Climatic Change (2018) 146:103–116
DOI 10.1007/s10584-017-2065-2

Vulnerability of forests of the Midwest and Northeast United States to climate change

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Received: 11 November 2016 / Accepted: 21 August 2017 / Published online: 6 September 2017

Abstract Forests of the Midwest and Northeast significantly define the character, culture, and economy of this large region but face an uncertain future as the climate continues to change. Forests vary widely across the region, and vulnerabilities are strongly influenced by regional differences in climate impacts and adaptive capacity. Not all forests are vulnerable; longer growing seasons and warmer temperatures will increase suitable habitat and biomass for many temperate species. Upland systems dominated by oak species generally have low vulnerability due to greater tolerance of hot and dry conditions, and some oak, hickory, and pine species are expected to become more competitive under hotter and physiologically drier conditions. However, changes in precipitation patterns, disturbance regimes, soil moisture, pest and disease outbreaks, and nonnative invasive species are expected to contribute forest vulnerability across the region. Northern, boreal, and montane forests have the greatest assessed vulnerability as many of their dominant tree species are projected to decline under warmer conditions. Coastal forests have high vulnerability, as sea level rise along the Atlantic coast increases damage from inundation, greater coastal erosion, flooding, and saltwater intrusion.

This article is part of a Special Issue on "Vulnerability Assessment of US Agriculture and Forests developed by the USDA Climate Hubs" edited by Jerry L. Hatfield, Rachel Steele, Beatrice van Horne, and William Gould.

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Considering these potential forest vulnerabilities and opportunities is a critical step in making climate-informed decisions in long-term conservation planning.

1 Introduction

The US Midwest and Northeast, covering 20 states, are the most heavily populated areas in the USA (Shifley et al. 2012). Forests are a defining landscape feature across the region, covering 42% of the region's land area (Oswalt et al. 2014). Most of the region's land is privately owned (74%), with most private forest held by small family forest owners (Shifley et al. 2012). Forests provide many benefits to the people that live in the region, such as clean drinking water, recreation opportunities, and timber products (Shifley et al. 2012).

The Climate Change Response Framework[1] (CCRF; Swanston et al. 2016) has generated vulnerability assessments of forest ecosystems across the Midwest and Northeast as a first step to identifying risks and adapting to climate changes (Brandt et al. 2014; Handler et al. 2014a, b; Janowiak et al. 2014; Butler et al. 2015; Butler-Leopold et al. 2017; Janowiak et al. 2017). Here, we synthesize findings from these forest ecosystem vulnerability assessments with consideration of common themes in nine ecological provinces (McNab et al. 2007) (Fig. 1). The CCRF assessments combine literature synthesis, statistical and process modeling, and expert judgment from scientists and managers to understand the key impacts and adaptive capacity factors that contribute to the vulnerability of particular plant species and forest types (see Brandt et al. 2017a and Iverson et al. 2017 for methods). We define potential impacts as the direct and indirect effects of climate change on the systems, which may be beneficial or disruptive to the existing system. Factors that may increase the potential impacts on an ecosystem include the following: major system drivers are projected to change; dominant species are projected to substantially decline or increase; and current stressors are projected to increase. Adaptive capacity is the ability of the species or ecosystem to accommodate or cope with potential climate change impacts with minimal disruption (Glick et al. 2011) and is strongly related to the concept of ecological resilience (Holling 1973; Walker et al. 2004). The synthesis of major forest vulnerabilities across the region can be used to inform national and global climate assessments, as well as adaptation policies at a range of spatial scales.

2 Changes in system drivers and stressors

The CCRF assessments identified ongoing and projected changes in current ecosystem drivers and stressors. Many impacts will be similar across ecoregions, but some will be different because of latitude, topography, land use, and proximity to large bodies of water (Table 1).

2.1 Shorter, warmer winters

Winter processes play an important role in forests across the region, although many tree species in the region lie dormant during the winter months. Snowpack is expected to decline by the end of the century (Notaro et al. 2014), which will alter ecosystem dynamics. Soils that typically remain insulated by snowpack can freeze in the absence of snow cover, which can kill fine roots and ultimately lead to reduced plant productivity and changes in nutrient and water cycling (Rustad et al.

[1] For more information, see www.forestadaptation.org.

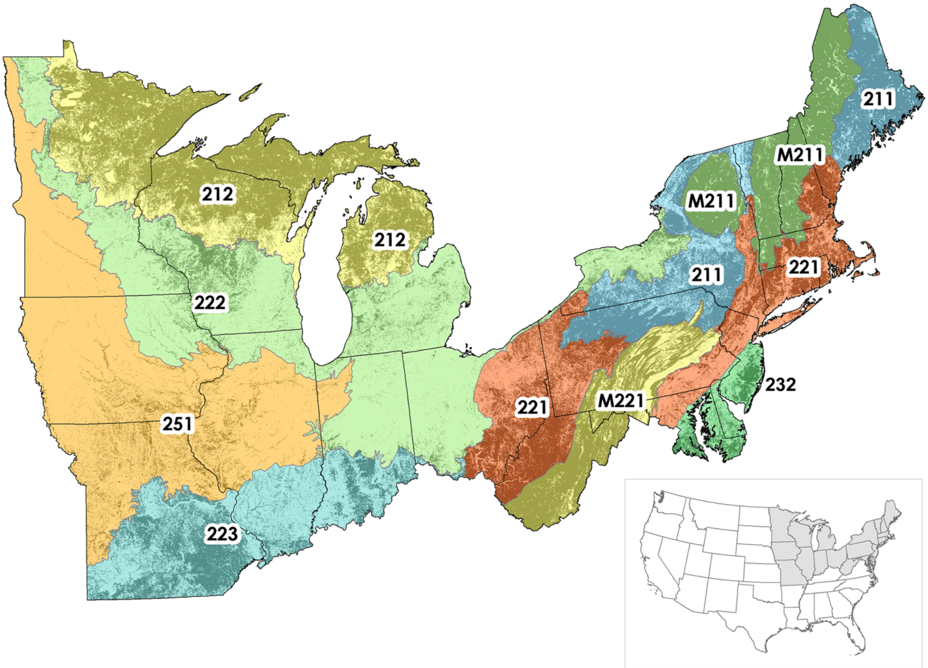

Fig. 1 Nine ecological provinces (Cleland et al. 2007) in the Northeast and upper Midwest: Northeastern Mixed Forest (211); Adirondack-New England Mixed Forest-Coniferous Forest-Alpine Meadow (M211); Laurentian Mixed Forest (212); Eastern Broadleaf Forest (221); Central Appalachian Broadleaf Forest-Coniferous Forest-Meadow (M221); Midwest Broadleaf Forest (222); Central Interior Broadleaf Forest (223); Outer Coastal Plain Mixed Forest (232); Prairie Parkland (251). Dark background shading indicates forest cover

2012). Milder winters with more variable snow and soil conditions can also affect forest management operations, increasing harvest windows for jack pine (*Pinus banksiana*) and red pine (*Pinus resinosa*), while reducing harvest windows for aspen (*Populus tremuloides*), black spruce (*Picea mariana*), hemlock (*Tsuga canadensis*), red maple (*Acer rubrum*), and white spruce (*Picea glauca*) (Rittenhouse and Rissman 2015). Across much of the central and southern parts of the region, winter precipitation is more likely to fall as rain rather than snow in the future (Ning and Bradley 2015), which may lead to an increase in runoff, sedimentation, and nutrient inputs from surrounding agricultural areas. Ice storms, which can lead to breakage and mortality of many trees, could become more frequent in some places but less frequent in others (Klima and Morgan 2015), potentially altering ecosystem succession in both situations. In areas adjacent to the Great Lakes, lake-effect snow is a major driver of forest community composition (Henne et al. 2007). An increase in lake-effect precipitation during winter months could be experienced because of reduced ice cover on the Great Lakes (Wright et al. 2013) but may ultimately lead to increased rain-on-snow dynamics as winter temperatures continue to increase (Notaro et al. 2014).

2.2 Increased extreme precipitation and flooding

Extreme precipitation events have increased since the mid-1900s in the Midwest and Northeast, more than any other region of the country, and this trend is expected to continue (Walsh et al. 2014). Projected increases in extreme precipitation events, combined with milder winters,

Table 1 Major impacts and adaptive capacity factors for each ecoprovince in the Midwest and Northeast, summarized from ecoregional vulnerability assessments (Brandt et al. 2014; Handler et al. 2014a, b; Janowiak et al. 2014; Butler et al. 2015, 2017; Janowiak et al. 2017)

Ecological province	Major climate change impacts	Major adaptive capacity factors
Northeastern Mixed Forest (211)	• Warming climate conditions will cause declines of forests dominated by northern species, particularly spruce-fir and other coniferous forests (−) • Rising winter temperatures are shifting or expanding some insect pest ranges northward, which is increasing mortality from species like the hemlock woolly adelgid (*Adelges tsugae*) (−), but may decrease future damage from eastern spruce budworm (*Choristoneura fumiferana*) in the region (+)	• The high levels of species diversity present in many forest communities may enable them to retain essential character and function, although existing assemblages are likely to change somewhat (+) • Historic fire suppression has increased the abundance of mesic hardwood species and created substantial challenges for maintaining forests dominated by oak (*Quercus*), hickory (*Carya*), and pine (*Pinus*) species that have a greater tolerance to heat and drought (−)
Adirondack-New England Mixed Forest-Coniferous Forest-Alpine Meadow (M211)	• Warming climate conditions will cause declines of forests dominated by northern species, particularly spruce-fir and other coniferous forests (−) • Warming temperatures will cause high-elevation habitats to shrink, increasing risk to species associated with these sites (−) • Reduced winter snow cover and extreme precipitation events will continue to alter hydrologic cycles and fundamental ecosystem processes in many forest communities (−)	• Forest communities located near the southern extent of this province tend to have greater species diversity and contain more species that are expected to have increased suitable habitat (+) • Habitats in more northerly locations and higher elevations will remain colder for longer and may serve as refugia for some species (+) • Extensive forest cover and relatively low fragmentation across the ecoprovince may help forest communities migrate and re-assemble in response to climate impacts, enabling these communities to persist on the landscape (+)
Laurentian Mixed Forest (212)	• Warmer conditions and altered hydrology will cause declines in lowland conifer forests and peatlands (−) • Future conditions will reduce suitable habitat and productivity for boreal forest communities such as those containing spruce, fir, and paper birch (*Betula papyrifera*) (−) • Increased moisture stress, which is already occurring in parts of this region, may particularly affect drought-intolerant species such as quaking aspen (*Populus tremuloides*) or mesic species on drought-prone sites (−)	• Disturbance-adapted systems such as jack pine (*Pinus banksiana*) forests and oak-dominated forests may have greater competitiveness given more frequent wildfire and extreme weather (+) • Relatively low fragmentation across the region may benefit gene flow and help forest communities migrate and re-assemble in response to climate impacts, enabling these communities to persist on the landscape (+)
Eastern Broadleaf Forest (221)	• Heavy precipitation events will continue to alter hydrology and increase risk to riparian and lowland forests from excessive flooding, inundation, and streambank erosion (−)	• Historic fire suppression has increased the abundance of mesic hardwood species and created substantial challenges for maintaining forests

Table 1 (continued)

Ecological province	Major climate change impacts	Major adaptive capacity factors
	• Rising winter temperatures are allowing some insect pests to expand northward, such as hemlock woolly adelgid (*Adelges tsugae*) and southern pine beetle (*Dendroctonus frontalis*) (−) • Rising sea levels and increased storm surge will cause increased saltwater intrusion and inundation, resulting in habitat loss for coastal ecosystems (−)	dominated by oak (*Quercus*), hickory (*Carya*), and pine (*Pinus*) species that have a greater tolerance to heat and drought (−) • Forests in this ecoregion have been highly altered by urbanization and parcelization, and small private ownerships reduce the capacity for forest management in many areas (−) • Many nonnative invasive species have altered forest ecosystem function and impede regeneration of native species (−)
Central Appalachian Broadleaf Forest-Coniferous Forest-Meadow (M221)	• Drought may increase risk of wildfire, which is historically uncommon in this province (−) • Warmer temperatures and drier conditions may exceed the ecological tolerances of species located at high elevations and southern range extents, such as balsam fir (*Abies balsamea*) and red spruce (*Picea rubens*) (−)	• Red spruce (*Picea rubens*) and other high-elevation species have been negatively affected by acid deposition, which decreases natural resistance to other environmental changes (−) • This province has substantial geologic and topographic diversity, which may not only foster refugia in coves and valleys, but also buffer ecosystems from change by supporting high levels of species richness (+) • High rainfall and fog generated at higher elevations may reduce the risk of drought for some high-elevation ecosystems (+)
Midwest Broadleaf Forest (222)	• Heavy precipitation events will continue to alter hydrology and increase risk to riparian and lowland forests from increased erosion, runoff, sedimentation, and nutrient inputs from surrounding agricultural areas (−) • Increased drought stress will be harmful for mesic upland forests dominated by less drought-tolerant species such as red maple (*Acer rubrum*), sugar maple (*Acer saccharum*), and basswood (*Tilia americana*) (−)	• Upland forests occur in relatively small parcels and are highly fragmented by agriculture and developed land, reducing opportunities for migration and gene flow that might support landscape-level persistence (−) • Forested riparian corridors may provide some opportunities for migration and gene flow (+) • Oak woodlands and savannas may be better able to adapt to projected changes because they can tolerate a wide range of disturbances, including fire and drought (+)
Central Interior Broadleaf Forest (223)	• Drier conditions in summer could exacerbate oak decline in some oak-dominated forests, particularly upland forests in Missouri (−)	• Water infrastructure and land use change has dramatically altered hydrology

Table 1 (continued)

Ecological province	Major climate change impacts	Major adaptive capacity factors
	• Milder winters may expand the range of southern pine beetle (*Dendroctonus frontalis*), which attacks shortleaf pine (*Pinus echinata*) and other planted pines (−)	and increased fragmentation in lowland areas, reducing the capacity of bottomland hardwood species to cope with additional stressors (−) • Past fire suppression has led to an increase in maple-dominated mesic forests, which may be less tolerant of hotter and drier conditions (−) • Glade and savanna ecosystems are dominated by species that are adapted to hot, dry conditions that are projected for this region (+)
Outer Coastal Plain Mixed Forest (232)	• Rising sea levels and increased storm surge will cause increased saltwater intrusion and inundation, resulting in habitat loss for coastal ecosystems (−) • Future climate conditions and sea level rise may reduce suitable habitat and productivity for species like pitch pine (*Pinus rigida)* and Atlantic white-cedar (*Chamaecyparis thyoides*), which are keystone species in some forest communities (−)	• This area is highly urbanized, which has led to landscape fragmentation, reducing opportunities for migration and gene flow that might support landscape-level persistence (−) • Salt-tolerant species and ecosystems will be better able to adapt to projected changes. (+) • Many pitch pine and oak forests are already unable to successfully regenerate, which threatens the ability of these systems to persist given additional stressors (−)
Prairie Parkland (251)	• Heavy precipitation events will continue to alter hydrology and increase risk to riparian and lowland forests from increased erosion, runoff, sedimentation, and nutrient inputs from surrounding agricultural areas (−) • Increased drought will stress mesic upland forests and may favor prairie and savanna systems over forests (−) • Wetter spring conditions may increase bur oak blight (*Tubakia iowensis* sp. nov), which can damage and kill bur oak (*Quercus macrocarpa*) (−) • Warmer temperatures and drier conditions may exceed the ecological tolerances of important species such as white oak (*Quercus alba*), black cherry (*Prunus serotina*), and shagbark hickory (*Carya ovata*) (−)	• Forests represent a small proportion of the landscape and are highly fragmented by agricultural areas, reducing opportunities for migration and gene flow that might support landscape-level persistence. (−) • Forested riparian corridors may provide opportunities for migration and gene flow (+) • Oak woodlands and savannas may be better able to adapt to climate change because they can tolerate a wide range of disturbances, including fire and drought (+) • Tree regeneration within oak-hickory forests is low and dominated by drought-sensitive species less suited to future conditions, such as American elm (*Ulmus americana*) (−)

(+) represents an impact or factor that is generally supportive of the ecosystem character and function, whereas (−) represents a disruptive impact or factor are expected to increase total runoff and peak stream flow during the winter and spring across the region (Cherkauer and Sinha 2010; Hayhoe et al. 2007), which may increase the magnitude or frequency of flooding (Hirabayashi et al. 2013). Flood frequency and duration are a major driver of forest composition in bottomland forests (De Jager et al. 2016), and any changes in flood dynamics will have important implications for diversity and nutrient cycling. Increased heavy precipitation events can also increase soil erosion (Nearing et al. 2004), with areas in Illinois, Indiana, Ohio, Vermont, and Maryland being among the most susceptible to erosion in the country (Segura et al. 2014). In coastal areas, storm surges combined with sea level rise may lead to significant increases in salinity and cause tree mortality (Titus et al. 2009). The Atlantic coast has experienced three to four times the global rate of sea level rise during the second half of the twentieth century (Sallenger et al. 2012; Kunkel et al. 2013), which has increased the risk of erosion, damage from storm surges, flooding, and damage to infrastructure and coastal ecosystems.

2.3 Changes in drought and moisture stress

Drought occurrence has not changed in much of the region in recent decades, although drought has decreased in New England and the Ohio River Valley and increased in parts of the upper Midwest (Ficklin et al. 2015). Amidst general increases in annual precipitation, more of the annual rainfall is occurring in fewer events with longer dry periods between the events (Karl et al. 2008; Melillo et al. 2014). Most models project greater drought frequency across the eastern USA in the coming decades (Vose et al. 2016). Longer growing seasons and warmer temperatures could result in greater vapor pressure deficit and evaporative demand, causing greater evapotranspiration and decreased soil-water availability, especially later in the growing season (Gutowski et al. 2008; Hayhoe et al. 2007; Diffenbaugh and Ashfaq 2010; Mishra et al. 2010). Since many trees are already functioning at their hydraulic limits, even a small increase in moisture stress could lead to ecological shifts and widespread decline of mesic species (Choat et al. 2012; Pederson et al. 2014).

2.4 Enhanced fire risk

Wildfires are currently relatively infrequent in the region due to a combination of past management history, relatively high precipitation, and fire suppression efforts (Nowacki and Abrams 2008). However, fire has played an important role in shaping many of the region's forest communities in the past, especially oak-hickory and oak-pine forests. By the end of the century, most models project an increase in wildfire probability (Moritz et al. 2012), with weather conditions that tend to promote large wildfires (hot, dry conditions with upper atmosphere instability) occurring more frequently (Tang et al. 2015). The increase in wildfire risk may be greatest in southern Ohio, West Virginia, and western Pennsylvania (Heilman et al. 2015). Fuel loads from pest-induced mortality or blowdown events could further increase fire risk, but the relationship between these factors can be complex (Hicke et al. 2012).

2.5 Intensified biological stressors

Changes in climate may allow some undesirable plant species, insect pests, and pathogens to expand their ranges (Dukes et al. 2009; Ryan and Vose 2012; Weed et al. 2013). Insects such as hemlock woolly adelgid (*Adelges tsugae*) and southern pine beetle (*Dendroctonus frontalis*) have been able to expand their ranges northward due to milder winters (Rustad et al. 2012; Weed et al. 2013). Increased spring precipitation has been favorable to bur oak blight (*Tubakia iowensis*) in Iowa and some parts of Illinois (Harrington et al. 2012). Forest pests and pathogens are also able to disproportionately damage already stressed ecosystems (Sturrock et al. 2011; Weed et al. 2013). For example, oak decline, a disease complex exacerbated under drought conditions in parts of the Central Interior Broadleaf Forest region, may become more pronounced under drier conditions with higher evaporative demand (Dwyer et al. 1995; Fan et al. 2006). Nonnative invasive species such as honeysuckle (*Lonicera* spp.), reed canary grass (*Phalaris arundinacea*), and common buckthorn (*Rhamnus cathartica*) will also likely be favored by climate change due to life history traits that enhance their adaptive capacity (Brandt et al. 2017b). It is also possible that nonnative plant species will take advantage of shifting forest communities and unoccupied niches if native forest species are limited (Hellmann et al. 2008; Vose et al. 2012).

3 Changes to forest communities and species distribution

Several tree species and ecosystems have emerged as being highly vulnerable, while others may be more adapted to future climates (Table 1). These vulnerability ratings have been derived from local scientific and management expertise that was further informed by habitat suitability and process models (Brandt et al. 2017a; Iverson et al. 2017).

3.1 Reduced habitat for northern and boreal tree species

Across northern latitudes, warmer temperatures are expected to be stressful to trees occurring near their southern species range extent (Iverson et al. 2008). Results from climate impact models project declines in suitable habitat and landscape-level biomass for northern and boreal ecosystems dominated by black spruce (*Picea mariana*), red spruce (*Picea rubens*), white spruce (*Picea glauca*), tamarack (*Larix laricina*), jack pine (*Pinus banksiana*), balsam fir (*Abies balsamea*), and paper birch (*Betula papyrifera*) (Rustad et al. 2012; Butler et al. 2015; Handler et al. 2014a, b; Lucash et al. 2017). In fact, northward shifts in abundance in many of these boreal species are already documented (Woodall et al. 2009; Fei et al. 2017). Boreal tree species may have limited ability to adapt their hydraulic anatomy to warmer conditions (McCulloh et al. 2016), even though they may be able to adjust photosynthesis to accommodate higher temperatures (Sendall et al. 2015). However, some species may be able to persist in the region at high elevations and north-facing slopes and other areas with cooler microclimates, or if competitor species are unable to colonize these areas (Iverson et al. 2008; Iverson et al. 2011).

3.2 Stresses to lowland forests

Multiple vulnerability assessments have shown lowland forests to be among the most vulnerable to projected changes in most of the region (Manomet and NWF 2012; Brandt et al. 2014; Handler et al. 2014a, b; Janowiak et al. 2014; Butler et al. 2015). Although lowland forests are adapted to annual and seasonal water table fluctuations, more intense and variable precipitation events may present risks to this system through excessive flooding, inundation, streambank erosion, or prolonged droughts between heavy precipitation events (Williams et al. 2015). Lowland forests may be particularly vulnerable to climate change if they are already under stress from altered hydrology and if they occur in watersheds with highly impervious surface area or erosion-prone land uses (WICCI 2011; Handler et al. 2014c).

3.3 Shifts in upland Forest composition

Temperate broadleaf forests are common in upland areas across the region. The composition of these forests varies greatly; maple species (*Acer rubrum* and *A. saccharum*) are more abundant in mesic sites, whereas oak (*Quercus* spp.), hickory (*Carya* spp.), and pine (*Pinus* spp.) species are more common in warmer and drier locations with periodic fire. Vulnerability of these ecosystems can vary depending on location within the region. There is evidence that temperate tree species such as red maple are crossing ecotones into boreal forest patches, potentially in response to warming in northern Minnesota and Wisconsin (Fisichelli et al. 2013), even as boreal species abundance is shifing northward (Fei et al. 2017). Models indicate this northward expansion will likely continue in the future (Iverson et al. 2008, 2011). Fire suppression in temperate forests for nearly a century has allowed widespread expansion of mesic, shade-tolerant species (e.g., red maple, sugar maple, basswood [*Tilia americana*]), often to the detriment of fire-dependent species in a general mesophication of habitats (Nowacki and Abrams 2008; McEwan et al. 2011; Hanberry et al. 2012). Forest communities featuring a greater abundance of oak and southern pine species have generally been assessed as being less vulnerable to projected changes in climate (Manomet and NWF 2012; Brandt et al. 2017a). These systems are adapted to hot, dry summers and frequent fires, which are predicted to increase across much of the region. The ability of these forests to expand to new areas will likely depend on the role of fire on specific sites and the overall balance between soil moisture and evaporative demand during summer months.

4 Adaptive capacity of forests in the region

The Midwest and Northeast is highly heterogeneous, including relatively flat agriculturally dominated regions, highly urbanized areas, and heavily forested landscapes with complex topography. These regional differences can lead to differences in adaptive capacity and have a strong influence on the overall vulnerability of forest ecosystems across the region (Table 1).

4.1 Diversity of habitats and species

Biodiversity plays a large role in maintaining ecosystem identity and function in the face of environmental change, with more diverse communities generally exhibiting a greater resilience to extreme environmental conditions and a greater ability to recover from disturbance (Oliver et al. 2015; Duveneck and Scheller 2016; Isbell et al. 2015; Tilman et al. 2014). Some parts of the region are considered hotspots of biodiversity, such as the Central Appalachians, the Missouri Ozarks, and far southern Illinois (Stein et al. 2000), which increases the adaptive capacity for some ecosystems (Brandt et al. 2014; Butler et al. 2015). The northern forests often have lower diversity at the stand level than many areas in the USA (Stein 2002). This can be due to habitat loss, fragmentation, or prior management that has reduced species or structural diversity, or simply because some ecosystems such as boreal forests naturally have lower biodiversity (Millennium Ecosystem Assessment 2005). Topographic and geologic diversity are strongly related to biodiversity (Anderson and Ferree 2010). Large elevational gradients can create diverse habitats and provide opportunities for species migration and gene flow within mountainous landscapes like the Catskills, Ozarks, and Appalachians. Montane forest communities will contract in response to a warming climate, but high-elevation areas or north-facing slopes may be able to serve as refugia for alpine meadow and red spruce communities in the Appalachians (Morelli et al. 2016). The more diverse habitats across the region are generally considered to have a greater capacity to adapt to climate change while maintaining their character.

4.2 Anthropogenic forest change and fragmentation

Forests across the entire region have been affected by human actions for centuries. Past changes include periods of exploitive timber harvesting, land clearing and fire burning to benefit agriculture, fire suppression, urbanization, and landscape fragmentation and parcelization that have created the forests of today (Shifley et al. 2014) and influence the ability of forests to respond to anthropogenic climate change. Forest coverage and the integrity of forest communities have been greatly reduced in some areas as a result of human activities, including agricultural land use in the central and southern Midwest, urban development along the Atlantic coast, and oil and gas development in the Appalachians. Fragmentation decreases the movement of species and genes within a landscape (Ibáñez et al. 2006; Scheller and Mladenoff 2008; Duveneck et al. 2014), thereby reducing the ability of forests ecosystems to maintain identity and function as the climate shifts. Species migrate independently, and ecosystems and landscapes have lower adaptive capacity when the component species depend upon particular hydrologic, soil, or site conditions. In contrast, large and intact forested landscapes may support greater adaptive capacity that allows for some degree of species movement in response to changing conditions while also maintaining the character and function of forest communities at a landscape level. Further, many fragmented and degraded ecosystems have been invaded by nonnative plant species that complete with native species, alter ecosystem function, decrease biodiversity, and pose threats to forest regeneration (Shifley et al. 2014). Across the region, forest landscapes and communities that have been heavily altered or simplified by fragmentation, invasive species, and other stressors will be more susceptible to additional threats posed by climate change. In contrast, forest ecosystems within larger and more intact landscapes that have had less alteration in species composition and structure are generally expected to have greater resilience to future conditions.

5 Concluding remarks

Vulnerability assessments provide critical information for understanding the potential risks, challenges, and opportunities from climate change on a particular system. Empirical evidence and modeling projections point to decades- to centuries-long shifts in many forest communities in the Midwest and Northeast as suitable habitat, competitive relationships, and regeneration respond to changes in moisture, temperature, and disturbance regimes. Individual disturbances, or interactions among multiple disturbances and amplified stressors, may accelerate landscape change faster than anticipated. Given the deep challenges in anticipating forest response across a range of plausible future climates and associated disturbance regimes, it is important to transparently integrate scientific and management expertise into the assessment of climate vulnerability. Even so, most assessments are too broad in scale and content for direct application to management areas, necessitating that resource managers consider and adjust the assessed regional vulnerabilities within the unique context of their site characteristics as they pursue conservation planning.

Acknowledgements We would like to thank two anonymous reviewers for insightful and constructive comments on the manuscript.

Funding information This work was funded by the U.S. Department of Agriculture Forest Service Northern Research Station and Eastern Region.

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