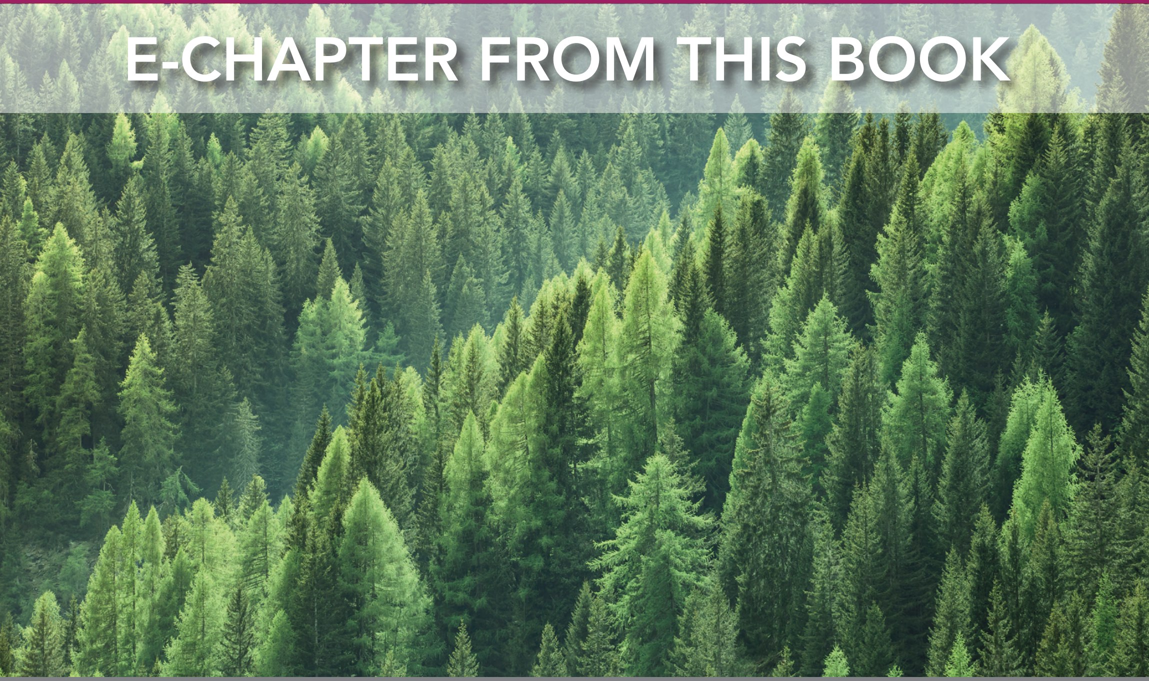
BURLEIGH DODDS SERIES IN AGRICULTURAL SCIENCE

Achieving sustainable management of boreal and temperate forests

Edited by Dr John A. Stanturf
Estonian University of Life Sciences, Estonia



burleigh dodds
SCIENCE PUBLISHING

The impact of climate change on forest systems in the northern United States: projections and implications for forest management

W. Keith Moser, USDA Forest Service, USA; Patricia Butler-Leopold, Michigan Technological University and Northern Institute of Applied Climate Science (NIACS), USA; Constance Hausman, Cleveland Metroparks, USA; Louis Iverson, USDA Forest Service and Northern Institute of Applied Climate Science (NIACS), USA; Todd Ontl, Michigan Technological University and Northern Institute of Applied Climate Science (NIACS), USA; Leslie Brandt, USDA Forest Service and Northern Institute of Applied Climate Science (NIACS), USA; Stephen Matthews, Northern Institute of Applied Climate Science (NIACS) and The Ohio State University, USA; and Matthew Peters and Anantha Prasad, USDA Forest Service and Northern Institute of Applied Climate Science (NIACS), USA

1 Introduction

Forests play an essential role in the social, economic, and ecological lives of the inhabitants of the northern United States. Forests cover 69.6 million ha, or 42% of the land area of this region, which is both the most heavily forested and the most densely populated quadrant of the United States (Fig. 1). To preserve a full range of forest ecosystem services into the future, managers are working to identify and implement strategies and tactics that take into

http://dx.doi.org/10.19103/AS.2019.0057.09
Published by Burleigh Dodds Science Publishing Limited, 2020.

Chapter taken from: Stanturf, J. A. (ed.), *Achieving sustainable management of boreal and temperate forests*, Burleigh Dodds Science Publishing, Cambridge, UK, 2019, (ISBN: 978 1 78676 292 4; www.bdspublishing.com)

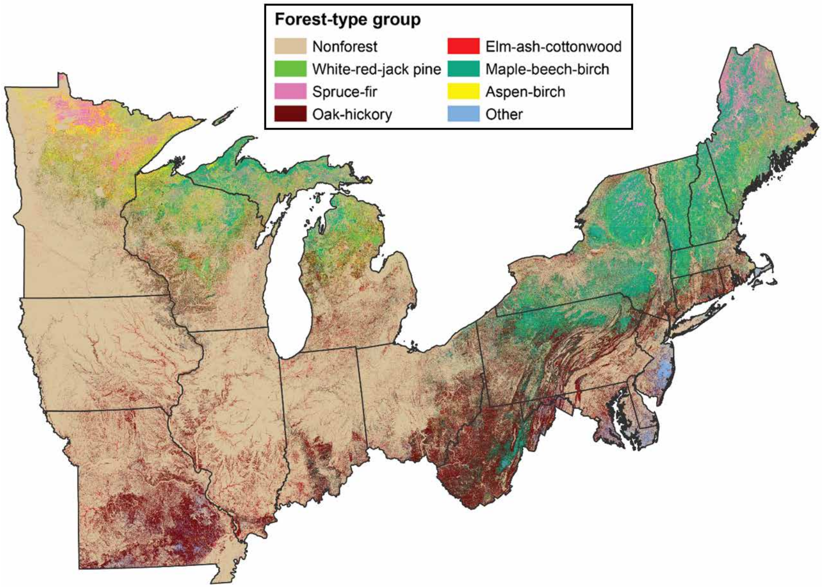


Figure 1 Distribution of forest-type groups in the northern United States, 2010. Source: adapted from Goerndt et al. (2016).

account the potentially dramatic effects of a changing climate (Nagel et al., 2010). The region encompasses almost 30° of longitude and 10° of latitude and extends from the Atlantic Ocean west to the Great Plains, containing 20 states: Connecticut, Delaware, Illinois, Indiana, Iowa, Maine, Maryland, Massachusetts, Michigan, Minnesota, Missouri, New Hampshire, New Jersey, Ohio, Maryland, Pennsylvania, New Hampshire, New York, Rhode Island, and Wisconsin.

Managers plan at several different scales and overlapping time horizons. In this chapter, we integrate different analyses that provide a range of projected outcomes over the medium and long term. In this chapter, we use several case studies to suggest some potential pathways for managers seeking to alleviate or otherwise mitigate potential climate change impacts. The intention is to provide examples of studies at several scales of analysis, using various tools of analysis and reporting. Readers can then move within their scale of analysis or interest to pursue the details cited within these case studies. We start with characterizations of mid- and long-term projected climate change impacts for trees and forests of the northern United States. Particular attention is drawn to the impacts of more frequent and severe precipitation and drought events. We then scale down the discussion to examples from the three-state Central Appalachians region, and last provide local examples in rural and urban landscapes. We conclude with some lessons learned and recommendations that managers might consider as they craft their own strategies.

2 Climate projections and their influence on forestland trends in the medium term—the Northern Forests Futures Project

2.1 The modeling process

A multistep process and many datasets were used to explore the potential medium-term impact of economics, demographics, and changing climate on the forested landscape of the northern United States. Trends in forest dynamics and the resultant changes in forest attributes in the region were projected and analyzed for the period 2010–2060 using two cycles of data sets from the USDA Forest Service, Northern Research Station Forest Inventory and Analysis (FIA) program (Woudenberg et al., 2010). Future forest conditions were imputed from the Forest Dynamics Model (Wear et al., 2011), which was previously employed in the national-level analysis of future conditions in Resources Planning Act (RPA) assessments (USDA FS, 2012a,c). The data were downscaled so that they could be matched up with individual FIA plots (USDA FS, 2011; Goerndt et al., 2016). The Intergovernmental Panel on Climate Change (IPCC) described a set of emissions scenarios or 'storylines'[1] based on assumptions of population growth, economics, and technological changes. The IPCC created four families (A1, A2, B1, and B2) of scenarios (Nakićenović et al., 2000), from which 12 individual storylines were developed. By using assumptions about changes in land use, population, and climate, along with modeled disturbances caused by harvesting of forest products and insect (emerald ash borer; *Agrilus planipennis*) attack, three storylines were linked with climate models to project climate scenarios and the associated future forest conditions at the local level (Goerndt et al., 2016; Shifley and Moser, 2016). These analyses resulted in 13 future scenarios, of which seven were studied in depth and three are presented in the following discussion.

Analyses for the RPA assessment projected the entire US population to increase between 2010 and 2060 from 309 million people to 397 million for the B2 scenario, 447 million for the A1B scenario, and 505 million for the A2 scenario, or increases of 29%, 45%, and 64%, respectively (USDA FS, 2012b; Zarnoch et al., 2010). These population estimates are based on the 2004 Census population series for 2000–2050, which were extrapolated to 2060 (USDA FS, 2012b). Using human population projections incorporated into the 2010 RPA analyses (USDA FS, 2012b), the Northern Forest Futures Project (NFFP) projected population for the northern United States and then allocated the expected population to the states and their counties (Zarnoch et al., 2010; USDA FS, 2012c; Goerndt et al., 2016). The population of states in the northern

---

[1] 'coordinated groups of assumptions that describe future population, economic activity, land use, bioenergy use, and associated greenhouse gas emissions' Goerndt et al. (2016).

United States are expected to increase from 125 million in 2010 to 140 million (B2 scenario), 158 million (A1B scenario), and to 178 million (A2 scenario) by 2060, or increases of 12%, 25%, and 39%, respectively (Fig. 2). States along the Atlantic Ocean seaboard are projected to have the greatest increases in population (Fig. 3) (Goerndt et al., 2016).

Scientists throughout the world have developed models that project and map changes in selected weather factors, such as precipitation and temperature, based on each of the individual IPCC storylines. From these many combinations, NFFP selected two versions of a 'middle-of-the-road' model, the Canadian Global Circulation Model (Canadian Centre for Climate Modelling and Analysis 2012a,b; Shifley and Moser, 2016). These versions form the basis for the calculations in the following discussion.

The NFFP used the Forest Dynamics Model (Wear et al., 2013) to project changes in tree and stand conditions. Projections of future FIA plot conditions were used to model future wood volumes, species groups, and a host of ecosystem services (Goerndt et al., 2016; Moser et al., 2016; Tavernia et al., 2016). Plots were partitioned into groups based on biophysical, stand age, and climate factors, with growing stock volume per ha used as a point of similarity.

Changes in land use are a function of changes in population, economic activity, and any potential climate change influence over the 50-year time period

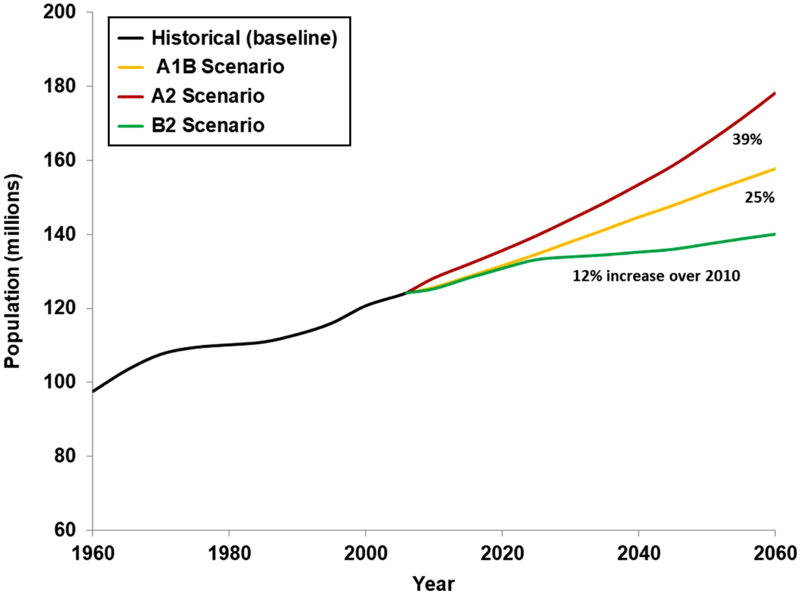


Figure 2 Projected increases in population of the northern United States, 2010–2060. Source: adapted from Goerndt et al. (2016).

Published by Burleigh Dodds Science Publishing Limited, 2020.

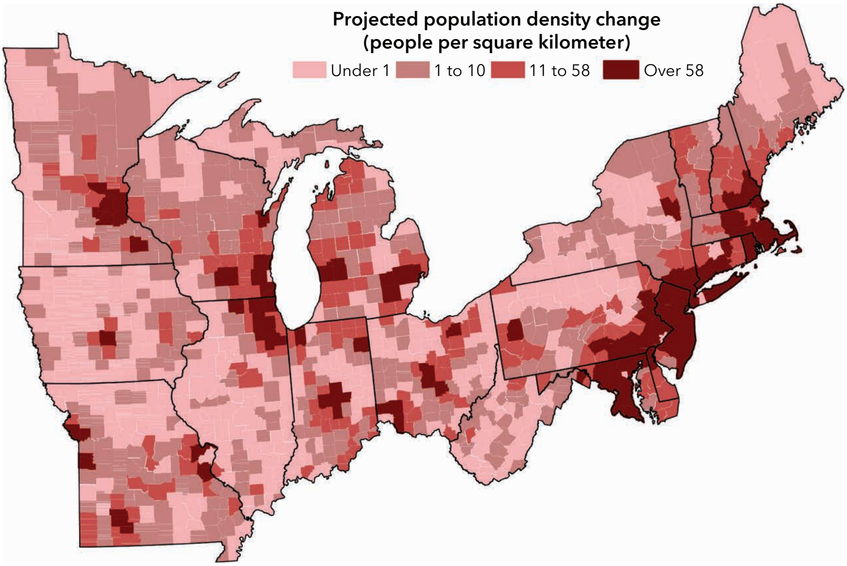


Figure 3 Pattern of projected percentage increases in population (2010–2060) under the A2 storyline. Source: adapted from Goerndt et al. (2016).

of this study (Wear et al., 2013; Goerndt et al., 2016). The NFFP used land use projections from the RPA assessment (USDA FS, 2012c), which assumed that there would be no land use changes on federal forest land across the northern United States, and that nonfederal forest land would decline by two to four million ha by 2060.

Projected harvesting levels were extrapolated from observed harvesting in the prior FIA inventories and tied to variables of tree size, age, species, density, stand diversity, site conditions, and previous harvest types (full or partial) (Wear et al., 2013; Goerndt et al., 2016). Model algorithms replaced inventory plots affected by harvesting with suitable replacement plots representing the postharvest conditions (e.g. a newly regenerated plot; Goerndt et al., 2016). A transition model, which predicted changes in plot age and species composition over time, determined forest age, harvesting, and regeneration. These projected values, along with climate variables, were applied as inputs to an imputation model. This model selected a replacement (updated) plot from a subset of observed FIA plots 'that best matches conditions that are projected for each plot location', based on age, species group, climate, and proportions of hardwood and softwood. This new plot became the starting point for the next 5-year projection. Results for all plots were summarized at the end of each interval and used as a starting point for the next interval (Goerndt et al., 2016).

2.2 Northern Forest Futures Project results of the medium-term projections

According to the analyses for the RPA (USDA FS, 2012c), the area of forest land in the northern United States will decrease from 70 million ha in 2010 to 66 million ha (a 6.4% decrease) under the A1B scenario, 67 million ha (a 5.4% decrease) under the A2 storyline, and 68 million hectares (a 3.5% decrease) under the B2 storyline (Fig. 4). The greatest declines are expected to occur near urban areas and in states along the eastern seaboard, which are also highly urbanized. Per capita forest land area in the northern United States is expected to decline from about 0.6 ha to 0.4 ha as the population increases and forest land area declines (Moser et al., 2016). Oak/hickory and maple/beech/birch forest-type groups, together making up 61% of forest land area in 2010, will continue to be the most prominent forest-type groups under all three scenarios, with a projected 64% of forest land area in 2060 (Table 1). Despite this prominence, oak/hickory is expected to decrease slightly in the area under all scenarios, along with elm/ash/cottonwood, spruce/fir, and aspen/birch. The maple/beech/birch forest-type group is expected to increase somewhat in the area under all scenarios.

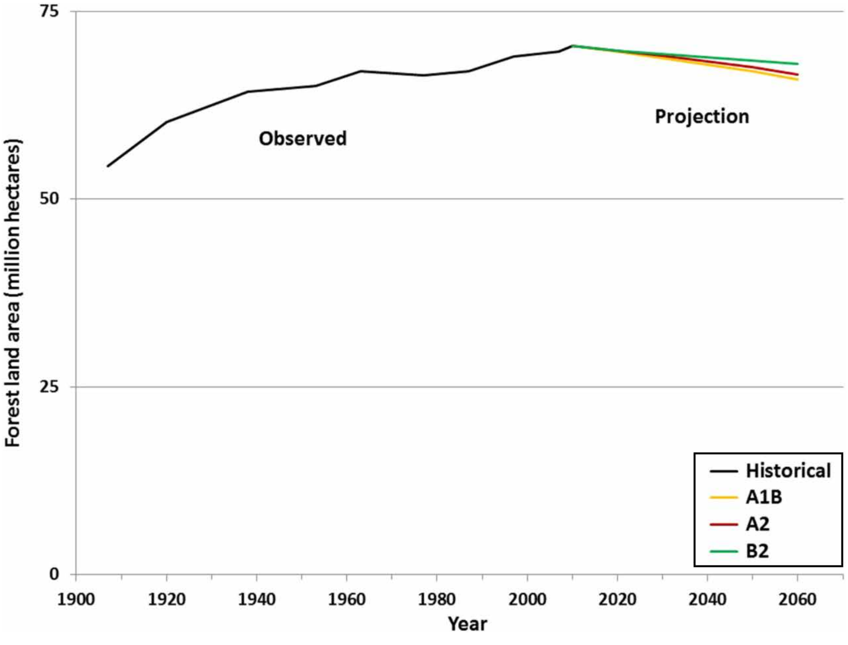


Figure 4 Forest land area, historical and projected, in million hectares, 1900–2060. Source: adapted from Moser et al. (2016).

Published by Burleigh Dodds Science Publishing Limited, 2020.

Table 1 Projected area, in hectares, by forest-type group in 2060 based on forest land area of 2010, A2 scenario

Forest-type group (scientific name)	2010 (%)		2060 (%)	
Aspen/birch (*Populus* spp./*Betula* spp.)	6 983 038	10	5 747 767	8
Elm/ash/cottonwood (*Ulmus* spp./*Fraxinus* spp./*Populus* spp.)	4 915 592	7	4 033 138	6
Maple/beech/birch (*Acer* spp./*Fagus* spp./*Betula* spp.)	18 203 541	26	18 872 550	27
Nonforest	-	0	3 817 506	5
Oak/hickory (*Quercus* spp./*Carya* spp.)	25 569 666	36	24 009 601	34
Other	5 158 122	7	4 676 753	7
Spruce/fir (*Picea* spp./*Abies* spp.)	6 183 077	9	5 599 335	8
White/red/jack pine (*Pinus alba*/*P. resinosa*/*P. banksiana*)	3 438 607	5	3 694 993	5
Total	70 451 643		70 451 643	

Source: adapted from Moser et al. (2016).

The extent of each forest-type group is expected to change over the 50-year projection period (Table 1; Moser et al., 2016). The expectation of limited current forest products harvesting being extended into the future (Shifley et al., 2014) is expected to impede establishment of early successional forest-type groups, such as aspen/birch, thereby reducing their proportion. Another notable change is the projection that 5% of the current forest land is converted to nonforest uses by 2060 (Moser et al., 2016).

Approximately 70% of forests in the northern United States in 2010 was estimated to be 40–100 years old (Shifley et al., 2012). Applying slightly different definitions of early and late successional forests, Pan et al. (2011) observed relatively low percentages of early and late successional forests in the region. Region-wide, the current proportion of forest stands in the 40–100-year age bracket is not expected to change much (except for the natural aging of the cohort) through 2060 (Fig. 5; Moser et al., 2016; Tavernia et al., 2016).

Using calculations based on the FIA database and transition models (USDA FS, 2012b; Goerndt et al., 2016), the NFFP found that, particularly in the western part of the region, the current substantial percentage of younger age classes is expected to decline over the 50 years of the projection. Increased biomass harvesting (data not presented here) would increase the proportion of early successional forests in the future. The relatively low percentages of forest in the northern United States in 2010 that are in the 100+ year age classes are expected to change dramatically depending upon the scenario, barring substantial increases in harvesting or severe disturbances (Fig. 6; Moser et al., 2016; Tavernia et al., 2016). Severe disturbances, such as windstorms (Nelson and Moser, 2007; Moser and Nelson, 2009) or attacks by eastern spruce

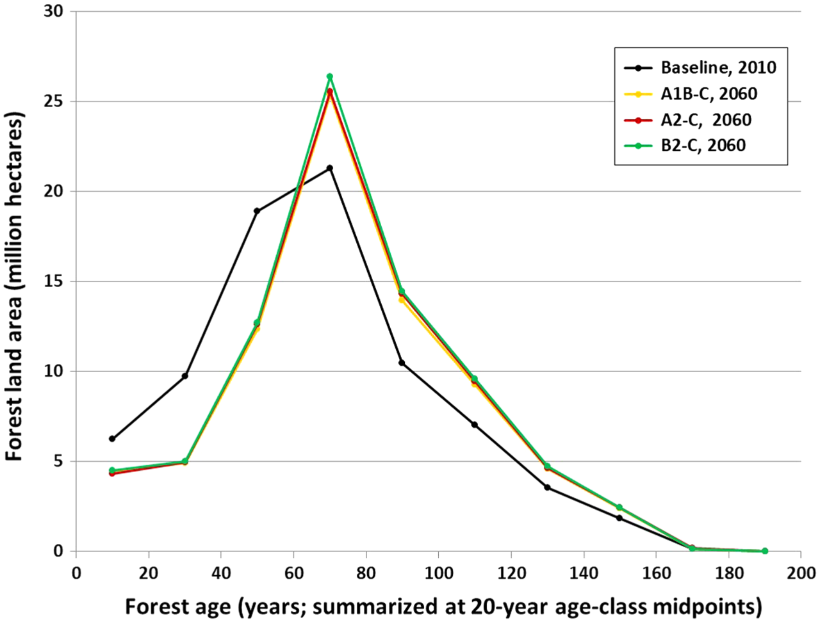


Figure 5 Distribution of forest land age in years, by storyline, 2010–2060. Source: adapted from Moser et al. (2016).

budworm (*Choristoneura fumiferana*) (Robert et al., 2018), could also accelerate succession, but there were not enough historical incidents during the study period to accurately project future occurrences.

Density- and age-induced mortality would have a significant effect on the number of all live trees, with the total number decreasing by 10–17% (Fig. 7a). Live-tree volume on forest land is projected to stay roughly the same (Fig. 7b; Moser et al., 2016).

2.2.1 Conclusions from the future forests of the northern United States project

In contrast to the more long-term projections presented later in this chapter, the expectations over the period 2010–2060 focus on the demographic and economic patterns behind the three climate storylines, not the changing climates themselves. Unless natural disturbance or anthropogenic activities such as biomass harvesting increase considerably, the current middle-aged forest cohort will continue to age with time (Shifley et al., 2014). Without such disturbances, young forests of all forest-type groups and early successional forest types such as aspen-birch will decline as a percentage of the total forested area. Managers charged with maintaining or enhancing the habitat for early

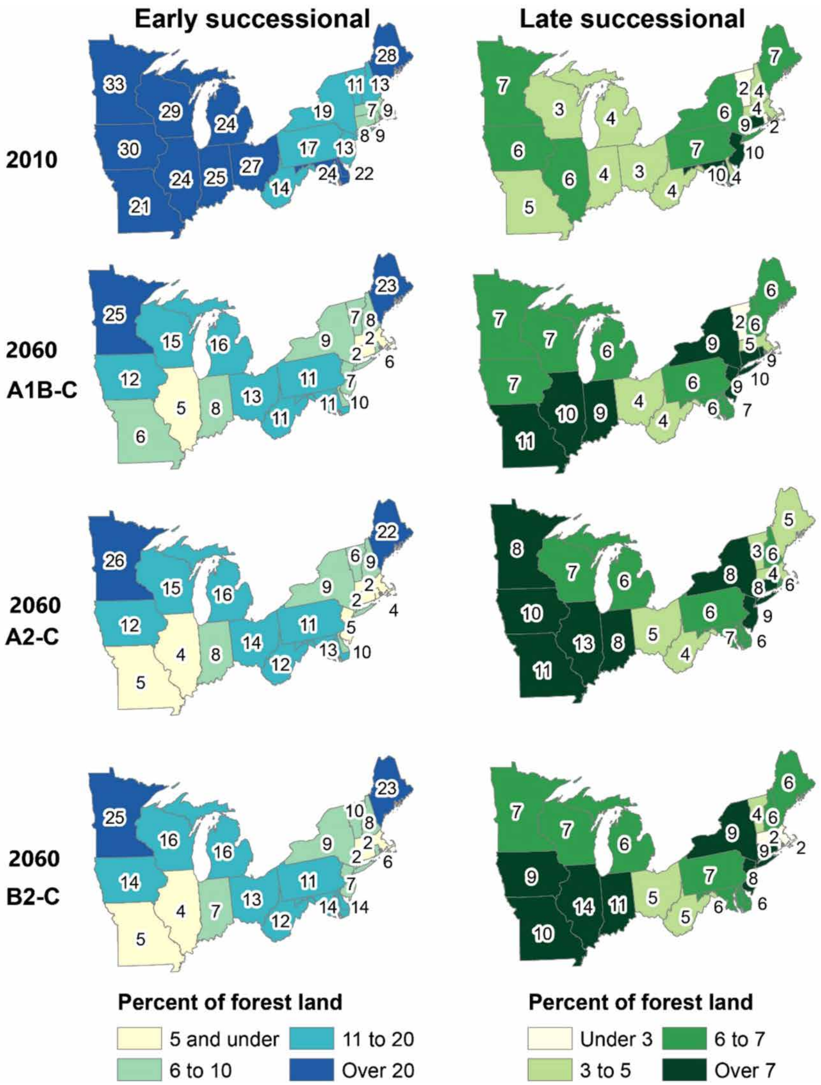


Figure 6 Proportion of forest land in early successional (young; <20 years) and late successional (old; >100 years) habitats, 2010 and 2060, by storylines and states. Source: adapted from Moser et al. (2016).

successional species or large-scale forest biodiversity will face the challenge of developing socially acceptable and economically viable approaches that provide for these species in an ever-aging forest as well as building resilience in response to projected changes in climate patterns.

Forest managers must deal creatively with the heightened challenges expected in the coming decades. By 2060, a projected 85% of the population in

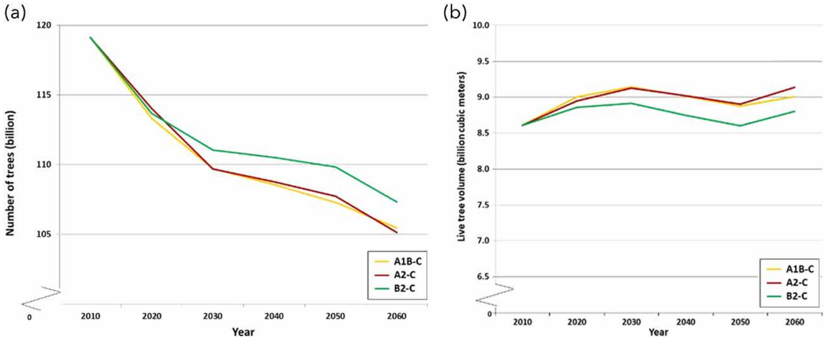


Figure 7 (a) Number of trees on forest land, by storyline, 2010–2060. (b) Live-tree volume on forest land in the northern United States by storyline, 2010–2060. Source: adapted from Moser et al. (2016).

the northern United States will be living in urban areas (Nowak and Greenfield, 2016). Greater pressure will be exerted on forests as private forest land area decreases due to land conversions and the accompanying fragmentation. The growing population will put ever more pressure on forest systems to meet demands for consumption, such as timber and fuelwood harvesting, and nonconsumptive uses satisfied by ecosystem services. With increased human contact, nonnative invasive species are projected to expand into the forest, further reducing its capacity to provide goods and services into the future. Management activities must take into account increasing the resilience of the forests to cope with a highly variable climate.

Decreased utilization of forests for industrial uses will have cascading effects on local economies and employment in rural areas. The continuation of current levels of harvesting or other human-caused disturbance will continue the trend toward aging of the currently 60–100-year-old forests, exacerbating low age-class diversity levels and reducing carbon sequestration rates (Shifley et al., 2014).

Local impacts of climate change are less certain than expected regional and global impacts. The projections of increased frequency and more pronounced swings in precipitation and drought cycles (IPCC, 2014; Clark et al., 2016) have the potential to pose challenges for forest planning activities and place stress on the regional ecosystem. The expected changes in the northern United States are not expected to be uniform and, at least for the 50-year period under discussion, will be more highly correlated with human demographic and invasive species issues than climatic influences per se.

Faced with such challenges, forest managers may aim to strengthen the increasingly urban populations' connections with their forests, helping urban voters and taxpayers understand the value, the possibilities, and the limitations of their forests. At larger scales, cross-ownership collaboration—an 'all lands approach'—is essential to counteract the decrease in ecosystem values that the remaining forest land area can support as greater human pressure and land fragmentation reduce forest land area and connectivity. As exemplified in the discussion of oak decline (see Section 2.3), older forests, particularly those composed of mid-seral species, are often more susceptible to insect and disease attack than their younger counterparts. Furthermore, a lack of disturbance will result in limited early successional forests, affecting the suite of animals and plants that depend on early and mid-successional tree species (Tavernia et al., 2016).

2.3 Precipitation variability and frequency and its effects on oak health

2.3.1 Background

Most climate models project a future climate regime where adverse weather events are likely to be more frequent and extreme (IPCC, 2014; Clark et al., 2016). These weather events have the potential to exacerbate forest health vulnerabilities by creating destructive disturbances such as severe drought events (Wehner et al., 2011; Clark et al., 2016), derechos (Pokharel et al., 2019), hurricanes (Dinan, 2017), extreme precipitation events (Kirtman et al., 2013), and tornadoes (Strader et al., 2017). Such disturbances may set back the normal patterns of succession (Oliver and Larson, 1996; Johnson, 2004) or may accelerate changes to another ecological state (IPCC, 2014). These climatic events can create novel conditions that the current ecosystem has not experienced before (Bauer et al., 2016) and to which it is not adapted. The following example shows how a forest ecosystem has been subjected to challenging current climatic conditions and suggests how future climate scenarios may exacerbate these issues.

2.3.2 Oak decline

Sinclair (1965) and Manion (1981) presented a model of forest tree decline that identified three categories of factors: predisposing, inciting, and contributing. The decline model for oak forests defined predisposing factors, such as age, long-term climate, air pollution, or poor site quality, as long-term factors that stress oak forests by reducing their vigor, and hence the accumulation of excess carbohydrate reserves, of a tree. This combination of responses makes oaks more vulnerable to the subsequent effects of inciting factors such as drought, defoliating insects, or frost. These inciting factors create a higher level of stress in a tree and can trigger the forest health complex called oak decline. Finally, contributing factors may be an accumulation of additional inciting factors or the introduction of other insect and disease species. Contributing factors are often the agents present during oak mortality and the ones which foresters focus on the most (Worrall, 2019).

Oak decline is a long-recognized forest health complex that particularly affects species in the *Quercus erythrobalanus* (red oak) species group. In the Ozark Mountains of Missouri and Arkansas, *Quercus* species exist today on land that was historically maintained by frequent fire as shortleaf pine (*Pinus echinata* Mill.) forests (Starkey and Oak, 1988; Cunningham and Hauser, 1989; Dwyer et al., 1995; Oak et al., 1996; Batek et al., 1999; Guyette and Spetich 2003). These pinewoods were mostly composed of large, widely spaced pine trees with an herbaceous understory (Schoolcraft, 1821). Upon removal of the pine overstory for timber or conversion to farmland, the sites often regenerated to *Quercus* species, such as black oak (*Q. velutina* Lam.), scarlet oak (*Q. coccinea* Münchh.), blackjack oak (*Q. marilandica* Münchh.), southern red oak (*Q. falcata* Michx.), and northern red oak (*Q. rubra* L.), frequently influenced by human-caused fires (Guyette and Spetich, 2003; Voelker et al., 2004).

This land use history and subsequent management led to the development of the Missouri Ozark forests into dense stands of oaks. Stands of scarlet and black oaks became prevalent on ridgetops and south- and west-facing slopes; sites with northern aspects contained more northern red oak (Cunningham and Hauser, 1989; Voelker et al., 2004). This dense stand structure created additional stress on the trees, which resulted in stands more prone to forest health problems than stands with widely spaced trees and high species diversity. Scarlet oaks, in particular, were more prone to forest health problems as they got older.

The principles of Manion's (1981) decline complex can be applied in this situation, where predisposing, inciting, and contributing factors are all manifested. In the Ozarks, the severe drought of 1998–2002 was the inciting factor (Fig. 8a). This extended drought reduced the vigor of oak trees and made them vulnerable to contributing factors, such as Armillaria root rot (*Armillaria* spp.), hypoxylon canker (*Hypoxylon* spp.), two-lined chestnut borer (*Agrilus bilineatus*), and red oak borer (*Enaphalodes rufulus;* Lawrence et al., 2002; Voelker et al., 2008). *Armillaria* root rot, particularly *Armillaria mellea*, was an especially severe pathogen, particularly with the high incidence of transmission via root-grafts between scarlet and black oaks (Jenkins and Pallardy, 1995; Bruhn et al., 2000). By examining fire scars, Guyette et al. (2007) suggested that moderate or severe drought conditions occurred every 10–20 years. Voelker et al. (2008) described a 'pulse of mortality' that occurred immediately after the 1999–2002 drought, suggesting that mortality was the response to the inciting condition (drought), in this case acting as a thinning agent.[2]

---

[2] For more discussion, see Grant et al. (2013).

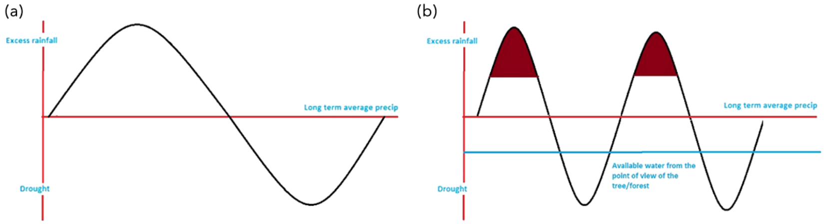


Figure 8 (a) Hypothetical representation of historical precipitation and water availability over a 10-year period in the Ozark Mountains of Missouri. The horizontal axis represents time. The proportions are not necessarily to scale, but represent a hypothetical cycle of water abundance and shortage over a period of time. For the purposes of this discussion, the point in time where the water availability line goes below zero is 1998–1999. It is generally believed that the drought ended in 2003. (b) Hypothetical representation of potential precipitation patterns under climate change scenarios projecting increased frequency and severity of weather events. For our purposes, each cycle represents approximately half the time of the cycle in Fig. 8a. The red-shaded area at the top of the cycle represents precipitation that comes down at an amount and rate such that not all can be absorbed by the ecosystem and thus leaves the site as overland surface water. The blue line represents the actual soil moisture available to the trees, which is less than the nominal total moisture.

Some climate scenarios project precipitation and drought swings of increasing frequency and severity (Clark et al., 2016), hypothetically represented by Fig. 8b. Two important effects result from such a new climate norm as it pertains to oak-hickory forests in the Ozark Mountains:

1 The rapid and dramatic oscillation and the attendant forest health impacts do not allow sufficient time for the oak forests to recover from previous disturbance cascades. In this case, drought increases tree and forest vulnerability to insect and disease attack, which precipitates decline and mortality before the next drought occurs. This relatively rapid sequence of disturbances virtually guarantees that the tree is weakened. Its response to the subsequent drought is less robust, increasing the probability of mortality.
2 As shown in Fig. 8b, the precipitation from the rain events—by being more severe—are not likely to be completely absorbed by the forest soil ecosystem. The infiltration rate, even in a dry soil, may not accommodate the total volume of the rainfall, with the excess sheeting off into the surface water system (Williams, 1991; Ritchie, 1998). Assuming a balanced, closed system where the total annual precipitation may not change (which will not necessarily be the case), the forest ecosystem will not obtain the full benefit of the precipitation (surplus) but will experience the full extent of the moisture deficit (i.e. drought). For the tree, the average long-term water availability is not the nominal average

precipitation rate (the red line in the graph, Fig. 8b), but rather the lower (blue) line, the effective average water availability. Coupled with the stress imposed by the boom-and-bust cycle of precipitation mentioned earlier, this long-term reduction in available soil moisture may result in a general decline in vigor in the current Ozark oak-hickory forest stands. A likely consequence is conversion to a suite of more drought-tolerant (xeric) species over time.

2.3.3 Oak decline lessons for managers

Forest managers have experienced the impacts of periodic drought events over the last centuries. These events are based on decadal or multi-decadal cycles. Such long periods between successive droughts allowed the forest ecosystem to recover at least somewhat under sufficient or even above-average levels of soil moisture. Climate change makes current drought cycles different from the cycles of the recent past. Droughts are expected to be relatively more frequent and severe (IPCC, 2014; Clark et al., 2016; but see Seager et al., 2009). Given the projected increased variability in rainfall, and the episodic nature of mortality, managers may find it logical to manage forests to sustain them through the more stressful times rather than for long-term average conditions.

Though standard stocking charts or measures of density are based on average climate conditions, managers could consider voluntarily forgoing maximizing productivity in order to reduce potential susceptibility to drought-induced mortality (D’Amato et al., 2013; Gleason et al., 2017). Voelker et al. (2008) suggested that stands with relatively low stocking and hence potentially less inter-tree competition may provide more resilience to drought. Forest managers could deliberately keep stands below full stocking. They would sacrifice some volume production and possibly reduce tree quality due to persistent branching, but at the same time they potentially would make them more resilient under drought conditions. The benefit gained would be the expected value of the volume lost to mortality multiplied by the probability that a decline would result in that mortality.

In terms of density reduction, Moser and Melick (unpublished memo, 2002) suggested that a pathological rotation of species prone to oak decline, such as scarlet oak, and a reduction of oak stand density to the C-line (represented by the red arrows in Fig. 9; Gingrich, 1967) – a density level normally reserved for attempts to regenerate the stand – would both reduce the moisture stress on trees and reduce the number of vulnerable trees on the site. Some have considered this stocking level to be too low (Johnson, pers. comm., 2002), and instead recommend keeping stand stocking near the B-line (represented by the blue arrows) and harvest oak decline-prone species around 70 years of age (Clatterbuck and Kauffman, 2006). Others have proposed a landscape-scale

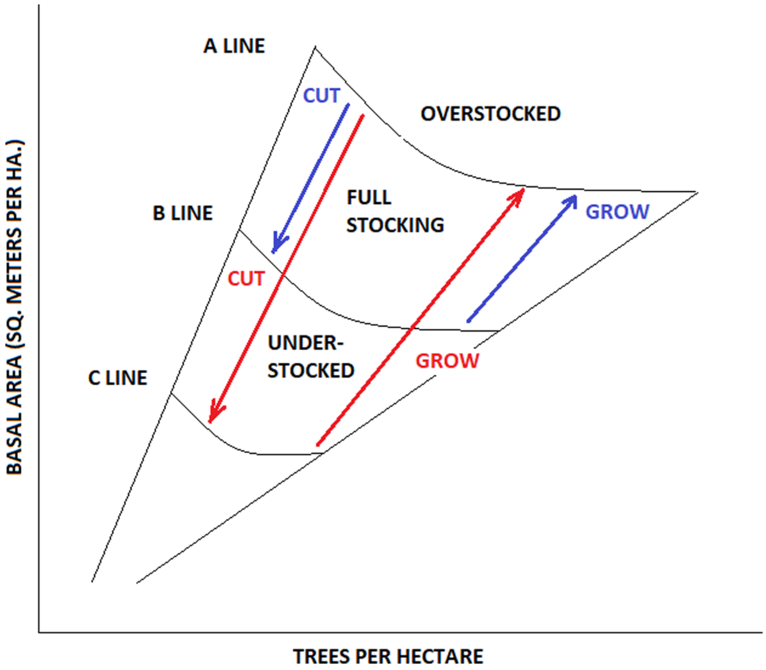


Figure 9 Stocking tables for upland central hardwoods, portraying the relationship between trees per hectare (horizontal axis), density (basal area per hectare, vertical axis), and the quadratic mean diameter (rays extending from lower left to upper right of the diagram). In this figure, adapted from Gin(g)rich (1967), the area above the A-line represents an overstocked stand. The area between the A- and B-lines represents full stocking and the area between the B- and C-lines represents an understocked stand. The A-line is based on the fully stocked stand that has never been thinned. A stand on the B-line is thought to have trees with no competition, yet there is no unused growing space. The C-line is estimated based on the normal yield table of the lowest stocking that will grow to the B-line within 10 years. Source: adapted from Larsen et al. (2010) and Larsen (2014).

matrix of even- and uneven-aged forests, depending on local site conditions, and shifting forest composition to more drought-resistant species such as shortleaf pine (*Pinus echinata*) and white oak (*Quercus alba*), as techniques to reduce the vulnerability to severe drought events (Johnson, pers. comm., 2002; Guyette et al., 2007).

For example, the prognosis for forest survival in the presence of gypsy moth (*Lymantria dispar*) depends on the forest stand's ability to survive one or multiple defoliations, through reducing the number of susceptible species or increasing the vigor of the trees on the site, or both (Gottschalk, 1993). After a few years, the gypsy moth population may decline or may move to other sites (Davidson et al., 1999). Such a model is a good template for managing a forest's overall vigor. Trees with greater vigor store more carbohydrates and sugars over winter. Consequently, they have the resources to develop more extensive root systems and produce abundant current-year carbohydrates to support defense against insect and disease attacks even beyond requirements for growth of fine roots and leaves, height growth, and reproduction.

Options for enhancing or shaping species diversity depend on current stand conditions. Older forests with limited species diversity offer few options. Such cases point toward improving tree vigor by thinning and perhaps preparing the stand for future regeneration where there are multiple species capable of reaching and being maintained in the overstory. After these conditions are achieved, more management options present themselves.

3 Methods of projection in the long term: modeling projected changes in habitat and potential migration

Modeling potential changes in habitat, and the potential migration into such habitats, requires a major simplification of reality in an uncertain and changing world. There is a great deal of complexity to consider, as evidenced by the many intrinsic (e.g. physical habitat specialization, successional stage, fecundity, dependence on particular disturbances) and extrinsic (e.g. browsing, pest/pathogens, dispersal barriers, climatic extremes) factors that may increase a species' or population's risk of extinction, extirpation, or genetic degradation. For models to be useful (Box and Draper, 1987), they must enhance our understanding of current and potential future species distributions.

To tackle these complexities, our approach has been to combine a species distribution model (SDM; DISTRIB-II, an updated version of the Random Forest DISTRIB model [Peters et al., 2019; Iverson et al., 2019a]), for projecting potential future suitable habitats), and a migration model (SHIFT, for estimating colonization likelihoods based on historical migration rates into projected suitable habitat within 100 years). In addition, we use a literature-based set of modification factors for assistance in interpretation (ModFacs), and a current forest inventory assessment (Forest Inventory and Analysis, FIA, www.fs.fed.us/fia) to better understand current tree species abundance for a particular geographic unit (Iverson et al., 2008, 2019a, 2019b; Iverson and McKenzie, 2013; Prasad et al., 2006).

The resulting outputs of these individual species models provide a wealth of information across the eastern United States. As a background to our modeling framework, the response variables are derived from FIA and we use a hybrid grid (Peters et al., 2019) of 10 × 10 or 20 × 20 km cells to account for the differential density of FIA plots. The FIA plot data were tabulated and averaged within each of the 55 national forests to yield a ranked list of tree species, by importance value (IV) derived equally from total basal area and number of stems. These

IV data were also used in conjunction with 45 environmental variables (e.g. climate, elevation, and soil) in a statistical model (Random Forest, Prasad et al., 2016) to generate modeled estimates (DISTRIB-II) of current IV for each species across the eastern United States. Then, by swapping current climatic variables with potential future climate variables according to three models (CCSM4, GFDL-CM3, and HadGEM2-ES) and two representative concentration pathways (4.5 and 8.5), for 30-year periods ending in 2039, 2069, and 2099, projections were made regarding potential suitable habitat for each species (Prasad et al., 2016; Iverson et al., 2019a). Using multiple literature sources, each species was also scored on nine biological traits and 12 traits related to resilience from disturbances (Matthews et al., 2011) and given a rating as to the species' adaptability to the changing climate. The SHIFT model is also paramount to this effort, to assess colonization likelihood within the suitable habitats based on habitat suitability and the strength of the source abundance (Prasad et al., 2013, 2016). By combining DISTRIB-II and SHIFT results, we not only identify potential changes in suitable habitat under various scenarios of climate change, but also provide, for each species present currently or potentially in the future, estimates of colonization likelihood through the currently fragmented landscapes (Iverson et al. 2019b). We assumed a generous migration rate of 50 km/century within 100 years; this migration rate represents the high end of average estimates of migration during the Holocene period through extant forest (Davis, 1981; Davis and Shaw, 2001; Schwartz, 1993) although McLachlan et al. (2005) have determined from molecular studies that 25, or even 10 km, may be more realistic for some species that were assisted by seed sources in climatic refugia. We continue to use 50 km/century because we do not assume future formations of climatic refugia.

With the combination of results from DISTRIB-II, SHIFT, Modification Factors, and current FIA estimates of IV, we are able to present a detailed presentation of (1) species importance currently, (2) the potential changes in suitable habitat by 2100, (3) the adaptability of each species to the changing climate, (4) the capability of each species to cope with the 2100 climate based on adaptability and abundance currently within the National Forest (NF), (5) the likelihood of each species to naturally migrate into the NF, and (6) an assessment of the potential for the species to be used for planting or otherwise promoting within the NF.

In order to facilitate comparisons and quantify potential risks and opportunities under climate change, we focus here on the collective outputs for the following geographic units: state, 1 × 1° grid, ecoregion, hydrologic unit, and NF. This can be done, and tabulated or mapped, for any geographic location in the eastern United States, so long as it occupies an area of at least 8000 km^2 to allow sufficient FIA plots for analyses. We briefly report here on DISTRIB-II and SHIFT outputs for three analyses: (1) DISTRIB-II outputs of changes in suitable habitats for the entire eastern US region; (2) DISTRIB-II with SHIFT outputs for 55 national forests in this region, with an emphasis on one, the Chequamegon-Nicolet NF in northern Wisconsin; and (3) DISTRIB-II with SHIFT outputs for 464 1 × 1° grids across this same region east of the 100th meridian.

3.1 DISTRIB-II projections of suitable habitat by 2100

We evaluated 125 tree species that had sufficient FIA samples for modeling. Results show potentially large impacts, especially under a high emissions trajectory (RCP 8.5), on suitable habitat for tree species in the eastern United States. Of the 45 variables used in the Random Forest modeling, the seven climate variables were ranked among the top nine variables, indicating an overall influence of climate associations with capturing patterns at the species range extent. Inserting new possible climates caused large changes in potential suitable habitat. Our analysis found that about 88 of the 125 species would gain and 26 species would lose at least 10% of their suitable habitat. The projected change in the mean center for each species shows a general movement to the northeast, with the habitat centers for 81 species potentially moving over 100 km under RCP 8.5. For example, *Quercus nigra* (water oak) shows a potential movement of 377 km under the mean of RCP 8.5 scenarios (Fig. 10). Overall, many tree species are likely to have better success in tracking their suitable habitats under RCP 4.5 as compared to RCP 8.5. Details are presented in Iverson et al. (2019a).

3.1.1 Chequamegon-Nicolet NF assessment

The results of combining model outputs of DISTRIB-II and SHIFT, along with the modification factors and current FIA estimates, are all presented within an information-packed, but easily unpacked table (Table 2, see also Iverson et al. 2019b for full explanation of table variables and derivatives). Besides a suite of species-level information related to current and potential future capacities to cope with the changing climate, it also provides suggestions as to species that are (1) rare now but good candidates for increasing prominence in future (Infill); (2) likely there now but missed by FIA plots (Likely); and (3) good candidates for assisted migration because they are nearby with good potential for natural migration into the area within 100 years (Migrate). In our example Chequamegon-Nicolet NF, we show six species for Infill, two for Likely, and six to nine for Migrate, depending on RCP (Table 2).

3.1.2 1 × 1-degree assessment

Each of the 464 1 × 1° grids was tabulated in the same way as described for the Chequamegon-Nicolet NF. These tables allow anyone east of the 100th meridian (eastern half of the United States) the ability to determine their current

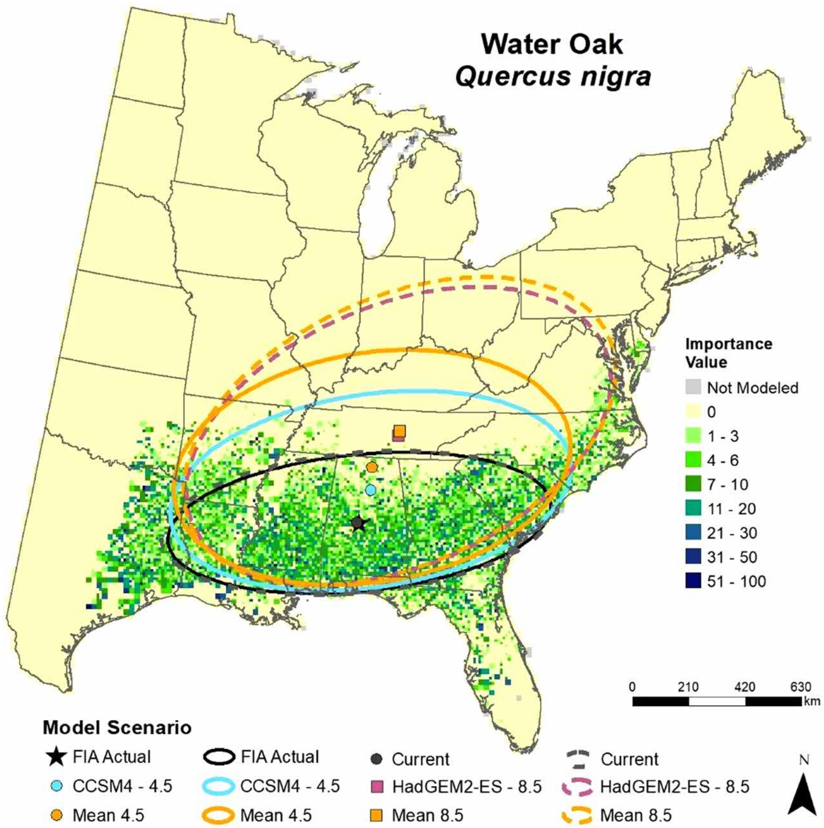


Figure 10 Ellipses of one standard deviation and mean centers for the current distribution and suitable habitat according to CCSM4 RCP 4.5, mean RCP 4.5, mean RCP 8.5, and HadGEM2-ES RCP 8.5 for water oak (*Quercus nigra*). FIA Actual refers to the known FIA plot locations of the species, while Current refers to the modeled current distribution of the species.

and potential tree species attributes during this century. All that is necessary is for the user to know his/her geographic coordinates (e.g. 41.334 latitude and −82.201 longitude) and the name of the grid will indicate the southeast corner of the grid for the file to use, either online or downloaded (e.g. S41_E82.pdf, see www.fs.fed.us/nrs/atlas). The area considered within grids varies slightly north to south due to the curvature of the earth, so each 1 × 1° cell was calibrated to equal 10 000 km^2, which represents roughly 100 10 × 10 km cells or 25 20 × 20 km cells (usually some combination of each).

By collectively evaluating all 1 × 1° grids, we can map the counts of species within any of the fields of the 464 tables. These can be as simple as counting the number of species recorded on FIA plots or the number of oak species recorded, to more advanced queries such as the number of tree species with

Table 2 DISTRIB-II/SHIFT output table for Chequamegon-Nicolet National Forest, sorted in decreasing order of current species abundance (FIAsum)

Common name	Scientific name	MR	FIAsum	FIAiv	ChngCl45	ChngCl85	Adapt -	Abund	Capabil45	Capabil85	SHIFT45	SHIFT85	N
Quaking aspen	*Populus tremuloides*	High	641.22	16.76	Sm. dec.	Sm. dec.	Medium	Abundant	Good	Good			1
Red maple	*Acer rubrum*	High	548.33	13.84	No change	No change	High	Abundant	Very Good	Very Good			2
Sugar maple	*Acer saccharum*	High	485.17	13.65	Sm. dec.	Sm. dec.	High	Abundant	Good	Good			3
Balsam fir	*Abies balsamea*	High	315.42	8.63	Sm. dec.	Sm. dec.	Low	Abundant	Good	Good			4
Black ash	*Fraxinus nigra*	Medium	221.35	6.96	Sm. dec.	Sm. dec.	Low	Abundant	Good	Good			5
Red pine	*Pinus resinosa*	Medium	176.33	10.63	Sm. dec.	Sm. dec.	Low	Abundant	Good	Good			6
Tamarack (native)	*Larix laricina*	High	161.77	7.35	No change	No change	Low	Abundant	Very Good	Very Good			7
Paper birch	*Betula papyrifera*	High	159.6	4.41	No change	No change	Medium	Abundant	Very Good	Very Good			8
Black spruce	*Picea mariana*	High	124.91	6.47	Sm. dec.	Sm. dec.	Medium	Abundant	Good	Good			9
Northern red oak	*Quercus rubra*	Medium	122.8	5.11	Sm. inc.	Sm. inc.	High	Abundant	Very Good	Very Good			10
Northern white-cedar	*Thuja occidentalis*	High	113.9	7.16	Sm. dec.	No change	Medium	Abundant	Good	Very Good			11
American basswood	*Tilia americana*	Medium	112.45	4.37	Sm. inc.	No change	Medium	Abundant	Very Good	Very Good			12
Bigtooth aspen	*Populus grandidentata*	Medium	106.74	4.85	No change	Sm. dec.	Medium	Abundant	Very Good	Good			13
Yellow birch	*Betula alleghaniensis*	High	105.82	3.51	Sm. dec.	Sm. dec.	Medium	Abundant	Good	Good			14

Eastern white pine	*Pinus strobus*	High	96.91	4.47	Sm. inc.	Sm. inc.	Low	Abundant	Very Good	Very Good			15
Eastern hemlock	*Tsuga canadensis*	High	79.45	3.85	No change	No change	Low	Abundant	Very Good	Very Good			16
Jack pine	*Pinus banksiana*	Medium	77.19	12.67	Sm. dec.	Lg. dec.	High	Abundant	Good	Good			17
White spruce	*Picea glauca*	Medium	56.88	2.4	No change	No change	Medium	Common	Good	Good			18
Black cherry	*Prunus serotina*	Medium	49.63	1.81	Lg. inc.	Lg. inc.	Low	Common	Very Good	Very Good			19
American elm	*Ulmus americana*	Medium	44.77	2.4	Sm. inc.	Sm. inc.	Medium	Common	Very Good	Very Good			20
White ash	*Fraxinus americana*	Medium	36.96	1.95	Sm. inc.	Sm. inc.	Low	Common	Very Good	Very Good			21
Eastern hophornbeam	*Ostryavirginiana*	Low	36.95	1.48	Sm. inc.	Sm. inc.	High	Common	Very Good	Very Good			22
Northern pin oak	*Quercus ellipsoidalis*	Medium	36.02	4.63	Sm. dec.	Sm. dec.	High	Common	Fair	Fair	Infill +	Infill +	23
Green ash	*Fraxinus pennsylvanica*	Low	24.22	1.49	Sm. inc.	Sm. inc.	Medium	Common	Very Good	Very Good			24
Bur oak	*Quercus macrocarpa*	Medium	20.33	4.29	No change	No change	High	Common	Good	Good	Infill ++	Infill ++	25
American hornbeam	*Carpinus caroliniana*	Low	16.52	1.28	Sm. dec.	Sm. dec.	Medium	Common	Fair	Fair			26
Chokecherry	*Prunus virginiana*	FIA	5.46	0.54	Unknown	Unknown	Medium	Common	FIA Only	FIA Only			27
Pin cherry	*Prunus pensylvanica*	Low	5.45	0.89	No change	Very Lg. dec	Medium	Common	Good	Lost			28

(*Continued*)

Table 2 (Continued)

Common name	Scientific name	MR	FIAsum	FIAiv	ChngCl45	ChngCl85	Adapt -	Abund	Capabil45	Capabil85	SHIFT45	SHIFT85	N
Serviceberry	*Amelanchier spp.*	Low	3.94	0.53	Sm. inc.	No change	Medium	Rare	Good	Fair			29
Silver maple	*Acer saccharinum*	Low	3.7	10.93	Sm. dec.	Sm. dec.	High	Rare	Poor	Poor	Infill +	Infill +	30
Butternut	*Juglans cinerea*	FIA	1.74	1.71	Unknown	Unknown	Low	Rare	FIA Only	FIA Only			31
Balsam poplar	*Populus balsamifera*	Medium	1.4	0.83	Very Lg. dec	Very Lg. dec	Medium	Rare	Lost	Lost			32
Slippery elm	*Ulmus rubra*	Low	0.82	0.81	Sm. inc.	Sm. inc.	Medium	Rare	Good	Good	Infill ++	Infill ++	33
Bitternut hickory	*Carya cordiformis*	Low	0.45	0.66	Sm. inc.	Sm. inc.	High	Rare	Good	Good	Infill +	Infill +	34
White oak	*Quercus alba*	Medium	0.43	0.63	No change	No change	High	Rare	Fair	Fair	Infill +	Infill +	35
Mountain maple	*Acer spicatum*	Low	0.43	0.25	Lg. dec.	Lg. dec.	High	Rare	Poor	Poor			36
Norway spruce	*Picea abies*	FIA	0.27	0.8	Unknown	Unknown	NA	Rare	NNIS	NNIS			37
Scotch pine	*Pinus sylvestris*	FIA	0.18	0.52	Unknown	Unknown	NA	Rare	NNIS	NNIS			38
Peachleaf willow	*Salix amygdaloides*	FIA	0.13	0.37	Unknown	Unknown	Medium	Rare	FIA Only	FIA Only			39
Rock elm	*Ulmus thomasii*	FIA	0.09	0.27	Unknown	Unknown	Low	Rare	FIA Only	FIA Only			40
Boxelder	*Acer negundo*	Low	0	0	New Habitat	New Habitat	High	Absent	New Habitat	New Habitat	Likely +	Likely +	41
Swamp white oak	*Quercus bicolor*	Low	0	0	New Habitat	New Habitat	Medium	Absent	New Habitat	New Habitat	Likely +	Likely +	42

Black oak	*Quercus velutina*	High	0	0	New Habitat	New Habitat	Medium	Absent	New Habitat	New Habitat	Migrate++	Migrate++	43
Eastern redcedar	*Juniperus virginiana*	Medium	0	0	New Habitat	New Habitat	Medium	Absent	New Habitat	New Habitat	Migrate+	Migrate++	44
American beech	*Fagus grandifolia*	High	0	0	New Habitat	New Habitat	Medium	Absent	New Habitat	New Habitat	Migrate+	Migrate+	45
Black locust	*Robinia pseudoacacia*	Low	0	0	New Habitat	New Habitat	Medium	Absent	New Habitat	New Habitat	Migrate+	Migrate+	46
Black walnut	*Juglans nigra*	Low	0	0	New Habitat	New Habitat	Medium	Absent	New Habitat	New Habitat	Migrate+	Migrate+	47
Shagbark hickory	*Carya ovata*	Medium	0	0	New Habitat	New Habitat	Medium	Absent	New Habitat	New Habitat	Migrate+	Migrate+	48
Eastern cottonwood	*Populus deltoides*	Low	0	0	New Habitat	New Habitat	Medium	Absent	New Habitat	New Habitat		Migrate+	49
Hackberry	*Celtis occidentalis*	Medium	0	0	New Habitat	New Habitat	High	Absent	New Habitat	New Habitat		Migrate+	50
Blackgum	*Nyssa sylvatica*	Medium	0	0	New Habitat	New Habitat	High	Absent	New Habitat	New Habitat		Migrate+	51
Pignut hickory	*Carya glabra*	Medium	0	0	New Habitat	New Habitat	Medium	Absent	New Habitat	New Habitat			52
Sycamore	*Platanus occidentalis*	Low	0	0	New Habitat	New Habitat	Medium	Absent	New Habitat	New Habitat			53
Yellow-poplar	*Liriodendron tulipifera*	High	0	0	New Habitat	New Habitat	High	Absent	New Habitat	New Habitat			54
Mockernut hickory	*Carya alba*	Medium	0	0	New Habitat	New Habitat	High	Absent	New Habitat	New Habitat			55

(Continued)

Table 2 (Continued)

Common name	Scientific name	MR	FIAsum	FIAiv	ChngCl45	ChngCl85	Adapt -	Abund	Capabil45	Capabil85	SHIFT45	SHIFT85	N
Post oak	*Quercus stellata*	High	0	0	New Habitat	New Habitat	High	Absent	New Habitat	New Habitat			56
Red spruce	*Picea rubens*	High	0	0	New Habitat	New Habitat	Low	Absent	New Habitat	New Habitat			57
Scarlet oak	*Quercus coccinea*	Medium	0	0	New Habitat	New Habitat	Medium	Absent	New Habitat	New Habitat			58
Pecan	*Carya illinoinensis*	Low	0	0	Unknown	New Habitat	Low	Absent	Unknown	New Habitat			59
Sweetgum	*Liquidambar styraciflua*	High	0	0	Unknown	New Habitat	Medium	Absent	Unknown	New Habitat			60
Sugarberry	*Celtis laevigata*	Medium	0	0	Unknown	New Habitat	Medium	Absent	Unknown	New Habitat			61
Flowering dogwood	*Cornus florida*	Medium	0	0	Unknown	New Habitat	Medium	Absent	Unknown	New Habitat			62
Bigleaf magnolia	*Magnolia macrophylla*	Low	0	0	Unknown	Unknown	Medium	Absent	Unknown	Unknown			63

MR is to model reliability (see Iverson et al., 2019 for explanation). FIAiv is the average importance value for the species when present on FIA plots. ChngCl45 or 85 presents the change classes (increase, decrease, or no change) of habitat suitability by 2100, according to RCP 4.5 (low emissions) or 8.5 (high emissions). Adapt is a class of adaptability of the species according to the modification factors. Abund is an abundance class based on FIAsum. Capabil45 or 85 is the capability of the species to cope with the climates of RCP 4.5 or 8.5 at 2100, based on abundance, change classes, and adaptability. SHIFT45 and 85 are derived from several outputs of the SHIFT model in combination with the suitable habitat from DISTRIB-II to derive two levels of potential for the species to Infill (+ or ++) for species that are currently found rarely in the NF and likely to expand in the next 100 years, Likely (+ or ++) for species that are likely already present in the area but not found by FIA plots, and Migrate (+ or ++) for species that did not occur on FIA plots, but SHIFT (RCP 4.5 or 8.5) did indicate potential for colonization in the NF within 100 years. Finally, the N column simply is a counter. Further details are found in Iverson et al. 2019b..

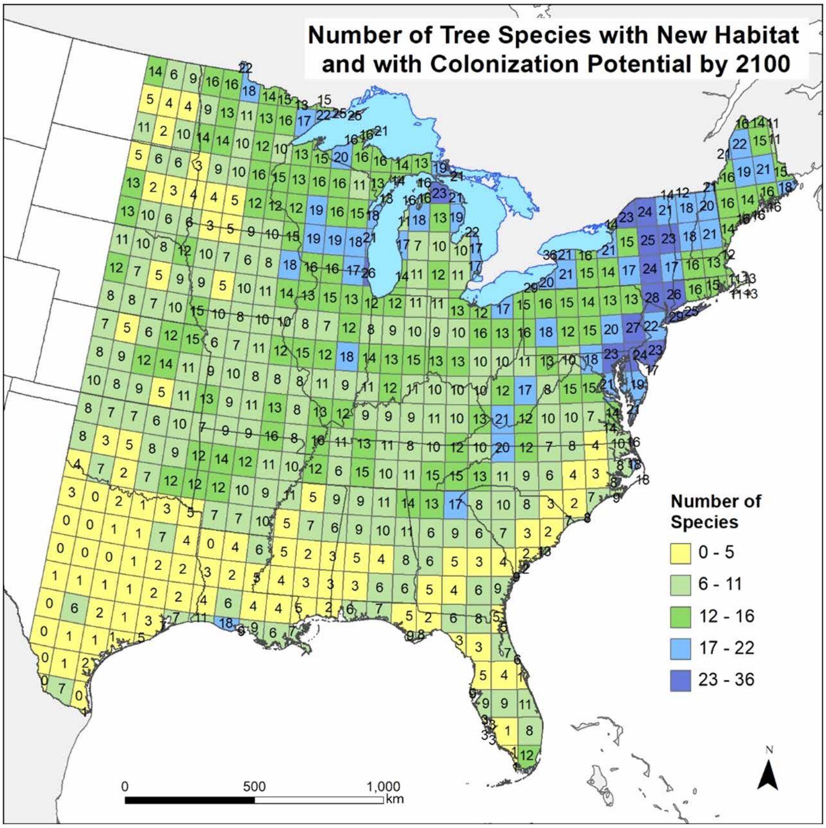


Figure 11 Map showing the number of tree species, by 1 × 1° grid, with both new habitat appearing (via DISTRIB-II) and some potential to be colonized within 100 years (via SHIFT).

New Habitat and with at least some colonization potential by 2100 (Fig. 11). From these summaries, we can begin to address questions at the community levels where these data indicate that northern locations have more options in selecting species for assisted migration as compared to southern locations that only have the Gulf of Mexico to the south (Fig. 11). By assisted migration, we mean the physical moving of propagules northward from points south as the climate warms (Dumroese et al., 2015; Iverson and McKenzie, 2013). Maps such as these allow regional planners, researchers, and interested publics to better understand the forest resource now and potentially into the future.

4 Ecoregional vulnerability assessments

Forest managers often seek the best available science to inform their management, and they could spend significant amounts of time sorting through and digesting the vast number of research publications on climate and its effects on ecosystems. However, much of this literature is still too broad scale for site-level management, and therefore lacking in relevancy and confounded by numerous climate models, climate scenarios or representative concentration pathways, downscaling algorithms, time scales, ecological models, and sources of uncertainty.

The Climate Change Response Framework addressed this information challenge by creating a series of forest ecosystem vulnerability assessments written specifically for land managers. Each assessment was informed at the outset by regional experts, including both scientists and managers. The series covers several ecological provinces and uses the same climate models and scenarios, and forest impact models. Each assessment also follows a similar format. Each assessment describes the contemporary landscape and identifies key stressors that have shaped forest ecosystems over the past century. Past and projected trends in climate are then summarized from climate observations and downscaled global circulation models. This information is then used to parameterize forest impact models that project future forest change. The results from several forest impact models, along with published research on the effect of climate on ecosystem processes, are considered by an expert panel that relies on local knowledge and expertise to identify the factors that contribute to the vulnerability of major forest ecosystems within each assessment area through the end of this century. A final chapter summarizes the implications of these vulnerabilities on a variety of forest-related ecological, social, and economic topics across the region.

The primary goal of this series of assessments is to summarize potential changes to the forest ecosystems of each region under a range of possible future climates, and determine the vulnerability of forest ecosystems to these changes during the next century. Uncertainties in modeling and gaps in understanding are also addressed in each assessment.

Vulnerability is defined here as ‘the degree to which a system is susceptible to and unable to cope with the adverse effects of climate change’. Forest ecosystem vulnerability is defined here as susceptibility ‘to a reduction in health and productivity or a change in species composition that would alter its fundamental identity’.

Each assessment summarized statistically downscaled climate projections for three future time periods, using two climate models (GFDL and PCM) under two contrasting greenhouse gas emission scenarios (A1FI: high emissions and B1: low emissions) for the years 2070–2100. GFDL A1FI projects a greater amount of warming and hot, dry summers throughout the region. PCM B1 projects a lesser amount of warming and wetter summers with modest temperature increases in summer. These model-scenario combinations were selected because they had been used previously for projecting changes in habitat suitability for tree species and represented the least and most amount of climate change, respectively. Both downscaled climate scenarios were used as climate inputs for three forest impact models, which were used to project climate-induced impacts on selected tree species or forest cover types. Each assessment also synthesized published research on projected changes in forest productivity; natural disturbance regimes; forest composition; intensified stressors; sea-level rise and salt water intrusion; and interactions among climate change and other ecosystem processes.

4.1 Impacts

Major impacts to system drivers and stressors were identified across each assessment area. The most frequently identified impacts contributing to ecosystem vulnerability in all assessment areas included changes in fire regime, soil moisture, pest and disease outbreaks, and nonnative invasive species. Some impacts were specific to certain geographic regions, such as sea-level rise and hurricanes along the Mid-Atlantic and New England coastal areas. A recent analysis of adaptation plans across the northeastern United States similarly identified changes in the frequency and amount of precipitation, and increased vegetation moisture stress, among the most-cited impacts of concern among land managers. These regional concerns are also identified by the most recent National Climate Assessment, which concluded the following:

- Heavy rainfall has increased in recent decades, and is expected to continue to intensify.
- Heatwaves have become more common, and annual temperatures are expected to continue to rise.
- Earlier spring melt and reduced snowpack contribute to changes in growing season hydrology.

Forest impact models projected significant changes in tree species' habitat availability, growth, and productivity within each of the areas, with different species' responses between assessment areas (specific results for the Central Appalachians are discussed later). Generally, changes in climate and hydrology tend to intensify many of the stressors that may already exist for many species and can increase their susceptibility to drought, pests, disease, or competition from other species.

4.2 Adaptive capacity

A review of ecosystem vulnerability assessments found that factors that contributed the most to adaptive capacity were generally consistent across the assessment areas. Systems with high adaptive capacity had one or more of the following traits: high diversity of native species in both the understory and the canopy; distribution on a variety of landforms, soil types, and geologic substrates; distribution with a large extent; high genetic diversity; and high species richness and/or diversity. Systems with low adaptive capacity often exhibited traits such as low species diversity and/or richness; low genetic diversity; systems where the natural disturbance regime has been altered significantly; systems where past management or land use reduced the diversity of species, ages, or genotypes. Although forest management can influence some of these adaptive capacity factors, future management was not addressed in the vulnerability assessment; only the current adaptive capacity of the ecosystem was addressed in each assessment.

4.3 Forest ecosystem vulnerability in the Central Appalachian Mountains[3]

The Central Appalachians region covers 117 400 km^2 from the shores of Lake Erie to the peaks of the Allegheny Mountains and spans three states: Maryland, Ohio, and West Virginia. This region contains a mosaic of high-elevation boreal forests, upland forests and woodlands, riparian, and floodplain forests that are an essential part of the landscape.

As part of the Central Appalachians Climate Change Response Framework project, more than 40 scientists and forest managers collaborated to assess the vulnerability of forest ecosystems in this region to the likely range of projected climate change.

Although the annual average temperature in the Central Appalachians has remained generally the same between 1901 and 2011, minimum temperatures have increased by 0.6°C. By season, minimum temperatures have warmed the most during summer and fall. Both minimum and maximum temperatures increased in April and November, the two fastest warming months. Across the region, precipitation has increased in the fall by an average of 5.8 cm (8%) and has decreased in the winter by an average of 2.5 cm. Extreme rain events of 7.6 cm or greater have become more frequent, while light rain events have decreased.

All climate models project that average temperatures will increase in the Central Appalachians. For the low emissions climate scenario, the projected change ranges from 0.6°C to 2.2°C. For the high emissions climate scenario, projected change increases range from 2.2°C to 6.7°C. Both models agree that precipitation is projected to increase in winter and spring, more so under the

---

[3] This section was adapted from Butler-Leopold et al. (2018). https://forestadaptation.org/sites/default/files/evas_technicalsummary_centralapps_June%202016_0.pdf.

high emissions climate scenario. Models disagree about the timing of possible seasonal decreases in either summer or fall, depending on scenario. There may be greater moisture stress later in the growing season, especially as increasing temperatures lead to increased water loss from evaporation and transpiration. Evidence also suggests rain may occur during heavier rain events interspersed among relatively drier periods.

Two climate models, three forest impact models, hundreds of scientific papers, and professional expertise were combined to assess the effects of climate change on regional forest ecosystems. Based on this information, there is a large amount of evidence to suggest that the following impacts will occur in the Central Appalachians region:

- Soil moisture patterns will change, with drier soil conditions in summer and fall. Due to potential decreases in summer and fall precipitation and increases in winter and spring precipitation, it is likely that soil moisture regimes will also shift. Longer growing seasons and warmer temperatures may also result in greater evapotranspiration and lower soil water availability later in the growing season.
- Fire risks will increase. National and global studies agree that wildfire risk will increase across the region, especially in drier areas. Fire is expected to accelerate changes in forest composition, promoting changes in species faster than temperature or moisture availability.
- Early growth and advanced regeneration will be vulnerable to changes in moisture. Predicted changes in temperature, precipitation, growing season onset, and soil moisture may alter the duration or quality of germination conditions. After establishment, saplings may still be more sensitive than mature trees to disturbances such as drought, heat stress, frost, fire, and flooding.
- Suitability for southern species will increase. Forest impact models project increases in suitable habitat and volume for many species with ranges largely south of the region, including shortleaf pine, post oak, and blackjack oak. Habitat suitability may increase for species currently planted in the region, such as loblolly pine. Most species are not expected to migrate fast enough to keep up with the shifting habitat. Development, fragmentation, and other physical barriers to seed dispersal may further slow natural migration of trees.
- Suitability for northern species will decline. Forest impact models project decreases in habitat suitability for northern species such as eastern hemlock (*Tsuga canadensis*), and red spruce (*Picea rubens*), which are currently limited to specific landscape positions where conditions are cool and moist. These microhabitats may provide some refugia for these species, but their presence on the landscape may become rare.

Populations of sugar maple (*Acer saccharum*) and other northern species may be able to persist in southern refugia if new competitors from the south are unable to colonize.

- Invasive plants, pests, and pathogens will increase or become more damaging. A warming climate has allowed some invasive plant species, insect pests, and pathogens to survive further north. Threats such as the southern pine beetle (*Dendroctonus frontalis*), oak decline, and invasive plants such as kudzu (*Pueraria* spp.), bush honeysuckles (*Lonicera* spp.), and cogongrass (*Imperata cylindrica*) may increase in the future.

Climate change will not affect all forest species, communities, and parts of the landscape in the same way. Of nine forest ecosystems assessed, the spruce/fir and Appalachian (hemlock)/northern hardwood forests were considered highly vulnerable due to negative impacts on dominant species and a limited capacity to adapt to disturbances such as drought and defoliation. Dry oak and oak/pine forests were considered less vulnerable because they have more drought and such heat-adapted species are better able to withstand large-scale disturbances. Riparian forests are also vulnerable to potential shifts in flood dynamics.

These determinations of vulnerability are general across the region, and will be influenced by local conditions, forest management, and land use. The high diversity in landforms, microclimates, hydrology, and species assemblages across the region greatly complicates assessment of vulnerability. It is essential to consider local characteristics when interpreting vulnerabilities at local scales. The assessment does not consider adaptive management actions, changes in land use, or other social or economic factors that could affect forest health or productivity.

The Climate Change Response Framework (https://forestadaptation.org/) also developed forest adaptation resources, with both an adaptation workbook and a menu of adaptation strategies and approaches, to help land managers devise highly relevant adaptation actions for their project site and objectives.

4.4 Climate change adaptation at the local scale[4]

4.4.1 Climate-informed restoration in the Appalachian Mountains–Lambert Run Demonstration Project

The high elevation region of the Appalachian Mountains was largely influenced by over 4000 km^2 of spruce forest over 150 years ago. At that time, the high volume of spruce in the overstory was a driver of above- and below-ground ecological processes. Strip coal mining and logging are local drivers of the

---

[4] This section is adapted from Butler et al. (online) https://forestadaptation.org/adapt/demonstration-projects/monongahela-national-forest-lambert-restoration-project.

Published by Burleigh Dodds Science Publishing Limited, 2020.

degradation of spruce forests that has greatly impacted the land, hydrology, and vegetation of the project area.

In May 2014, the Monongahela National Forest worked with the Northern Institute of Applied Climate Science to use a five-step adaptation workbook process (Swanston et al., 2016) to carefully consider near- and long-term restoration goals and demonstrate how management actions can enhance long-term resilience to climate change. The 1079-ha project encompasses the Lambert Run watershed and two small adjacent watersheds. In addition to the Lambert Run Strip coal mine, the project area contains approximately 405 ha of legacy coal mine lands (reclaimed according to mining laws at the time). The project is located 8 km northwest of Durbin, in Randolph County, West Virginia, USA. The Monongahela National Forest works closely with a number of partners on this project who provide funding and collaboration, including the Appalachian Regional Reforestation Initiative, Green Forests Work, Canaan Valley Institute, the Nature Conservancy, West Virginia Division of Natural Resources, USDA-NRCS Plant Materials Center, and the Central Appalachians Spruce Restoration Initiative.

Management goals (Step 1): The Lambert Run Strip–abandoned coal mine lands were mined in the 1970s and bought by the US Forest Service in the 1980s as a portion of the 16380-ha Mower Tract acquisition. Rehabilitation efforts in the 1970s consisted of reshaping the mined areas to a more stable condition and planting species, mostly nonnative, for erosion control. The contemporary result is large areas of heavily compacted soil with low water infiltration, where the predominant cover is nonnative invasive grasses and Norway spruce (*Picea abies*) planted as part of the mining reclamation plan. Grass-dominated areas remain in a condition called arrested succession. The Monongahela National Forest is implementing the Lambert Restoration Project to essentially restore ecological function by improving watershed conditions, providing wildlife habitat, and restoring native red spruce–northern hardwood ecosystems on Lambert Run and adjacent lands.

Climate change impacts (Step 2): According to numerous climate and process models and the Central Appalachians Forest Ecosystem Vulnerability Assessment (Butler et al., 2015), climate change impacts are expected to intensify over the next century, including:

- Regional increase of roughly 1–4°C in mean annual temperature, with high-elevation areas projected to warm less than low elevation areas.
- Depending on the model, regional decrease of roughly 2.5–10 cm of precipitation in summer or fall, with more severe drying in high-elevation areas.
- Increased frequency of intense rain events, which is expected to increase erosion potential, especially on steep slopes and where hydrology has been altered.

- Projected declines in red spruce, sugar maple, bigtooth aspen (*Populus grandidentata*), and other native species.

Challenges and opportunities (Step 3): Red spruce is currently expanding on the landscape, recovering from past logging, acidification, and wildfire to regain an important ecological niche. Current restoration efforts are focused on restoring site ecological functions related to soil and water, and restoring native tree, shrub, and herb species. Although climate impact models project severe declines for red spruce by the end of the century, these high-elevation areas provide the last remaining habitat that is cool and wet enough to support red spruce. Restoration of these sites now may increase the ability of red spruce forest to cope with future changes in climate by correcting arrested succession, reconnecting forested landscapes, and providing a greater suite of red spruce sites with the potential to serve as refugia.

Adaptation actions (Step 4): Numerous adaptation approaches and tactics were identified for the project area (Table 3). Adaptation approach 1.1 was selected to restore and sustain the ecological function so that the hydrology of the system will be better able to withstand future climate-related disturbances (Swanston et al., 2016); the tactic to leave thinned wood on site is designed to improve nutrient inputs. Adaptation approaches 5.1–5.3 were selected to enhance species and structural diversity in the spruce-fir forest; tactics included releasing red spruce by removing some mid-story hardwoods, but specifically retaining underrepresented species such as black cherry and disease-resistant beech. Another tactic is to monitor native species at lower elevations in order to detect and monitor upward migration, allowing species to establish naturally. These tactics are designed to set up the ecosystem to function as best as possible in the short term so that it can better withstand future climate changes. Although red spruce is projected to decline across the region due to climate, the red spruce in this region are currently occupying the best possible habitat. Restoring the ecological function and diverse forests now may delay or buffer the effects of climate change locally.

Monitoring (Step 5): Information was also gathered in order to evaluate whether the selected actions were effective and could inform future management. Because standard monitoring is detailed within the management plan for this area, and the restoration of this site requires a high level of flexibility, staff did not identify any additional monitoring that is recommended at this time. However, several monitoring variables were chosen for future consideration, including monitoring stream flow, pH, and dissolved oxygen in order to detect the progress made in the hydrologic restoration.

Table 3 Adaptation approaches and tactics for the Lambert Run Demonstration Area

Sites	Management objectives	Adaptation approach	Adaptation tactic
Mixed hardwood forest These forests were formerly red spruce forest. Red spruce is expanding on the landscape. Other native species include: red maple, black cherry, cucumber tree, and black birch.	• Improve composition by increasing red spruce component to 30% • Enhance growth rate and stand structure	6.2: Maintain and restore diversity of native species 6.1: Promote diverse age classes 1.1: Reduce impacts to soils and nutrient cycling 6.3: Retain biological legacies	• Release existing red spruce by removal (herbicide) of midstory hardwoods and create wildlife snags • Protect black cherry and disease-resistant beech (other northern hardwood species are not a concern at this time due to current abundance on the landscape) • Leave-thinned wood on site for woody material
Mine bench These areas are either compacted bare soil or are covered with Norway spruce and aggressive grasses. They are typically convex parts of the landscape so soils are drier already. There is little to no infiltration into the soil, but runoff is being captured by mining pools.	• Establish native species • Increase coarse woody material • Restore hydrologic function	• Maintain and restore diversity of native species • Reduce landscape fragmentation • Prevent the introduction and establishment of invasive plant species and remove existing invasives • Reduce impacts to soils and nutrient cycling • Maintain or restore hydrology	• Plant native tree species and herbaceous species from local nursery stock • Prioritize native species in this location, which may serve as long-term refugia, and monitor upward-migrating species • Remove nonnative trees mechanically (Norway spruce) and herbaceous species (spotted knapweed) • Increase input of coarse woody material (leave-uprooted Norway spruce, mulch trees on site, and import clean mulch from other sites) • Prior deep-ripped slopes have not shown increased erosion. Increase allowable slope to <45% to loosen soils and increase rainwater filtration over more land area • Decommission roads that are impeding hydrologic function or repurpose for recreation • Assess road stream crossings and upgrade culverts to handle higher peak stream flow and allow aquatic organism passage

Next steps: Climate change considerations are integrated into forest management under the Lambert Restoration Project. At the time of this publication, some areas have already been deep ripped and planted, while others are in progress. Wetland creation and road decommissioning is also ongoing. Native species will continue to be planted according to availability, with an emphasis on greater native species diversity.

4.4.2 Climate-informed development of LEAP regional biodiversity vision—Implementation project at Cleveland Metroparks

The Lake Erie Allegheny Partnership for Biodiversity (LEAP) is a consortium of over 50 conservation-minded organizations (park districts, museums, consultants, watershed groups, state and local government agencies and nonprofits) dedicated to protecting and restoring the biodiversity of the Glaciated Lake Erie Allegheny Plateau Ecoregion. This includes approximately 57000 km^2 of land and waters south of Canada from Sandusky Bay in Ohio to the Allegheny Mountains in Pennsylvania.

The region's natural landscape was primarily a deciduous forest (upland and riparian) with extensive wetland complexes reflecting the impact of the last glacial retreat 18 000 years ago. Much of the region's forests were cut over and its wetlands drained over a century ago to allow industrial development and agricultural expansion. Today's fragmented landscape continues to reflect the intersection of urban sprawl and agriculture with natural communities sparsely connected through forest remnants, riparian corridors, and reverting farm and pasture land. The result is a region with a mosaic pattern of human development interspersed with natural areas. LEAP collectively protects through ownership or easement ~126 140 ha scattered across the region.

In 2018, LEAP worked with the US Forest Service and the Northern Institute of Applied Climate Science to develop customized climate assessments for the region. These efforts were broken down to capture various spatial scales where changing climate could affect differences in tree species distributions. The spatial scales include (1) LEAP regional scale, (2) five ecoregional subsections, (3) five large watershed (HUC 6) designations, (4) 13 small watershed (HUC 8)[5] designations, and (5) 11-1 × 1-degree grid cells. Breaking down the regional landscape into these functional units increases the likelihood that the fragmented patches of protected lands were accurately captured. It also provides individual LEAP and local landowners of those various fragments with modeled species adaptation information to consider as they look to implement forest management strategies.

---

[5] The HUC stands for hydrologic unit code (HUC) consisting of two to eight digits based on the four levels of classification in the hydrologic unit system developed by the US Geological Survey. https://water.usgs.gov/GIS/huc.html.

Climate change impacts: The projected regional climate change impacts are expected to intensify over the next century, and include:

- Regional increase of 3.7–6.1°C in mean annual temperature.
- Regional increase of 9.9–13.2 cm of precipitation with the greatest increases projected to occur in NE Ohio, NW Pennsylvania, and SW New York.
- Plant hardiness zones[6]: A shift of one full zone with RCP 4.5 and two full zones with RCP 8.5.
- Average number of days above 30°C are projected to increase by an additional 41–109 days annually.
- Projected declines in eastern hemlock, pin oak (*Quercus palustris*), bigtooth aspen, and others.

4.4.2.1 Management goals

Results from the climate data were integrated into the development of a regional biodiversity vision (Beach, 2018). This resource provides priorities for protecting nature across the Glaciated Allegheny Plateau. Five priorities were established such as (1) preserve large blocks of natural land, (2) link natural areas, (3) reduce habitat fragmentation, (4) reduce other stressors (invasive species, pollution, overabundance of white-tailed deer (*Odocoileus virginianus*)), and (5) prepare for a changing climate (see example project). Each priority contributes to ensuring suitable opportunities for forests across the region to adapt to climate change (Table 4).

4.4.2.2 Challenges and opportunities

While models provide possible climate scenarios with potential species range shifts, several factors should be considered when interpreting the outputs. Models rely on generalizations, and scale resolution may not be adequate to capture unique microsite variability or subtle landscape features that affect species distributions. Species recommendations for climate tolerance do not consider plant community assemblages, and careful review by local experts is required for determining management activities suitable for a given habitat. Finally, a forest may be compromised by existing site conditions and stressors (invasive plant species, forest pests or pathogens, browse pressure) that can be exacerbated by climate change and mitigating those stressors are also as important to maintaining or increasing forest health.

---

[6] Plant hardiness zones are delineated by average annual minimum winter temperature, divided into 10-degree F zones. https://planthardiness.ars.usda.gov/PHZMWeb/.

4.4.2.3 Example implementation

Cleveland Metroparks (CM), in northeast Ohio, is a partner within LEAP and is using the climate data generated to assist with forest management. The park district has over 9700 ha of protected land predominately in Cuyahoga County which serves a population of 1.25 million people. Approximately 80% of the land is undeveloped and comprised of various natural communities (forests, wetlands, meadows etc.). The current forested communities, however, reflect the changes caused by various land use activities and historic impacts from the spread of the Chestnut Blight (Flinn et al., 2018). As an example project, CM identified a small forested track (~10 ha) to implement management activities that enhance forest resilience to climate change. Originally cleared for pasture prior to the 1930s, the stand has since been colonized by ruderal tree species dominated by poorly formed (multi-stemmed), single-cohort red maple (*Acer rubrum*) with minor representation of wild black cherry (*Prunus serotina*) and sugar maple (*Acer saccharum*). Based on climate models, northern red oak (*Quercus rubra*), yellow-poplar (*Liriodendron tulipifera*), bitternut hickory (*Carya cordiformis*), shagbark hickory (*Carya ovata*), and American elm (*Ulmus americana*) are all species projected to do well under climate projections. These tree species are also part of the mixed forest that occurs in this area and are limitedly found on or near the project site. Forest management will target a reduction in density and dominance of red maple and other poorly formed tree species on site (Table 4). The harvest will reduce basal area, create small gap openings, release desirable crop trees (i.e. oaks and hickories), and increase light reaching the forest floor. Large exclosure fences will allow regenerating seedlings time to establish without deer browse pressure.

While no tree planting projects are immediately planned at the example forest project, CM regularly implements tree plantings to mitigate the impacts of climate change. Special attention is provided during planning of those projects to track provenance source of the trees. In this way, source location is considered a significant factor determining potential local genetic adaptations that may affect climate adaptability and ensuring suitable gene flow into our area.

5 Management implications

Guidance on incorporating information on projected climate changes and impacts to natural ecosystems into planning efforts can aid on-the-ground implementation of forest management actions (Keenan, 2015; Woodruff and Stultz, 2016). To help overcome barriers to implementing climate adaptation actions, planning efforts must be able to deploy resources on climate change

Table 4 Adaptation approaches and tactics for the Cleveland Metroparks

Landscape scale	Management objectives	Adaptation approach	Adaptation tactic
Glaciated Allegheny Plateau This ecoregion is highly fragmented and includes intact forest communities like Beech/Maple and successional forests from land use conversion	• Preserve large block of natural land • Link natural areas • Reduce habitat fragmentation • Reduce other stresses in nature • Prepare for climate change (see below)	• Expand size of existing or add new large forested areas for refugia • Create migration corridors by linking key landscape fragments • Encourage tree regeneration	• Identify unprotected land (public) and determine easement or fee purchase potential • Build linkage buffers along physical and physiographic features (riparian corridors, watershed divides, Lake Erie shoreline and Portage Escarpment) • Manage invasive plant species competition and mitigate deer browse pressure on young seedlings (fence protection, culling or hunting)
Cleveland Metroparks Example Forest Project: Former cleared pasture converted to forest and dominated by ruderal tree species - red maple.	• Eliminate non-native woody plant competition • Increase tree species diversity • Encourage young tree regeneration	• Reduce invasive plant populations	• Manage existing invasive species populations. Combine physical and chemical control with prior and subsequent treatments following forest management
		• Reduce stem density of red maple	• Single tree selection removal
		• Reduce impacts of deer browse	• Install fenced exclosure areas • Consider implementing culling in cut zone
		• Increase light gaps	• Remove dead/dying ash trees • Remove poorly formed (double/triple trunk) trees • Create small group openings

impacts and adaptation responses that are at the same spatial scales as those used in management decisions. For example, interviews with state agency land managers suggested that adaptation actions that were needed at a local scale were limited because adaptation planning tended to occur at a regional scale (Anhalt-Depies et al., 2016). The Adaptation Workbook is a structured adaptation planning process designed to help managers consider the potential effects of climate change in identifying management actions that help reduce risks and increase the ability to cope with changing conditions (Janowiak et al., 2014). Managers use resources such as ecoregional vulnerability assessments to understand the broad-scale climate changes and ecosystem impacts in order to ascertain site-level impacts that present important risks to meeting management goals and objectives for particular projects or parcels of land. The process of ‘stepping down’ regional-scale information to the salient climate impacts allows forest managers to identify specific and tangible adaptation actions to minimize climate risks to achieving management objectives (Swanston et al., 2016). Many case studies of climate adaptation in forest management have been developed through the Climate Change Response Framework using the Adaptation Workbook. These serve as important examples of how managers are responding to a changing climate. They provide insights into how adaptation in forestry and natural resources management is occurring and highlight similarities across regions and types of land ownerships as well as factors that influence differences in adaptation responses.

The overarching similarity across adaptation projects developed through the Climate Change Response Framework is that adaptation decision-making is significantly shaped by people’s values of the land they manage and the conditions of the site that they are managing. The recognition of the critical importance of the uniqueness of both people and place to adaptation planning emphasizes that adaptation is not a one-size-fits-all process. This is evident in the broad array of land managers’ goals across the various ownership types and the climate-driven changes with which they are primarily concerned. Despite this diversity, regional trends suggest that adaptation projects and parcels reflect the predominant—as well as the unique—ecosystems and resources of a place (Ontl et al., 2018). Similarly, the climate impacts that concern managers the most vary depending on site conditions, but suggest the importance of regional climate trends and impacts. For example, based on regional forest vulnerability assessments (Janowiak et al., 2018), forest managers in northern New England showed the greatest concern with declines in northern and boreal tree species, while managers working in southern New England were most concerned about the impacts on soil moisture stress for the health and regeneration of forests on their management units.

These regional trends are apparent in the general patterns of emphasis on either resisting climate change, enhancing resilience, or transitioning forests to conditions that are different from current conditions and better adapted to a future climate (Millar et al., 2007). In the central hardwoods region (southern Missouri, Illinois, and Indiana), the low adaptive capacity of forests resulting from the encroachment of mesic species such as maples and altered forest structure from closure of the canopy in the absence of fire, combined with a concern with changes in precipitation patterns, resulted in an emphasis on adaptation actions that aim to transition forests toward a more historical species composition (e.g. increased cover of oak and hickory species) and structural conditions (increased canopy openings; Ontl et al., 2018). In northern regions of both the Midwest and New England, recognition of the greater adaptive capacity of forests resulting from higher species diversity or reduced sensitivity to projected changes in many forest types seems to contribute to an emphasis on adaptation actions that enhance resilience of forests to important system stressors, such as insect pests and forest diseases. While actions aiming to enhance resilience of forests were the most common in southern New England as well, there was a greater relative emphasis on transition actions compared to northern New England. This difference in emphasis is very likely a result of differing relative levels of concern over forest health impacts from climate change and nonnative insect pests (e.g. gypsy moth defoliation and tree mortality; Kretchum et al., 2014) and climate influences on potential tree regeneration failures in the region.

While these adaptation case studies highlight the importance of regional differences in climate concerns and adaptation responses, they also illustrate important commonalities in forest adaptation. Across all adaptation projects, managers identified numerous adaptation strategies appropriate for individual projects that spanned the continuum of resisting climate impacts, enhancing system resilience, and transitioning systems to be better adapted to future conditions (Ontl et al., 2018). Similar to diversifying an investment portfolio to spread financial risk, these managers may be seeing the value in using a multitude of adaptation tactics that address both near-term challenges and long-term climate impacts to enhance the capacity of the system to cope with change. Identifying an ‘adaptation portfolio’ that includes actions across this resistance-resilience-transition continuum may also reduce risk when planning for a range of possible future conditions at a particular site. Despite this diversified approach to adaptation planning, there were strong links between concern about particular climate impacts and adaptation responses, as summarized in the following examples:

- Identifying increased stressors associated with warming winters and greater pest and disease pressures correlated with actions that aimed to increase species and structural diversity.

- Concern over altered precipitation patterns and related impacts were linked to tactics that aimed to facilitate species transitions.
- Impacts of extreme precipitation events correlated with actions that increased landscape connectivity, generally in streams and aquatic ecosystems.
- Increased risk of wildfire was associated with a focus on actions that realign systems following disturbance.

The preceding sections on climate change and near- or longer-term impacts point to higher temperature and increased possibility of drought as a common projected outcome. With episodes of lower amounts of rainfall a possibility, and higher temperatures – which can further reduce soil moisture availability due to higher transpiration (Clark et al., 2016) – there would be periods of reduced growing space for trees and other plants. Although some species may be more adaptable to these swings, the moisture stress can reduce the vigor of a tree and make it more vulnerable to other disturbances, such as insect or disease attack. Trees with reduced vigor store lower amounts of plant sugars over the winter, so the plant starts out the new year in an even more vulnerable state. As water becomes limiting, current stand densities are no longer adaptive.

The ongoing reduction in anthropogenic disturbances, such as harvesting, will perpetuate the decline in the proportion of forests in an early successional stage. With this decrease in early to mid-successional tree species comes a loss of habitat for the animals, birds, insects, and other co-occurring species that rely on them.

6 Conclusion and future trends

This chapter is designed to inform land managers and policymakers as they think about what their forests might look like in the future and consider approaches to preparing for that future. In the short term – the next decade or two – the human-caused demographic and economic factors that contribute to future climate change scenarios have more influence than a changing climate on the extent and composition of forests. The anthropogenic variables affect forest extent and fragmentation. Meanwhile, the biological trends of succession and composition reflect the historical development and current structure to a greater degree than do near-term climate influences. Eventually, however, this ecological momentum is projected to be overwhelmed by the outside abiotic influences of altered temperature and precipitation.

The information in this chapter provides context for climate change considerations and lays the foundation for the management actions discussed in the case studies. While there is deserved attention paid to the potential impact of climate change on forest land extent, composition, and health, readers are urged to bear in mind the other forces that help to shape these aspects of forests. These other influences, such as land use change, may magnify the projected climate change effect or may slow or otherwise mitigate it. The outcome depends on the attributes of the forest. In turn, the nature and timeline of the effects depend not only on forest characteristics, but also on the type of stressor. For example, nonnative invasive species have an impact that is more pronounced in the near term than over the long term, but they can also reduce the longer-term resilience of the forests to withstand changing climatic conditions.

The social and economic factors that drive climate change also have a direct effect on the extent, composition, and structure of the forest. In some cases, managers can employ these factors to bring about the desired outcomes, but the potential longer-term impacts of a changing climate will gradually increase in importance.

Ecologists speak of resistance and resilience in the face of disturbance, usually with the former being a more pre-disturbance response and the latter being post-disturbance response. Such a model is predicated on a discrete event or block of time. What managers are urged to comprehend going forward is that the future forests may face both kinds of influences simultaneously. Managers need to consider both resistance and resilience in their management plans. Some disturbances will set back the successional clock within the current ecological progression (Oliver and Larson, 1996). Given the right circumstances, however, the same disturbance may set the forested landscape on a new trajectory.

Resiliency in future forests depends upon the collective response of individual tree vigor. As mentioned in the oak decline section mentioned previously, trees with adequate or even a surplus of resources should be better able to withstand periods of drought or forest health attacks. Leaving some unoccupied growing space, some ‘slack’ in the system gives room for the forest to absorb temporary resource restrictions. From a management point of view, models of productivity based on full stocking often do not consider the expected impacts of attacks on forest health (Moser et al., 2003). If a more demanding climate makes recovery from mortality events more challenging, expectations of future productivity must be reduced and management actions must reflect this new reality by deliberately keeping forests below the historical, nominal levels of full stocking. Such forests are anticipated to be able to better withstand climate influences than might the previous dense forests. Regardless of the extent of climate change impacts, the forests of the northern United States will require management to maintain their vigor and health. Tools and approaches for guiding wise management are available today to help ensure that forests continue to provide the values and benefits that people expect from them.

7 Acknowledgements

We thank Dr. Stephen R. Shifley for his valuable comments on earlier versions of this manuscript and Cynthia F. Moser for her wide-ranging editorial contributions. We are grateful to both for giving their insight and time so generously. Reviewers of earlier versions of this chapter provided many valuable comments and suggestions.

8 References

Anhalt-Depies, C. M., Knoot, T. G., Rissman, A. R., Sharp, A. K. and Martin, K. J. 2016. Understanding climate adaptation on public lands in the Upper Midwest: implications for monitoring and tracking progress. *Environmental Management* 57(5), 987–97. doi:10.1007/s00267-016-0673-7.

Batek, M. J., Rebertus, A. J., Schroeder, W. A., Haithcoat, T. L., Compas, E. and Guyette, R. P. 1999. Reconstruction of early nineteenth-century vegetation and fire regimes in the Missouri Ozarks. *Journal of Biogeography* 26(2), 397–412. doi:10.1046/j.1365-2699.1999.00292.x.

Bauer, A., Farrell, R. and Goldblum, D. 2016. The geography of forest diversity and community changes under future climate conditions in the eastern United States. *Ecoscience* 23(1–2), 41–53. doi:10.1080/11956860.2016.1213107.

Beach, D. 2018. Natural Connections: a vision for conserving the diversity of habitats and wildlife in the Lake Erie Allegheny region. Available at: https://www.leapbio.org/biodiversity-plan (accessed on 13 June 2019).

Beilmann, A. P. and Brenner, L. G. 1951. The recent intrusion of forests in the Ozarks. *Annals of the Missouri Botanical Garden* 38(3), 261–82. doi:10.2307/2394637.

Box, G. and Draper, N. R. 1987. *Empirical Model-Building and Response Surfaces*. Wiley, New York.

Brandt, L. A., Butler, P. R., Handler, S. D., Janowiak, M. K., Shannon, P. D. and Swanston, C. W. 2017. Integrating science and management to assess forest ecosystem vulnerability to climate change. *Journal of Forestry* 115(3), 212–21. doi:10.5849/jof.15-147.

Bruhn, J. N., Wetteroff Jr., J. J., Mihail, J. D., Kabrick, J. M. and Pickens, J. B. 2000. Distribution of *Armillaria* species in upland Ozark Mountain forests with respect to site, overstory species composition and oak decline. *Forest Pathology* 30(1), 43–60. doi:10.1046/j.1439-0329.2000.00185.x.

Butler, P. R., Iverson, L., Thompson, F. R., Brandt, L., Handler, S., Janowiak, M., Shannon, P. D., Swanston, C., Karriker, K., Bartig, J., Connolly, S., Dijak, W., Bearer, S., Blatt, S., Brandon, A., Byers, E., Coon, C., Culbreth, T., Daly, J., Dorsey, W., Ede, D., Euler, C., Gillies, N., Hix, D. M., Johnson, C., Lyte, L., Matthews, S., McCarthy, D., Minney, D., Murphy, D., O'Dea, C., Orwan, R., Peters, M., Prasad, A., Randall, C., Reed, J., Sandeno, C., Schuler, T., Sneddon, L., Stanley, B., Steele, A., Stout, S., Swaty, R., Teets, J., Tomon, T., Vanderhorst, J., Whatley, J. and Zegre, N. 2015. Central Appalachians forest ecosystem vulnerability assessment and synthesis: a report from the Central Appalachians Climate Change Response Framework project. Gen. Tech. Rep. NRS-146. United States Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA, 310p.

Butler-Leopold, P. R., Iversion, L. R., Thompson III, F. R., Brandt, L. A., Handler, S. D., Janowiak, M. K., Shannon, P. D., Swanston, C. W., Bearer, S., Bryan, A. M., Clark, K. L., Czarnecki, G., DeSenze, P., Dijak, W. D., Fraser, J. S., Gugger, P. F., Hille, A., Hynicka, J., Jantz, C. A., Kelly, M. C., Krause, K. M., La Puma, I. P., Landau, D., Lathrop, R. G., Leites, L. P., Madlinger, E., Matthews, S. N., Ozbay, G., Peters, M. P., Prasad, A., Schmit, D. A., Shephard, C., Shirer, R., Skowronski, N. S., Steele, A., Stout, S., Thomas-Van Gundy, M., Thompson, J., Turcotte, R. M., Weinstein, D. A. and Yáñez, A. 2018. Mid-Atlantic forest ecosystem vulnerability assessment and synthesis: a report from the Mid-Atlantic Climate Change Response Framework project. Gen. Tech. Rep. NRS-181. United States Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA, 294p.

Canadian Centre for Climate Modelling and Analysis. 2012a. CGCM2-coupled global climate model, medium resolution (T47). Environment Canada, Ottawa, ON, Canada. Available at: http://www.cccma.bc.ec.gc.ca/models/cgcm2.shtml (accessed on 20 August 2014).

Canadian Centre for Climate Modelling and Analysis. 2012b. CGCM3.1-coupled global climate model (CGCM3), medium resolution (T47). Environment Canada, Ottawa, ON, Canada. Available at: http://www.cccma.bc.ec.gc.ca/models/cgcm3.shtml (accessed on 20 August 2014).

Clark, J. S., Iverson, L., Woodall, C. W., Allen, C. D., Bell, D. M., Bragg, D. C., D'Amato, A. W., Davis, F. W., Hersh, M. H., Ibanez, I., Jackson, S. T., Matthews, S., Pederson, N., Peters, M., Schwartz, M. W., Waring, K. M.. and Zimmerman, N. E. 2016. The impacts of increasing drought on forest dynamics, structure, and biodiversity in the United States. *Global Change Biology* 22(7), 2329–52. doi:10.1111/gcb.13160.

Clatterbuck, W. K. and Kauffman, B. W. 2006. Managing oak decline. University of Kentucky Cooperative Extension Publication FOR-099. University of Tennessee Extension SP675, Knoxville, TN.

Cunningham, R. J. and Hauser, C. 1989. The decline of the Missouri Ozark forest between 1880 and 1920. In: Waldrop, T. A. (Ed.), *Proceedings of Pine-Hardwood Mixtures: A Symposium on the Management and Ecology of the Type*. Gen. Tech. Rep. SE-58. United States Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Asheville, NC, pp. 34–7.

D'Amato, A. W., Bradford, J. B., Fraver, S. and Palik, B. J. 2013. Effects of thinning on drought vulnerability and climate response in north temperate forest ecosystems. *Ecological Applications* 23(8), 1735–42. doi:10.1890/13-0677.1.

Davidson, C. B., Gottschalk, K. W. and Johnson, J. E. 1999. Tree mortality following defoliation by the European gypsy moth (*Lymantria dispar* L.) in the United States: a review. *Forest Science* 45(1), 74–84.

Davis, M. B. 1981. Quaternary history and the stability of forest communities. In: West, D. C. and Shugart H. H. (Eds), *Forest Succession: Concepts and Application*. Springer-Verlag, New York, pp. 132–53.

Davis, M. B. and Shaw, R. G. 2001. Range shifts and adaptive responses to quaternary climate change. *Science* 292(5517), 673–9. doi:10.1126/science.292.5517.673.

Delworth, T. L., Broccoli, A. J., Rosati, A., Stouffer, R. J., Balaji, V., Beesley, J. A., Cooke, W. F., Dixon, K. W., Dunne, J., Dunne, K. A., Durachta, J. W., Findell, K. L., Ginoux, P., Gnanadesikan, A., Gordon, C. T., Griffies, S. M., Gudgel, R., Harrison, M. J., Held, I. M., Hemler, R. S., Horowitz, L. W., Klein, S. A., Knutson, T. R., Kushner, P. J., Langenhorst, A.

R., Lee, H. C., Lin, S. J., Lu, J., Malyshev, S. L., Milly, P. C. D., Ramaswamy, V., Russell, J., Schwarzkopf, M. D., Shevliakova, E., Sirutis, J. J., Spelman, M. J., Stern, W. F., Winton, M., Wittenberg, A. T., Wyman, B., Zeng, F.. and Zhang, R. 2006. GFDL's CM2 global coupled climate models. Part I: formulation and simulation characteristics. *Journal of Climate* 19(5), 643–74. doi:10.1175/JCLI3629.1.

DeSantis, R. D.. and Moser, W. K. 2016. Maintenance of forest ecosystem health and vitality. In: Shifley, S. R. and Moser, W. K. (Eds), *Future Forests of the Northern United States*. Gen. Tech. Rep. NRS-151. United States Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA, pp. 107–43. Chapter 5.

Dinan, T. 2017. Projected increases in hurricane damage in the United States: the role of climate change and coastal development. *Ecological Economics* 138, 186–98. doi:10.1016/j.ecolecon.2017.03.034.

Dumroese, R. K., Williams, M. I., Stanturf, J. A. and St Clair, J. B. S. 2015. Considerations for restoring temperate forests of tomorrow: forest restoration, assisted migration, and bioengineering. *New Forests* 46(5–6), 947–64. doi:10.1007/s11056-015-9504-6.

Dwyer, J. P., Cutter, B. E. and Wetteroff, J. J. 1995. A dendrochronological study of black and scarlet oak decline in the Missouri Ozarks. *Forest Ecology and Management* 75(1–3), 69–75. doi:10.1016/0378-1127(95)03537-K.

Fan, Z. F., Fan, X. L., Spetich, M. A., Shifley, S. R., Moser, W. K., Jensen, R. G. and Kabrick, J. M. 2011. Developing a stand hazard index for oak decline in upland oak forests of the Ozark Highlands, Missouri. *Northern Journal of Applied Forestry* 28(1), 19–26. doi:10.1093/njaf/28.1.19.

Flinn, K. M., Mahany, T. P. and Hausman, C. E. 2018. Form forest to city: plant community change in northeast Ohio from 1800 to 2014. *Journal of Vegetation Science* 29(2), 297–306. doi:10.1111/jvs.12621.

Gingrich, S. F. 1967. Measuring and evaluating stocking and stand density in upland hardwood forests in the Central States. *Forest Science* 13(1), 38–53.

Gleason, K. E., Bradford, J. B., Bottero, A., D'Amato, A. W., Fraver, S., Palik, B. J., Battaglia, M. A., Iverson, L. R., Kenefic, L. and Kern, C. C. 2017. Competition amplifies drought stress in forests across broad climatic and compositional gradients. *Ecosphere* 8(7), e01849. doi:10.1002/ecs2.1849.

Goerndt, M., Moser, W. K., Miles, P. D., Wear, D. N., DeSantis, R. D., Huggett, R., Shifley, S. R. and Aguilar, F. X. 2016. Projection methods. In: Shifley, S. R. and Moser, W. K. (Eds), *Future Forests of the Northern United States*. Gen. Tech. Rep. NRS-151. United States Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA, pp. 13–42. Chapter 2.

Gottschalk, K. W. 1993. Silvicultural guidelines for forest stands threatened by the gypsy moth. Gen. Tech. Rep. NE-171. United States Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, Radnor, PA, 49pp.

Grant, G. E., Tague, C. L. and Allen, C. D. 2013. Watering the forest for the trees: an emerging priority for managing water in forest landscapes. *Frontiers in Ecology and the Environment* 11(6), 314–21. doi:10.1890/120209.

Guyette, R. P. and Spetich, M. A. 2003. Fire history of oak–pine forests in the Lower Boston Mountains, Arkansas, USA. *Forest Ecology and Management* 180(1–3), 463–74. doi:10.1016/S0378-1127(02)00613-8.

Guyette, R. P., Muzika, R. M. and Voelker, S. L. 2007. The historical ecology of fire, climate, and the decline of shortleaf pine in the Missouri Ozarks. In: Kabrick, J. M., Dey, D. C. and Gwaze, D. (Eds), *Shortleaf Pine Restoration and Ecology in the Ozarks:*

Proceedings of a Symposium, 7–9 November 2006, Springfield, MO. Gen. Tech. Rep. NRS-P-15. United States Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA, pp. 8–18.

Hayhoe, K. A. 2010. A standardized framework for evaluating the skill of regional climate downscaling techniques. PhD Dissertation. University of Illinois at Urbana-Champaign. Doctor of Philosophy in Atmospheric Sciences, Urbana, IL, 153+v p.

Hubbart, J. A., Guyette, R. and Muzika, R. M. 2016. More than drought: precipitation variance, excessive wetness, pathogens and the future of the western edge of the eastern deciduous forest. *Science of the Total Environment* 566–567, 463–7. doi:10.1016/j.scitotenv.2016.05.108.

Ince, P. J., Kramp, A. D., Skog, K. E., Spelter, H. N. and Wear, D. N. 2011. U.S. Forest Products module: a technical document supporting the Forest Service 2010 RPA assessment. Res. Pap. FPL– RP–662. United States Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI, 61p.

Intergovernmental Panel on Climate Change (IPCC). 2007. Climate change 2007: synthesis report. *Contribution of Working Groups I, II, and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Core Writing Team, Pachauri, R. K. and Reisinger, A. (Eds). Intergovernmental Panel on Climate Change, Geneva, Switzerland.

Intergovernmental Panel on Climate Change (IPCC). 2014. Climate change 2014: impacts, adaptation, and vulnerability. Working Group II Contribution to the IPCC 5th Assessment Report. Intergovernmental Panel on Climate Change, Stanford, CA.

Iverson, L. R. and McKenzie, D. 2013. Tree-species range shifts in a changing climate – detecting, modeling, assisting. *Landscape Ecology* 28(5), 879–89. doi:10.1007/s10980-013-9885-x.

Iverson, L. R., Schwartz, M. W. and Prasad, A. M. 2004. How fast and far might tree species migrate under climate change in the eastern United States? *Global Ecology and Biogeography* 13(3), 209–19. doi:10.1111/j.1466-822X.2004.00093.x.

Iverson, L. R., Prasad, A. M., Matthews, S. N. and Peters, M. 2008. Estimating potential habitat for 134 eastern US tree species under six climate scenarios. *Forest Ecology and Management* 254(3), 390–406. doi:10.1016/j.foreco.2007.07.023.

Iverson, L. R., Thompson, F. R., Matthews, S., Peters, M., Prasad, A., Dijak, W. D., Fraser, J., Wang, W. J., Hanberry, B., He, H., Janowiak, M., Butler, P., Brandt, L. and Swanston, C. 2017. Multi-model comparison on the effects of climate change on tree species in the eastern U.S.: results from an enhanced niche model and process-based ecosystem and landscape models. *Landscape Ecology* 32(7), 1327–46. doi:10.1007/s10980-016-0404-8.

Iverson, L. R., Peters, M. P., Prasad, A. M. and Matthews, S. N. 2019a. Analysis of climate change impacts on tree species of the eastern US: results of DISTRIB-II modeling. *Forests* 10(4), 302. doi:10.3390/f10040302.

Iverson, L. R., Prasad, A. M., Peters, M. P., and Matthews, S. N. 2019b. Facilitating adaptive forest management under climate change: A spatially specific synthesis of 125 species for habitat changes and assisted migration over the eastern United States. *Forests* 10, 989.

Janowiak, M. K., Swanston, C. W., Nagel, L. M., Brandt, L. A., Butler, P. R., Handler, S. D., Shannon, P. D., Iverson, L. R., Matthews, S. N., Prasad, A. and Peters, M. P. 2014. A practical approach for translating climate change adaptation principles into forest management actions. *Journal of Forestry* 112(5), 424–33. doi:10.5849/jof.13-094.

Janowiak, M. K., D'Amato, A. W., Swanston, C. W., Iverson, L., Thompson, F. R., Dijak, W. D., Matthews, S., Peters, M. P., Prasad, A., Fraser, J. S., Brandt, L. A., Butler-Leopold, P., Handler, S. D., Shannon, P. D., Burbank, D., Campbell, J., Cogbill, C., Duveneck, M. J., Emery, M. R., Fisichelli, N., Foster, J., Hushaw, J., Kenefic, L., Mahaffey, A., Morelli, T. L., Reo, N. J., Schaberg, P. G., Simmons, K. R., Weiskittel, A., Wilmot, S., Hollinger, D., Lane, E., Rustad, L. and Templer, P. H. 2018. New England and northern New York forest ecosystem vulnerability assessment and synthesis: a report from the New England Climate Change Response Framework project. Gen. Tech. Rep. NRS-173. United States Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA, 234p.

Jenkins, M. A. and Pallardy, S. G. 1995. The influence of drought on red oak group species growth and mortality in the Missouri Ozarks. *Canadian Journal of Forest Research* 25(7), 1119–27. doi:10.1139/x95-124.

Johnson, P. S. 2004. Thinking about oak forests as responsive ecosystems. Gen. Tech. Rep. SRS-73. United States Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, pp. 13–8.

Keenan, R. J. 2015. Climate change impacts and adaptation in forest management: a review. *Annals of Forest Science* 72(2), 145–67. doi:10.1007/s13595-014-0446-5.

Kirtman, B., Power, S. B., Adedoyin, J. A., Boer, G. J., Bojariu, R., Camilloni, I., Doblas-Reyes, F. J., Fiore, A. M., Kimoto, M., Meehl, G. A., Prather, M., Sarr, A., Schär, C., Sutton, R., van Oldenborgh, G. J., Vecchi, G. and Wang, H. J. 2013. Near-term climate change: projections and predictability. In: *Climate change 2013: the Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P. M. (Eds). Cambridge University Press, Cambridge, UK and New York, NY.

Kretchum, A. M., Scheller, R. M., Lucash, M. S., Clark, K. L., Hom, J. and Van Tuyl, S. 2014. Predicted effects of gypsy moth defoliation and climate change on forest carbon dynamics in the New Jersey pine barrens. *PLoS ONE* 9(8), e102531. doi:10.1371/journal.pone.0102531.

Larsen, D. R. 2014. Gingrich stocking diagram. Available at: http://oak.snr.missouri.edu/silviculture/tools/gingrich.html (accessed on 28 January 2019).

Larsen, D. R., Dey, D. C. and Faust, T. 2010. A stocking diagram for midwestern eastern cottonwood-silver maple-American sycamore bottomland forests. *Northern Journal of Applied Forestry* 27(4), 132–9. doi:10.1093/njaf/27.4.132.

Lawrence, R., Moltzan, B. and Moser, W. K. 2002. Oak decline and the future of Missouri's forests. *Missouri Conservationist* 63(7), 11–8.

Manion, P. D. 1981. *Tree Disease Concepts*. Prentice-Hall, Inc., Englewood Cliffs, NJ, 399p.

Matthews, S. N., Iverson, L. R., Prasad, A. M., Peters, M. P. and Rodewald, P. G. 2011. Modifying climate change habitat models using tree species-specific assessments of model uncertainty and life history factors. *Forest Ecology and Management* 262(8), 1460–72. doi:10.1016/j.foreco.2011.06.047.

McLachlan, J. S., Clark, J. S. and Manos, P. S. 2005. Molecular indicators of tree migration capacity under rapid climate change. *Ecology* 86, 2007–17.

Millar, C. I., Stephenson, N. L. and Stephens, S. L. 2007. Climate change and forests of the future: managing in the face of uncertainty. *Ecological Applications* 17(8), 2145–51. doi:10.1890/06-1715.1.

Morelli, T. L., Daly, C., Dobrowski, S. Z., Dulen, D. M., Ebersole, J. L., Jackson, S. T., Lundquist, J. D., Millar, C. I., Maher, S. P., Monahan, W. B., Nydick, K. R., Redmond, K. T., Sawyer, S. C., Stock, S. and Beissinger, S. R. 2016. Managing climate change refugia for climate adaptation. *PLoS ONE* 11(8), e0159909. doi:10.1371/journal.pone.0159909.

Moser, W. K. and Melick, R. 2002. Management recommendations for oak decline. Unpublished Missouri Department of Conservation memo to all field personnel outlining suggested silvicultural strategies for managing Missouri oak forests in the face of oak decline complex, 2p.

Moser, W. K., Treiman, T. B. and Johnson, E. E. 2003. Species choice and the risk of disease and insect attack: Evaluating two methods of choosing between longleaf and other pines. *Forestry* (Oxford). 76(2):137–47.

Moser, W. K. and Nelson, M. D. 2009. Windstorm damage in Boundary Waters Canoe Area Wilderness (Minnesota, USA): evaluating landscape-level risk factors. *Baltic Forestry* 15(2), 248–54.

Moser, W. K., Hansen, M. H., Nelson, M. D., Crocker, S., Perry, C. H., Schulz, B., Woodall, C. W., Nagel, L. and Mielke, M. 2007. The Boundary Waters and the blowdown: a resource assessment of the Boundary Waters Canoe Area Wilderness, 1999–2003. Gen. Tech. Rep. NRS-7. United States Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA, 54p.

Moser, W. K., Miles, P. D., Stephens, A., Shifley, S. R., Wear, D. N., Huggett, R. and Li, R. 2016. Maintenance of productive capacity of forest ecosystems. In: Shifley, S. R. and Moser, W. K. (Eds), *Future Forests of the Northern United States*. Gen. Tech. Rep. NRS-151. United States Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA, pp. 77–106. Chapter 4.

Nagel, L. M., Swanston, C. W. and Janowiak, M. K. 2010. Integrating climate change considerations into forest management tools and training. In: Jain, T. B., Graham, R. T. and Sandquist, J. (Eds), *Integrated Management of Carbon Sequestration and Biomass Utilization Opportunities in a Changing Climate*. Proceedings of the 2009 National Silviculture Workshop, 15–18 June 2009, Boise, ID. Proceedings RMRS-P-61. United States Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, pp. 27–35.

Nakićenović, N., Davidson, O., Davis, G., Grübler, A., Kram, T., La Rovere, E. L., Metz, B. M., Tsuneyuki, M., Pepper, W., Pitcher, H., Sankovski, A., Shuka, P., Swart, R., Watson, R. and Dadi, Z. 2000. *Summary for Policymakers. Emissions Scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge UK.

Nelson, M. D. and Moser, W. K. 2007. Integrating remote sensing and forest inventory data for assessing forest blowdown in the Boundary Waters Canoe Area Wilderness. In: Greer, J. D. (Ed.), *New Remote Sensing Technologies for Resource Managers, Proceedings of the Eleventh Forest Service Remote Sensing Applications Conference*, 24-28 April 2006, Salt Lake City, UT. American Society for Photogrammetry and Remote Sensing, 8p.

Nelson, M. D., Healey, S. P., Moser, W. K. and Hansen, M. H. 2009. Combining satellite imagery with forest inventory data to assess damage severity following a major blowdown event in northern Minnesota, USA. *International Journal of Remote Sensing* 30(19), 5089–108. doi:10.1080/01431160903022951.

Nowak, D. J. and Greenfield, E. J. 2016. Urban forests. In: Shifley, S. R. and Moser, W. K. (Eds), *Future Forests of the Northern United States*. Gen. Tech. Rep. NRS-151. U.S.

Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA, pp. 299–313. Chapter 10.

Oak, S., Tainter, F., Williams, J. and Starkey, D. 1996. Oak decline risk rating for the southeastern United States. *Annales des Sciences Forestières* 53(2–3), 721–30. doi:10.1051/forest:19960248.

Oliver, C. D. and Larson, B. C. 1996. *Forest Stand Dynamics*. Wiley, New York.

Ontl, T. A., Swanston, C., Brandt, L. A., Butler, P. R., D'Amato, A. W., Handler, S. D., Janowiak, M. K. and Shannon, P. D. 2018. Adaptation pathways: ecoregion and land ownership influences on climate adaptation decision-making in forest management. *Climatic Change* 146(1–2), 75–88. doi:10.1007/s10584-017-1983-3.

Pan, Y., Birdsey, R. A., Fang, J., Houghton, R., Kauppi, P. E., Kurz, W. A., Phillips, O. L., Shvidenko, A., Lewis, S. L., Canadell, J. G. and Ciais, P. 2011. A large and persistent carbon sink in the world's forests. *Science* 333(6045), 988–93.

Peters, M. P., Iverson, L. R., Prasad, A. M. and Matthews, S. N. 2019. Utilizing the density of inventory samples to define a hybrid lattice for a macro-level species distribution model. *Ecology and Evolution* 9(15), 8876–99, doi:10.1002/ece3.5445 .

Pokharel, B., Wang, S. -Y. S., Meyer, J., Gillies, R. and Lin, Y. H. 2019. Climate of the weakly-forced yet high-impact convective storms throughout the Ohio River Valley and Mid-Atlantic United States. *Climate Dynamics* 52(9–10), 5709–21. doi:10.1007/s00382-018-4472-0.

Prasad, A. M., Iverson, L. R. and Liaw, A. 2006. Newer classification and regression tree techniques: bagging and random forests for ecological prediction. *Ecosystems*, 9(2), 181–99.

Prasad, A. M., Gardiner, J. D., Iverson, L. R., Matthews, S. N. and Peters, M. P. 2013. Exploring tree species colonization potentials using a spatially explicit simulation model: implications for four oaks under climate change. *Global Change Biology* 19(7), 2196–208. doi:10.1111/gcb.12204.

Prasad, A. M., Iverson, L. R., Matthews, S. N. and Peters, M. P. 2016. A multistage decision support framework to guide tree species management under climate change via habitat suitability and colonization models, and a knowledge-based scoring system. *Landscape Ecology* 31(9), 2187–204. doi:10.1007/s10980-016-0369-7.

Rentch, J. S., Schuler, T. M., Nowacki, G. J., Beane, N. R. and Ford, W. M. 2010. Canopy gap dynamics of second-growth red spruce-northern hardwood stands in West Virginia. *Forest Ecology and Management* 260(10), 1921–9. doi:10.1016/j.foreco.2010.08.043.

Ritchie, J. T. 1998. Soil water balance and plant water stress. In: Tsuji, G. W., Hoogenboom, G. and Thornton, P. K. (Eds), *Understanding Options for Agricultural Production*. Springer, Dordrecht, pp. 41–54.

Robert, L., Sturtevant, B. R., Cooke, B. J., James, P. M. A., Fortin, M., Townsend, P. A., Wolter, P. T. and Kneeshaw, D. 2018. Landscape host abundance and configuration regulate periodic outbreak behavior in spruce budworm *Choristoneura fumiferana*. *Ecography* 41(9), 1556–71. doi:10.1111/ecog.03553.

Schwartz, M. W. 1993. Modelling effects of habitat fragmentation on the ability of trees to respond to climatic warming. *Biodiversity and Conservation* 2(1), 51–61. doi:10.1007/BF00055102.

Schoolcraft, H. R. 1821. Journal of a tour into the interior of Missouri and Arkansaw from Potosi, or Mine a Burton, in Missouri Territory, in a south- west direction, toward the Rocky Mountains, performed in the years 1818 and 1819. Sir Richard Phillips, London.

Seager, R., Tzanova, A. and Nakamura, J. 2009. Drought in the southeastern United States: causes, variability over the last millennium, and the potential for future hydroclimate change. *Journal of Climate* 22(19), 5021–45. doi:10.1175/2009JCLI2683.1.

Shifley, S. R., Aguilar, F. X., Song, N., Stewart, S. I., Nowak, D. J., Gormanson, D. D., Moser, W. K., Wormstead, S. and Greenfield, E. J. 2012. Forests of the Northern United States. Gen. Tech. Rep. NRS-90. United States Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA, 202p.

Shifley, S. R., Moser, W. K., Nowak, D. J., Miles, P. D., Butler, B. J., Aguilar, F. X., DeSantis, R. D. and Greenfield, E. J. 2014. Five anthropogenic factors that will radically alter forest conditions and management needs in the US North over the next 50 years. *Forest Science* 60(5), 914–25. doi:10.5849/forsci.13-153.

Shifley, S. R., Moser, W. K., Wormstead, S. and Aguilar, F. X. 2016. The outlook for northern forests. In: Shifley, S. R. and Moser, W. K. (Eds), *Future Forests of the Northern United States*. Gen. Tech. Rep. NRS-151. United States Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA, pp. 299–313. Chapter 11.

Sinclair, W. A. 1965. Comparisons of recent declines of white ash, oaks, and sugar maple in northeastern woodlands. *Cornell Plantations* 20(4), 62–7.

Starkey, D. A. and Oak, S. W. 1988. Silvicultural implications of factors associated with oak decline in southern upland hardwoods. In: Miller, J. H. (Comp.), *Proceedings of the 5th Biennial Southern Silvicultural Research Conference*. Gen. Tech. Rep. SO-74, pp. 579–86.

Strader, S. M., Ashley, W. S., Pingel, T. J. and Krmenec, A. J. 2017. Observed and projected changes in United States tornado exposure. *Weather, Climate, and Society* 9(2), 109–23. doi:10.1175/WCAS-D-16-0041.1.

Swanston, C. W., Janowiak, M. K., Brandt, L. A., Butler, P. R., Handler, S. D., Shannon, P. D., Derby Lewis, A., Hall, K., Fahey, R. T., Scott, L., Kerber, A., Miesbauer, J. W. and Darling, L. 2016. *Forest Adaptation Resources: Climate Change Tools and Approaches for Land Managers* (2nd edn.). Gen. Tech. Rep. NRS-87-2. United States Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA, 161p.

Tavernia, B. G., Nelson, M. D., Riemann, R., Dickinson, B., Moser, W. K., Wilson, B. T. and Garner, J. D. 2016. Conservation of biological diversity. In: Shifley, S. R. and Moser, W. K. (Eds), *Future Forests of the Northern United States*. Gen. Tech. Rep. NRS-151. United States Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA, pp. 43–76. Chapter 3.

U.S. Department of Agriculture, Forest Service (USDA FS). 2011. *National Report on Sustainable Forests – 2010*. FS-979. United States Department of Agriculture, Forest Service, Washington DC, 212p. Available at: http://www.fs.fed.us/research/sustain/2010SustainabilityReport/ (accessed on 11 June 2012).

U.S. Department of Agriculture, Forest Service (USDA FS). 2012a. *Future of America's Forest and Rangelands: Forest Service 2010 Resources Planning Act assessment*. Gen. Tech. Rep. WO-87. United States Department of Agriculture, Forest Service, Washington DC, 198p.

U.S. Department of Agriculture, Forest Service (USDA FS). 2012b. *Future Scenarios: a Technical Document Supporting the Forest Service 2010 RPA Assessment*. Gen. Tech.

Rep. RMRS–GTR-272. United States Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, 34pp.

U.S. Department of Agriculture, Forest Service (USDA FS). 2012c. *Resources Planning Act (RPA) Assessment Online*. United States Department of Agriculture, Forest Service, Washington DC. Available at: http://www.fs.fed.us/research/rpa/ (accessed on 27 July 2012).

USGCRP. 2017. *Climate Science Special Report: Fourth National Climate Assessment*. Wuebbles, D. J., Fahey, D. W., Hibbard, K. A., Dokken, D. J., Stewart, B. C. and Maycock, T. K. (Eds). United States Global Change Research Program, Washington DC, 470p.

Voelker, S.L. 2004. *Causes of forest decline and consequences for oak-pine stand dynamics in Southeastern Missouri*. University of Missouri-Columbia, Missouri, USA.

Voelker, S. L., Muzika, R. M. and Guyette, R. P. 2008. Individual tree and stand level influences on the growth, vigor, and decline of red oaks in the Ozarks. *Forest Science* 54(1), 8–20.

Washington, W. M., Weatherly, J. W., Meehl, G. A., Semtner Jr., A. J., Bettge, T. W., Craig, A. P., Strand Jr., W. G., Arblaster, J., Wayland, V. B., James, R. and Zhang, Y. 2000. Parallel climate model (PCM) control and transient simulations. *Climate Dynamics* 16(10–11), 755–74. doi:10.1007/s003820000079.

Wear, D. N. 2011. Forecasts of county-level land uses under three future scenarios: a technical document supporting the Forest Service 2010 RPA Assessment. Gen. Tech. Rep. SRS-141. US Department of Agriculture Forest Service, Southern Research Station: Asheville, NC. 41 p.

Wear, D. N., Huggett, R., Li, R., Perryman, B. and Liu, S. 2013. Forecasts of forest conditions in regions of the United States under future scenarios: a technical document supporting the Forest Service 2012 RPA assessment. Gen. Tech. Rep. SRS-170. United States Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, 101p.

Wehner, M., Easterling, D. R., Lawrimore, J. H., Heim Jr., R. R., Vose, R. S. and Santer, B. D. 2011. Projections of future drought in the continental United States and Mexico. *Journal of Hydrometeorology* 12(6), 1359–77. doi:10.1175/2011JHM1351.1.

Williams, J. R. 1991. Runoff and water erosion. In: Hanks, R. J. and Ritchie, J. T. (Eds), *Modeling Plant and Soil Systems*. Agronomy Monograph #31. American Society of Agronomy, Madison, WI, pp. 439–55.

Woodruff, S. C. and Stultz, M. 2016. Numerous strategies but limited implementation guidance in US local adaptation plans. *Nature Climate Change* 6(8), 796–802. doi:10.1038/nclimate3012.

Worrall, J. J. 2019. Decline diseases. A section in the website Forest Pathology. Available at: https://forestpathology.org/decline-diseases/ (accessed on 1 May 2019).

Woudenberg, S. W., Conkling, B. L., O'Connell, B. M., LaPoint, E. B., Turner, J. A. and Waddell, K. L. 2010. *The Forest Inventory and Analysis Database: Database Description and User's Manual Version 4.0 for Phase 2*. Gen. Tech. Rep. RMRS-GTR-245. United States Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, 336p.

Zarnoch, S., Cordell, K., Betz, C. and Langner, L. 2010. Projecting county-level populations under three future scenarios: a technical document supporting the Forest Service RPA Assessment. USDA Forest Service Technical Report SRS-128. United States Department of Agriculture Forest Service, Southern Research Station, Asheville, NC, 8p.