide a plethora of ecosystem services, so that sustaining the biodiversity, cultural, aesthetic, and economic services provided by oaks is highly desired by society.

There is now a robust body of research, including that reported in this volume, which identifies effective silvicultural treatments to increase the probability of successful oak regeneration. Prescribed fire, partial harvesting, herbicide application, and herbivore exclusion can all improve oak regeneration if applied at the right time, at the right place and at the right frequency and/or intensity (Brose and others 2008, Iverson and others 2017, Johnson and others 2009). For example, research into the treatments necessary to

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achieve successful oak-hickory (*Carya* spp.) regeneration has been underway in Ohio since 1995 (Hutchinson and others 2005, 2012; Iverson and others 2008a; Sutherland and Hutchinson 2003), and has shown that a combination of removing mid- to upper story trees and repeated prescribed fire has the best potential to promote oak-hickory regeneration, but most successfully on drier ridges and southwest-facing sites. So when appropriate conditions are met (e.g., drier positions with advance oak regeneration), these 'zones of investment' for silvicultural treatment priority have been shown to increase the regeneration capacity for oaks. In contrast, areas not meeting criteria for the 'zones of investment' (e.g., mesic sites with little or no oak advance regeneration) are ill suited for silvicultural treatments aimed at oak regeneration based on limited available resources. A goal of this paper is to present a method to identify appropriate 'zones of investment' across southeastern Ohio where oak regeneration may be most successful per unit of effort and resources.

Meanwhile, the climate is warming, primarily caused by human-derived inputs of greenhouse gases (Wuebbles and others 2017), with heat, drought, and wildfire projected to increase in coming decades (Clark and others 2016, Matthews and others 2018, Wehner and others 2017). These conditions are expected to favor most oaks and hickories because they are physiologically more competitive under such conditions (Brose and others 2014, Butler and others 2015, Iverson and others 2017). It is therefore incumbent upon society and forest managers to work to sustain oaks and hickories so that adequate supplies of propagules, safe sites, and migration corridors are available into the future. A second goal of this paper is to present outputs of modeling efforts to identify the species that may do better or worse in coming decades under climate projections.

METHODS

Assessment of Climate Change Ongoing Now and Into the Future

We used several datasets of estimates of daily temperature and precipitation from 1980 to 2099 to evaluate past and potential future trends in climate indices related to biotic activity across the conterminous United States (Matthews and others 2018). These data allowed us to calculate, for four 30-year periods [1980–2009 (recent past), 2010–2039, 2040–2069, 2070–2099], four indices related to climate: Plant Hardiness Zones, Growing Degree Days, Heat Zones, and Cumulative Drought Severity Index. To explore the potential variation in projected changes of these climate patterns, we evaluated each metric under two scenarios, or 'bookends,' of projected climate change. These used, at the low end of potential change, a representative concentration pathway (RCP) 4.5 storyline of relatively rapid reduction of greenhouse gasses with peak emissions ~2040 (Moss and others 2008), combined with a general circulation model (GCM) with a relatively low sensitivity to carbon dioxide (CO_2). For the higher end of potential change, we used a model more sensitive to CO_2 with the RCP 8.5 storyline of continuing our current emissions path throughout this century. Unfortunately, global CO_2 levels have been tracking RCP 8.5 much more closely than RCP 4.5 levels in the time since these scenarios were generated in 2008 (Peters and others 2013). See Matthews and others (2018) for details on methods and results for the conterminous United States, but to demonstrate potential changes in conditions for tree success in the eastern forests, we here provide selected data on Heat Zones (the average number of days when maximum temperature exceeds 30 °C, averaged across the 30 years) and Cumulative Drought Severity Index (a weighted value derived from the occurrence and intensity of monthly drought events accumulated over 30 years (Peters and others 2014, 2015) for the Eastern United States, as they pertain to the eastern oak-prevalent geographies.

Modeling Potential Changes in Tree Species with the Changing Climate

The past climate has influenced species habitats for trees, as will future climates. Our group has been modeling, using the DISTRIB model, the potential change in suitable habitats under a changing climate for over 20 years, resulting in a number of publications (Iverson and Prasad 1998; Iverson and others 2008b, 2011), regional assessments (Brandt and others 2014, 2017, Butler and others 2015), and multiple updates to a Climate Change Atlas website (www.nrs.fs.fed.us/atlas). An update to the modeling was recently completed, and selected data are reported here. We use 45 environmental variables, including climate variables mentioned above, in combination with Forest Inventory and Analysis (FIA) inventory data (www.fia.fs.fed.us) to create a statistical model, DISTRIB II, projecting current and potential future suitable habitats in 30-year intervals throughout this century. A full explanation of the new modeling procedures and outcomes is in process and will be reported on the web site and future publications.

Besides the potential change in suitable habitats, the possible migration within those habitats has also been an ongoing investigation by our group, using the SHIFT model (Iverson and others 1999, 2004a, 2004b; Prasad and others 2013, 2016), and provides a basis for understanding the large lag time between the change in suitable habitats and the possible natural colonization in future decades based on historical migration rates.

Since models are unable to capture all aspects of potential change, we scored each of 134 species via literature- derived indications of 9 biological traits and 12 disturbance traits related to the capability to deal with climate change; these modification factors form the basis of the estimate of adaptability for each species (Iverson and others 2011, Matthews and others 2011).

For purposes of display and summarization, we report outputs of DISTRIB II and SHIFT by 1- by 1-degree grid, in this case for a portion of southeastern Ohio that encompasses the Athens District of the Wayne National Forest. This is an area bounded by 39-40° N latitude and 82-83° W longitude. The output includes estimates of species abundance (based on number of stems and basal area) both now and at century's end, the potential changes in habitat at low and high emissions, scores of adaptability, model reliability, and capability. The capability rating combines previously mentioned variables to assess the species' ability to cope with a changing climate, so that a species is ranked with a very good, good, fair, poor, very poor, lost, new habitat, or unknown capability, based on its current abundance within this 1- by 1-degree grid.

Assessment of Landtypes for Oak-Hickory Investment

To enable relatively large-scale treatments with limited resources, a mapping exercise was used to identify 'zones of investment' for oak-hickory restoration; a Geographic Information System (GIS) was used to rank every 10- by 10-m pixel across a 17-county region of southeastern Ohio into six landtype phases via derivatives of topography. The six landtype phases were further collapsed into three landtypes: Dry Oak forest (lovingly nicknamed 'Oaky-doaky sites'), Dry-mesic Mixed Oak Hardwood forest, and Rolling Bottomland Mixed Hardwood forest. See Iverson and others (2018) for details. For purposes of demonstration, we report a summary for the same 1- by 1-degree grid as reported above.

SILVAH is a decision-support system which enables forest managers to select appropriate silvicultural prescriptions based on multiple, small plot inventories from stands of interest (Brose and others 2008). SILVAH-based plot data are now routinely collected by State and Federal agencies in southeastern Ohio, and thus can be used in conjunction with the landtype mapping to assess potentials for oak-hickory restoration on particular parcels of land. As described in Iverson and others 2018, a GIS-based tool is available to summarize both the areas of landtypes (or landtype phases) within a user-specified area, and the SILVAH-derived statistics of species abundance in the under- and overstory.

RESULTS AND DISCUSSION

Changes in Heat and Drought

An analysis of potential trends in the Heat Zones and the Cumulative Drought Severity Index (CDSI) shows the potential for large changes, depending on the choice humans make relative to curbing emissions (fig. 1) (Matthews and others 2018). For example, in Midwestern States, under the high level of emissions, an average additional 95 days exceeding 30 °C are projected; in contrast, under low emissions, only 42 additional days are projected (Matthews and others 2018). With CDSI, again there is a large contrast of overall drought between low and high levels of emissions (fig. 1). Even under low emissions, however, there are projected increases in heat and drought which would have significant impacts on the biota of the region, including potential conditions which allow oaks and hickories to be more competitive against the more mesophytic species. Nonetheless in the meantime, the oaks and hickories are losing status relative to the maples such that near-heroic efforts need to be undertaken to sustain them into the near future so that sufficient propagules will be present should conditions turn to favor the oaks and hickories in the later decades of this century.

Changes in Tree Suitable Habitat

Suitable habitats for tree species are reported for the 1- by 1-degree grid bounded by 39-40° N and 82-83° W, a portion of southeastern Ohio (and of the 17-county study area) that encompasses the Athens District of the Wayne National Forest (tables 1 and 2). This area shows a total of 78 species, with 67 species present now and 68 species with habitat projected to be suitable at the end of this century. We also score the species for their current abundance, based on the FIA data-derived sum of importance in the 1- by 1-degree grid; it showed 18 abundant species led by red maple (*A. rubrum*), sugar maple (*A. saccharum*), yellow-poplar (*Liriodendron tulipifera*), sassafras (*Sassafras albidum*), white oak, and black cherry (*Prunus serotina*); 34 common species; and 15 rare species in the area (including 3 with some evidence for the species in the area but too rare for an acceptable model to be generated). Of the species present currently, 24 are projected to lose substantial habitat (large or very large decreaser) and another 17 to lose some habitat (small decreaser) if the climate changes according to the high emissions projection. On the other hand, one species is projected to gain substantial habitat and seven gain some habitat under high emissions (table 2). In addition, 15 species are projected to remain with about equivalent habitat, while 8 species not presently in the area (according to FIA plots) could gain habitat, and 5 species present currently could see their suitable habitat eliminated. Under low emissions, the projected changes are somewhat dampened, but still substantial (table 2).

By combining several attributes of the species and their modeled outputs, we also present an overall capability rating for the species, within that particular grid, to cope with a changing climate under a high level of

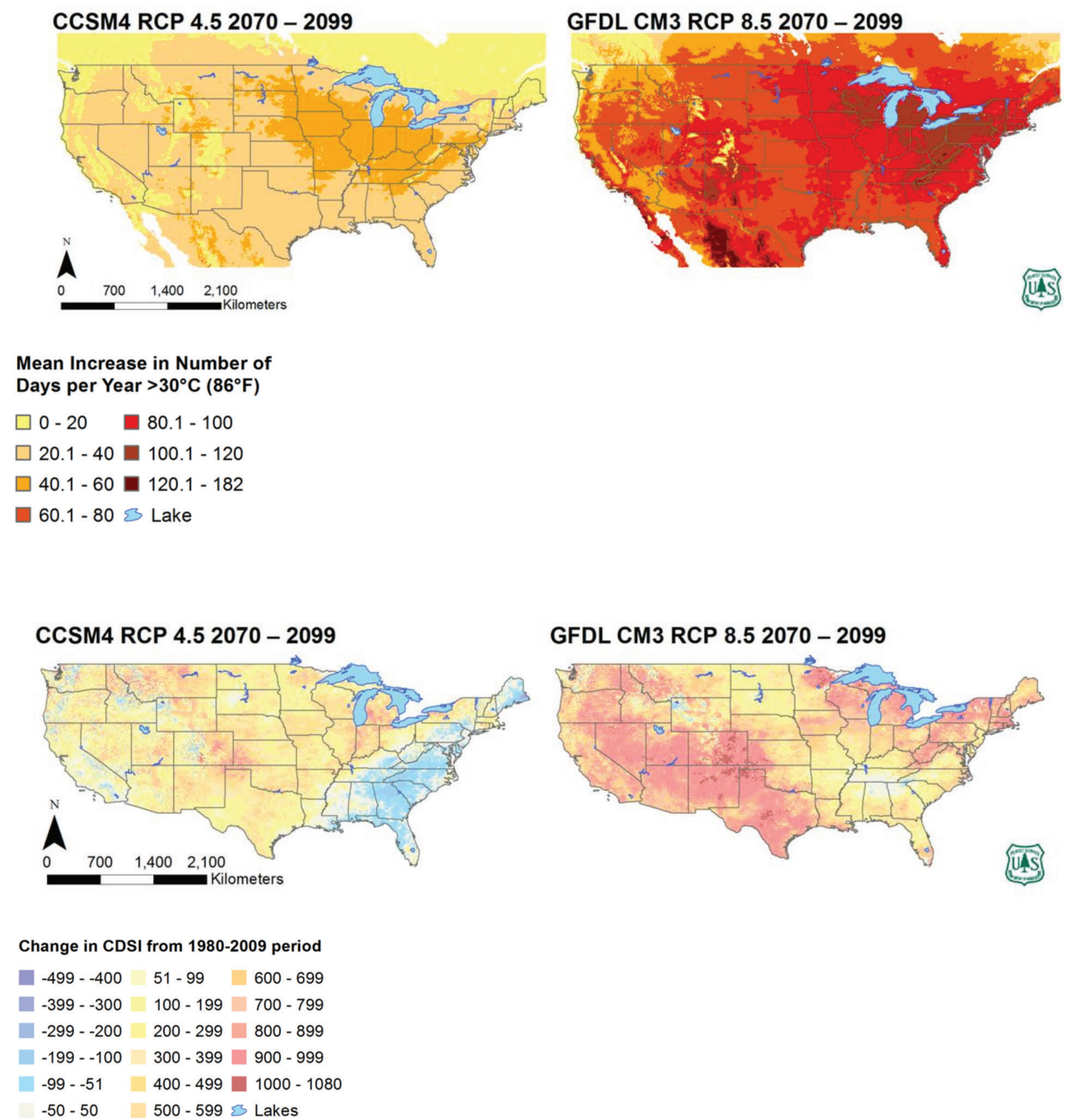

Figure 1—Change in Heat Zones (HZ) and Cumulative Drought Severity Index (CDSI) for the Eastern United States (oak-hickory-dominated regions) projected from current (1980–2009) to end of century (2070–2099) according to low and high emissions scenarios.

Table 1—Estimates of tree species characteristics for the 1- by 1-degree grid, 82°W 39°N, in southeastern Ohio

Common_Name	Scientific_Name	FIA code	Mod Rel	Pct Area	FIAi	FIAsum
White oak	*Quercus alba*	802	High	86.4	6.07	256.63
Black oak	*Quercus velutina*	837	High	85.34	4.53	148.56
Mockernut hickory	*Carya tomentosa*	409	Medium	49.79	3.08	67.91
Blackgum	*Nyssa sylvatica*	693	Medium	61.23	2.55	63.74
Red maple	*Acer rubrum*	316	High	88.33	10.69	491.06
Yellow-poplar	*Liriodendron tulipifera*	621	High	79.15	10.89	452.47
Chestnut oak	*Quercus prinus*	832	High	35.8	9.24	179.07
Sourwood	*Oxydendrum arboreum*	711	High	41.14	3.71	79.48
Sugar maple	*Acer saccharum*	318	High	100	12.33	484.73
Post oak	*Quercus stellata*	835	High	2.71	4.65	2.14
Northern red oak	*Quercus rubra*	833	Medium	91.18	4.03	112.49
American beech	*Fagus grandifolia*	531	High	81.47	4.87	139.14
Shortleaf pine	*Pinus echinata*	110	High	0	0.53	0.38
Red mulberry	*Morus rubra*	682	Low	3.14	0.59	0.42
Slippery elm	*Ulmus rubra*	975	Low	74.52	4.71	124.87
Bitternut hickory	*Carya cordiformis*	402	Low	56.84	3.35	56.25
Common persimmon	*Diospyros virginiana*	521	Low	7.3	1.56	9.55
Green ash	*Fraxinus pennsylvanica*	544	Low	24.28	2.5	19.03
Bigtooth aspen	*Populus grandidentata*	743	Medium	50.11	4.16	106.64
Boxelder	*Acer negundo*	313	Medium	35.42	12.43	69.48
American elm	*Ulmus americana*	972	Medium	90.6	7.5	203.78
White ash	*Fraxinus americana*	541	Medium	97.88	6.16	182.12
Pignut hickory	*Carya glabra*	403	Medium	76.91	3.04	91.27
Hackberry	*Celtis occidentalis*	462	Medium	22.67	2.85	18.11
Osage-orange	*Maclura pomifera*	641	Medium	8.62	4.11	10.85
Sassafras	*Sassafras albidum*	931	Medium	81.15	6.27	261.41
Shagbark hickory	*Carya ovata*	407	Medium	80.97	4.62	144.4
Black locust	*Robinia psuedoacacia*	901	Medium	76.18	5.84	141.48
Eastern red cedar	*Juniperus virginiana*	68	Medium	0	1.19	0.01
Virginia pine	*Pinus virginiana*	132	High	24.72	5.26	60.99
Scarlet oak	*Quercus coccinea*	806	High	31	3.42	51.74
Pitch pine	*Pinus rigida*	126	High	8.38	4.15	27.49
Sweetgum	*Liquidambar styraciflua*	611	High	5.24	13.63	15.48
Silver maple	*Acer saccharinum*	317	Low	8.54	23.21	49.57
River birch	*Betula nigra*	373	Low	4.17	9.65	27.39
Pawpaw	*Asimina triloba*	367	Low	10.79	2.58	26.83
Eastern hophornbeam	*Ostrya virginiana*	701	Low	11.18	2.16	14.34
Black walnut	*Juglans nigra*	602	Low	73.2	3.86	67.06
Sycamore	*Platanus occidentalis*	731	Low	45.66	3.83	66.78

continued

Mod Rel = model reliability; Pct Area = percent of the 1- by 1-degree grid occupied; FIAi = average importance value of the species when present); FIAsum = sum of the importance value for the entire grid.

NOTE: The asterisk (*) denotes percent of area with at least a 5-percent probability of colonization.

[a] For the “new habitat” species, the migration potential is based on the SHIFT model’s estimate of the percent of area with at least five percent probability of colonization within 100 years.

Table 1—(continued) Estimates of tree species characteristics for the 1- by 1-degree grid, 82°W 39°N, in southeastern Ohio

Common_Name	Scientific_Name	FIA code	Mod Rel	Pct Area	FIAi	FIAsum
American hornbeam	*Carpinus caroliniana*	391	Low	8.38	1.09	19
Eastern redbud	*Cercis canadensis*	471	Low	12.56	1.66	15.71
Ohio buckeye	*Aesculus glabra*	331	Low	12.9	1.71	13.39
Honeylocust	*Gleditsia triacanthos*	552	Low	18.21	3.81	12.69
Eastern cottonwood	*Populus deltoides*	742	Low	3.71	2.87	10.19
Shingle oak	*Quercus imbricaria*	817	Medium	4.18	1.76	7.48
Bur oak	*Quercus macrocarpa*	823	Medium	0	0.41	0.09
Black cherry	*Prunus serotina*	762	Medium	99.68	7.29	223.73
Flowering dogwood	*Cornus florida*	491	Medium	49.09	2.11	63.8
Chinkapin oak	*Quercus muehlenbergii*	826	Medium	1.05	4.08	5.8
Quaking aspen	*Populus tremuloides*	746	High	2.09	2.73	3.88
Red spruce	*Picea rubens*	97	High	7.33	0.88	0.63
Sweet birch	*Betula lenta*	372	High	6.28	3.66	15.61
Yellow buckeye	*Aesculus octandra*	332	Low	15.88	4.69	51.84
Pin oak	*Quercus palustris*	830	Low	2.62	13.71	6.09
Black maple	*Acer nigrum*	314	Low	0.32	1	2.07
Black willow	*Salix nigra*	922	Low	2.09	4.83	6.84
Serviceberry	*Amelanchier* sp.	356	Low	3.47	1.89	4.45
Shellbark hickory	*Carya laciniosa*	405	Low	1.69	3.65	4.2
Red pine	*Pinus resinosa*	125	Medium	1.02	11.01	7.63
Eastern white pine	*Pinus strobus*	129	High	15.01	11.16	74.71
Eastern hemlock	*Tsuga canadensis*	261	High	5.24	6.3	22.42
Butternut	*Juglans cinerea*	601	Low	7.3	0.86	3.15
Cucumbertree	*Magnolia acuminata*	651	Low	2.74	0.85	1.21
American basswood	*Tilia americana*	951	Medium	9.36	2.77	16.97
Yellow birch	*Betula alleghaniensis*	371	High	0.32	0	0
Bluejack oak	*Quercus incana*	842	Low	0	0	0
Striped maple	*Acer pensylvanicum*	315	Medium	2.31	0	0
Chokecherry	*Prunus virginiana*	763	Unacc	2.43	1.21	2
Northern catalpa	*Catalpa speciosa*	452	Unacc	0.32	0.83	0.18
Wild plum	*Prunus americana*	766	Unacc	0.01	4.56	0.03
Migration Potential[a]						
Loblolly pine	*Pinus taeda*	131	High	1.05	0	9.7*
Black hickory	*Carya texana*	408	High	0	0	0*
Water oak	*Quercus nigra*	827	High	0	0	0*
Pecan	*Carya illinoensis*	404	Low	0	0	0*
Winged elm	*Ulmus alata*	971	Medium	0	0	0.36*
Southern red oak	*Quercus falcata* var. *falcata*	812	Medium	0	0	26.6*
Sugarberry	*Celtis laevigata*	461	Medium	0	0	7.0*
Blackjack oak	*Quercus marilandica*	824	Medium	0	0	0.01*

Mod Rel = model reliability; Pct Area = percent of the 1- by 1-degree grid occupied; FIAi = average importance value of the species when present); FIAsum = sum of the importance value for the entire grid.

NOTE: The asterisk (*) denotes percent of area with at least a 5-percent probability of colonization.

[a] For the “new habitat” species, the migration potential is based on the SHIFT model’s estimate of the percent of area with at least five percent probability of colonization within 100 years.

Table 2—Estimates of tree species characteristics for the 1- by 1-degree grid, 82°W 39°N, in southeastern Ohio

Common_Name	ChngCl45	ChngCl85	Adapt	Abundance	Capability
White oak	No change	No change	6.1	Abundant	Very good
Black oak	Sm. inc.	Sm. inc.	4.9	Abundant	Very good
Mockernut hickory	Sm. inc.	Sm. inc.	5.4	Common	Very good
Blackgum	No change	Sm. inc.	5.9	Common	Very good
Red maple	Lg. dec.	Lg. dec.	8.5	Abundant	Good
Yellow-poplar	Lg. dec.	Lg. dec.	5.3	Abundant	Good
Chestnut oak	Lg. dec.	Lg. dec.	6.1	Abundant	Good
Sourwood	Sm. dec.	Lg. dec.	6.9	Abundant	Good
Sugar maple	Sm. dec.	Sm. dec.	5.8	Abundant	Good
Post oak	No change	Sm. inc.	5.7	Rare	Good
Northern red oak	No change	No change	5.4	Abundant	Good
American beech	Sm. dec.	Lg. dec.	3.6	Abundant	Fair
Shortleaf pine	Sm. inc.	Sm. inc.	3.6	Rare	Fair
Red mulberry	Lg. inc.	Lg. inc.	4.7	Rare	Fair
Slippery elm	No change	No change	4.8	Abundant	Fair
Bitternut hickory	No change	No change	5.6	Common	Fair
Common persimmon	No change	No change	5.8	Common	Fair
Green ash	Sm. inc.	Sm. inc.	4	Common	Fair
Bigtooth aspen	Lg. dec.	Lg. dec.	5.1	Abundant	Fair
Boxelder	Sm. dec.	Lg. dec.	7.4	Common	Fair
American elm	No change	No change	4	Abundant	Fair
White ash	No change	No change	2.7	Abundant	Fair
Pignut hickory	No change	No change	4.7	Abundant	Fair
Hackberry	No change	No change	5.7	Common	Fair
Osage-orange	No change	No change	6.3	Common	Fair
Sassafras	Sm. dec.	Sm. dec.	4.2	Abundant	Fair
Shagbark hickory	Sm. dec.	Sm. dec.	4.4	Abundant	Fair
Black locust	Sm. dec.	Sm. dec.	3.8	Abundant	Fair
Eastern red cedar	Sm. inc.	Sm. inc.	3.9	Rare	Fair
Virginia pine	Sm. dec.	Lg. dec.	3.8	Common	Poor
Scarlet oak	Sm. dec.	Lg. dec.	4.6	Common	Poor
Pitch pine	Sm. dec.	Lg. dec.	3.8	Common	Poor
Sweetgum	Sm. dec.	Sm. dec.	4.1	Common	Poor
Silver maple	Sm. dec.	Lg. dec.	5.6	Common	Poor
River birch	Sm. dec.	Lg. dec.	3.7	Common	Poor
Pawpaw	Lg. dec.	Lg. dec.	3.7	Common	Poor
Eastern hophornbeam	Lg. dec.	Lg. dec.	6.4	Common	Poor
Black walnut	No change	No change	4	Common	Poor
Sycamore	No change	No change	4.8	Common	Poor

continued

ChngCl45 and ChngCl85 = change classes for low and high emissions, respectively; Adapt = the adaptability of the species to a changing climate; Capability = score for potential of the species to cope with the RCP 8.5 climate at end of century within this 1- by 1-degree grid.

Table 2—(continued) Estimates of tree species characteristics for the 1- by 1-degree grid, 82°W 39°N, in southeastern Ohio

Common_Name	ChngCl45	ChngCl85	Adapt	Abundance	Capability
American hornbeam	Sm. dec.	Sm. dec.	5.1	Common	Poor
Eastern redbud	Sm. dec.	Sm. dec.	4.9	Common	Poor
Ohio buckeye	Sm. dec.	Sm. dec.	3.5	Common	Poor
Honeylocust	No change	Sm. dec.	5.5	Common	Poor
Eastern cottonwood	No change	Sm. dec.	3.9	Common	Poor
Shingle oak	No change	No change	4.9	Common	Poor
Bur oak	No change	No change	6.4	Rare	Poor
Black cherry	Sm. dec.	Sm. dec.	3	Abundant	Poor
Flowering dogwood	Sm. dec.	Sm. dec.	5	Common	Poor
Chinkapin oak	Sm. dec.	Sm. dec.	4.8	Common	Poor
Quaking aspen	Lg. dec.	Lg. dec.	4.7	Rare	Very poor
Red spruce	No change	No change	2.9	Rare	Very poor
Sweet birch	Sm. dec.	Sm. dec.	3.2	Common	Very poor
Yellow buckeye	Lg. dec.	Lg. dec.	3.1	Common	Very poor
Pin oak	Sm. dec.	Lg. dec.	2.8	Common	Very poor
Black maple	Lg. dec.	Lg. dec.	5.2	Rare	Very poor
Black willow	Sm. dec.	Sm. dec.	2.8	Common	Very poor
Serviceberry	Sm. dec.	Sm. dec.	4.8	Rare	Very poor
Shellbark hickory	Sm. dec.	Sm. dec.	3.7	Rare	Very poor
Red pine	Lg. dec.	Lg. dec.	3	Common	Very poor
Eastern white pine	Very Lg. dec.	Very Lg. dec.	3.3	Common	Lost
Eastern hemlock	Very Lg. dec.	Very Lg. dec.	2.7	Common	Lost
Butternut	Very Lg. dec.	Very Lg. dec.	2.3	Rare	Lost
Cucumbertree	Very Lg. dec.	Very Lg. dec.	3.6	Rare	Lost
American basswood	Very Lg. dec.	Very Lg. dec.	4.6	Common	Lost
Yellow birch	Unknown	Unknown	3.4	Absent	Unknown
Bluejack oak	Unknown	Unknown	4.8	Absent	Unknown
Striped maple	Unknown	Unknown	5.1	Absent	Unknown
Chokecherry	Unknown	Unknown	3.8	Rare	Unknown
Northern catalpa	Unknown	Unknown	4.2	Rare	Unknown
Wild plum	Unknown	Unknown	3.9	Rare	Unknown
Migration Potential[a]					
Loblolly pine	New habitat	New habitat	3.4	Absent	New habitat
Black hickory	New habitat	New habitat	4.1	Absent	New habitat
Water oak	New habitat	New habitat	3.7	Absent	New habitat
Pecan	New habitat	New habitat	2.2	Absent	New habitat
Winged elm	New habitat	New habitat	3.6	Absent	New habitat
Southern red oak	New habitat	New habitat	5.3	Absent	New habitat
Sugarberry	New habitat	New habitat	4.6	Absent	New habitat
Blackjack oak	New habitat	New habitat	5.6	Absent	New habitat

ChngCl45 and ChngCl85 = change classes for low and high emissions, respectively; Adapt = the adaptability of the species to a changing climate; Capability = score for potential of the species to cope with the RCP 8.5 climate at end of century within this 1- by 1-degree grid.

emissions. Four species attained the very good rating, three of which are oaks or hickories: white and black oak (*Q. velutina*), mockernut hickory (*C. tomentosa*), and blackgum (*Nyssa sylvatica*) (table 2). An additional seven species rated good, including three additional oak species: yellow-poplar, chestnut oak (*Q. prinus*), sourwood (*Oxydendrum arboretum*), sugar maple, post oak (*Q. stellata*), northern red oak (*Q. rubra*), and eastern white pine (*Pinus strobus*). These are species with high levels of abundance currently, projected to gain or at least remain stable in habitat, and well adapted to drought and other disturbances expected in the coming decades. Beyond those, 18 species rated fair, 20 poor, 10 very poor, 5 lost, 8 new habitat, and 6 unknown. Thus, according to this analysis, even though more species are expected to have new habitat appear (8) than disappear (5), at least 30 of the species present now are expected to have a reduction in their capability status by 2100.

For the eight species projected to gain newly suitable habitat by the end of century, we can use the results from SHIFT to evaluate the likelihood of that new habitat getting colonized. SHIFT can be visualized as the likelihood of propagules from current occupied cells colonizing unoccupied cells. The likelihood is based on post-glacial migration estimates (Prasad and others 2013) and depends on the abundance in the current cells and the habitat quality of the colonizing cells, and decays rapidly with distance, simulating long-distance seed-dispersal phenomenon. Thus, if the new habitat is a long distance from current occupied cells, especially if not highly abundant, the potential for migration into the 1- by 1-degree grid is severely compromised. In this study region, three species would have virtually no chance of being naturally colonized [water oak (*Q. nigra*), black hickory (*C. texana*), pecan (*C. illinoensis*)], another two with very little likelihood [winged elm (*Ulmus alata*) and blackjack oak (*Q. marilandica*)], and only three [southern red oak (*Q. falcata* var. *falcata*), loblolly pine (*Pinus taeda*), and sugarberry (*Celtis laevigata*)] would have a decent probability of colonizing into the region naturally (table 1). Of course, the species could be moved artificially to circumvent the limitations of natural migration; in this case perhaps selecting those species with new suitable habitat and some likelihood of colonization could be seen as the most likely for long-term successful establishment of new species to occupy the area.

Assessment of Landtypes for Oak-Hickory Investment

Of the 71.6 percent of the study area 1- by 1-degree grid that was analyzed for landtypes, 39 percent was classed as Dry Oak (DO, or 'oaky-doaky'), 28 percent as Dry-mesic Mixed Oak Hardwoods (DMMOH), and 32 percent as Rolling Bottomland Mixed Hardwoods (RBMH) (fig. 2). This area reveals a complex intermingling of the landtypes within this dissected landscape, [see also Iverson and others 2018 for high resolution images]. The DO areas can be considered the most suitable for silvicultural investment into promoting oaks and hickories; these investments include several approaches to increase light to the forest floor and the competitiveness of oaks and hickories, such as thinning, prescribed fire, herbiciding the competing species, or a combination thereof (Brose and others 2008). Land managers can use the maps, the data extraction tool, and the resulting statistics to target their silvicultural investments in an age of limited staff and financial resources.

CONCLUSIONS

In this brief summary paper, we outline several thrusts of research aimed at assisting land managers for both short- and long-term forest management. With the summaries of climate projections, we aim to portray the range of possible future growing conditions, pointing out potential future heat and drought conditions and the large differences projected between low and high emissions during this century (i.e., the choices humans make regarding curbing emissions). Next, we evaluate and tabulate the potential changes in tree species habitats for 78 species associated with one 1- by 1-degree grid in southeastern Ohio, according to the potential future climatic conditions previously described. We further assess the capability of the species to cope with the changing climate, in which only 11 of the 78 species are classed with a 'good' or 'very good' capability, in comparison to 30 species with 'poor' or 'very poor' capability to cope. We also evaluate the eight species shown to have new suitable habitat appearing in the area by 2100, and show that only three of the eight (southern red oak, loblolly pine, and sugarberry) are modeled to have a reasonable chance of naturally migrating to the area within 100 years. Notably, southern red oak and sugarberry have been found in southeastern Ohio but not yet recorded within FIA plots (thus our models), and they are likely to increase in prominence in the future. Finally, we mapped much of southeastern Ohio into three landtypes and six landtype phases for each of five subsections across southeastern Ohio for a total of 15 landtypes and 19 landtype phases. One landtype group, the Dry Oak forest landtype, is most suitable for investing in silvicultural treatments such as prescribed fire, thinning, or herbicides to promote oaks and hickories. Those species projected most favorably under these analyses include white oak, black oak, mockernut hickory, chestnut oak, post oak, northern red oak, and, gauging for the future, southern red oak; each of these species scored as viable species capable of coping with the hotter and physiologically drier future climate.

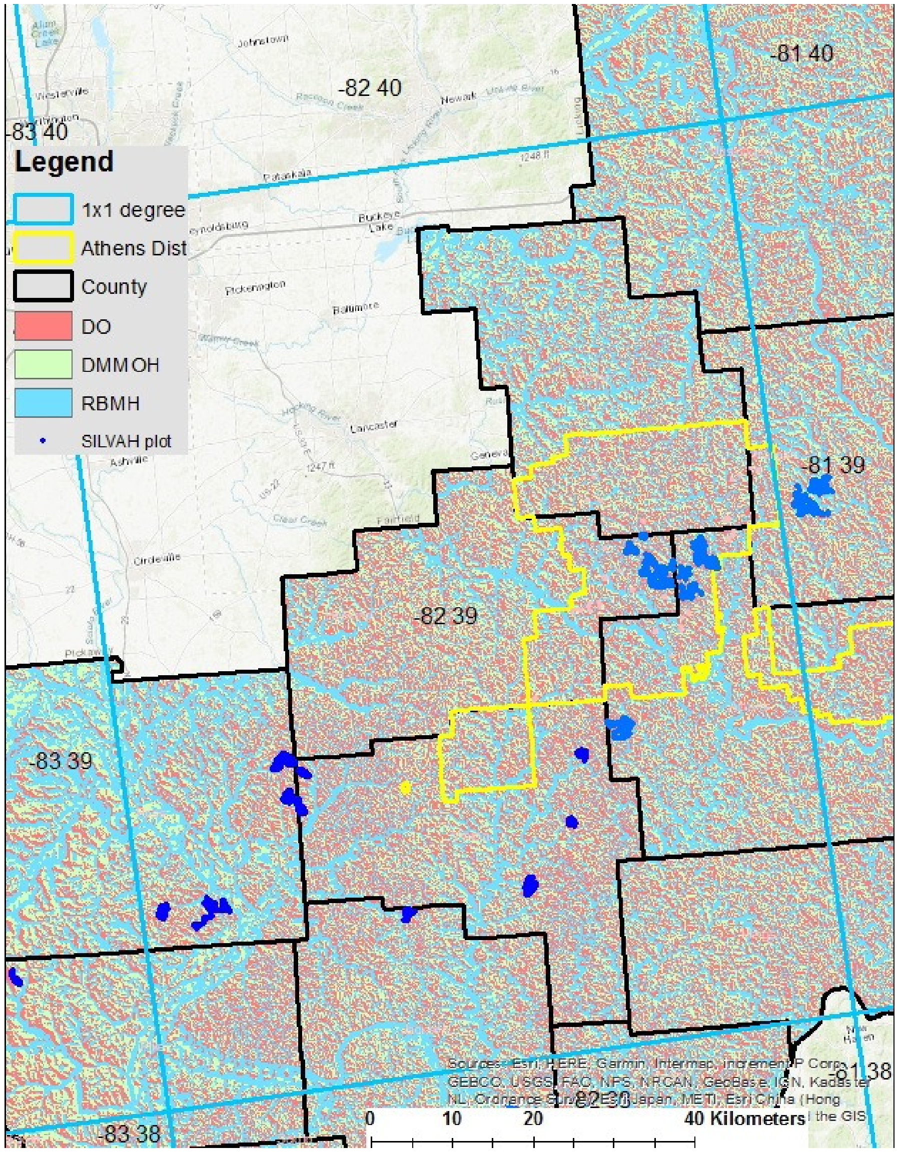

Figure 2—Landtypes for much of the 1- by 1-degree grid, 82°W 39°N, in southern Ohio. Also shown is the boundary of the Athens District of the Wayne National Forest, county lines, and locations of SILVAH plots.

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