Climatic Change
https://doi.org/10.1007/s10584-018-2326-8

An integrated assessment of the potential impacts of climate change on Indiana forests

Richard P. Phillips[1] · Leslie Brandt[2] · P. David Polly[3] · Patrick Zollner[4] · Michael R. Saunders[4] · Keith Clay[1] · Louis Iverson[5] · Songlin Fei[4]

Received: 15 March 2018 / Accepted: 30 October 2018/Published online: 05 January 2019

Abstract

Forests provide myriad ecosystem services, many of which are vital to local and regional economies. Consequently, there is a need to better understand how predicted changes in climate will impact forest dynamics and the implications of such changes for society as a whole. Here we focus on the impacts of climate change on Indiana forests, which are representative of many secondary growth broadleaved forests in the greater Midwest region in terms of their land use history and current composition. We found that predicted changes in climate for the state—warmer and wetter winters/springs and hotter and potentially drier summers—will dramatically shape forest communities, resulting in new assemblages of trees and wildlife that differ from forest communities of the past or present. Overall, suitable habitat is expected to decline for 17–29% of tree species and increase for 43–52% of tree species in the state, depending on the region and climate scenario. Such changes have important consequences for wildlife that depend on certain tree species or have ranges with strong sensitivities to climate. Additionally, these changes will have potential economic impacts on Indiana industries that depend on forest resources and products (both timber and non-timber).

This article is part of a Special Issue on "The Indiana Climate Change Impacts Assessment" edited by Jeffrey Dukes, Melissa Widhalm, Daniel Vimont, and Linda Prokopy.

Richard P. Phillips and Leslie Brandt contributed equally to this work.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s10584-018-2326-8) contains supplementary material, which is available to authorized users.

✉ Songlin Fei
sfei@purdue.edu

1 Department of Biology, Indiana University, Bloomington, IN 47405, USA

2 Northern Institute of Applied Climate Science, Northern Research Station, US Forest Service, St. Paul, MN 55108, USA

3 Department of Earth and Atmospheric Sciences, Indiana University, Bloomington, IN 47405, USA

4 Department of Forestry and Natural Resources, Purdue University, West Lafayette, IN 47907, USA

5 Northern Institute of Applied Climate Science, Northern Research Station, US Forest Service, Delaware, OH 43015, USA

Finally, we offer some practical suggestions on how management may minimize the extent of climate-induced ecological impacts and highlight a case study from a tree planting initiative currently underway in the Patoka River National Wildlife Refuge and Management Area.

1 Introduction

Forests provide food and habitat to a rich assemblage of animals and microorganisms, and also provide an array of ecosystem services, such as timber, protection of soil and water resources, recreational opportunities, and other cultural benefits. While it is well established that forest ecosystems are dynamic—constantly changing in response to direct and indirect biotic and abiotic drivers—the vulnerability and resilience of forests to climate change are not understood clearly enough to anticipate the consequences of expected scenarios at a local level. Changes in forest composition owing to climate change and shifting patterns of land use will no doubt influence forest productivity, carbon storage, and other ecosystem services. Here, we present an overview of how the forests of Indiana are projected to respond to climate change and associated stressors over the next several decades.

Indiana contains nearly five million acres of forest and an estimated 2.2 billion live trees (Goramson and Kurz 2017). The vast majority of this forest (~ 84%) is privately owned, with the remaining forest ownership split between local, state, and Federal government (Goramson and Kurz 2017). The amount of forest area grew by ~ 22% over the past 50 years, although this trend appears to have leveled off in recent years (Gormanson and Kurtz 2017). The forest products industry in Indiana brings in $7.5 billion annually (2.7% of the state's gross domestic product; Brandt et al. 2014), and spending on wildlife-related recreation brings in ~ $1.7 billion annually (US Department of Interior et al. 2011). Thus, the condition and functioning of Indiana's forests are vital to local and regional economies. The objectives of this report are to (1) describe the current composition of Indiana's forests, (2) identify potential impacts of climate change on these forests in terms of potential shifts in forest composition, wildlife, and ecosystem services, and (3) elucidate forest management strategies that could potentially reduce some of these impacts.

Sidebar Indiana is dominated by three physiographic regions, namely, the northern moraine, the central plains, and the southern hills. Most of the state's forests occur in the southern hills region and are dominated by a single cover type (oak–hickory), which occupies ~ 75% of the forested land (Brandt et al. 2014). However, variations in lithologies, landscape position, forest management practices, and glacial histories (most, but not all soils in the southern hills were unaffected by the most recent Wisconsin glaciation) gave rise to diverse forest overstory and understory communities that likely differ in their vulnerability and resiliency to change.

2 The nature of Indiana forests

Like most deciduous forests of eastern North America, Indiana's forests were strongly influenced by Native Americans, who used fire to promote prairie, savanna, and open woodland habitats (Parker and Ruffner 2004), and later by European settlers, who cleared forests for agriculture in the eighteenth and nineteenth centuries. Nearly 90% of Indiana was

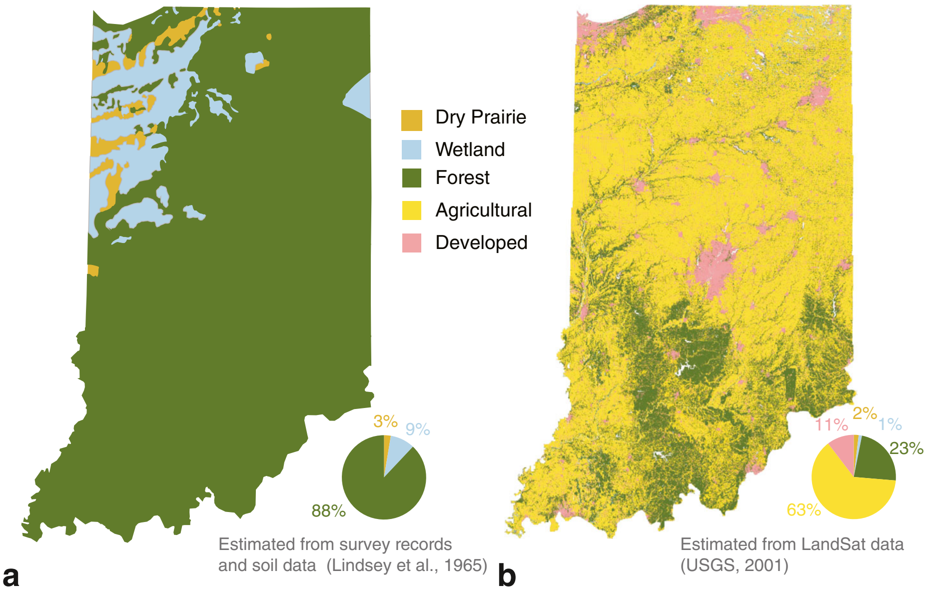

Fig. 1 Indiana vegetation cover, then and now. **a** Major biome cover as it would have been in approximately 1820, as reconstructed from analysis of land survey office records and associated soil types (Lindsey et al. 1965). Wetlands in the northwest were associated with prairie vegetation and those in the northeast were forested. **b** Land cover estimated from remote sensing data in 2001, color-coded to match the 1820 map (Indiana Geological Survey 2001)

forested at the time of European contact (circa 1650), yet only 7% of the state was forested by 1870 and a mere 4% by 1900 (Parker 1997; Fig. 1). This rapid deforestation roused the state to establish the Indiana State Board of Forestry in 1901, after which forest cover grew again to cover 23% by the end of the twentieth century.

Despite the extensive history of harvesting and the removal of most of the state's old growth (Parker and Ruffner 2004), Indiana forests have long been considered unique and worthy of protection. In Amos Butler's words, "Perhaps nowhere could America show more magnificent forests of deciduous trees, or more noble specimens of the characteristic forms than existed in the valleys of the Wabash and Whitewater." (p. 32, Butler 1896). Similarly, John Muir wrote in his autobiographical narrative (1867, Badè 1924) that Indiana forests were "one of the very richest forest of deciduous hardwood trees on the continent". In the Wabash valley, these forests were truly spectacular, with canopies at 100–120 ft. in height, and the tallest sycamores and tulip trees soaring above these canopies at heights of 160–200 ft. (Ridgway 1972).

As land clearing and widespread burning became less common by the mid-twentieth century, much of the abandoned agricultural land reverted back to forest naturally (U.S. Forest Service 2006). During the early to mid twentieth century, numerous laws and local bans on fire marked the beginning of major efforts to control wildfires. This led to a shift in species composition (particularly in the southern hills region), from fire-adapted oak (*Quercus* spp.) and hickory (*Carya* spp.) to fire-intolerant, mesophytic species, such as maple (*Acer* spp.) and tulip poplar (*Liriodendron tulipifera*; Fei and Steiner 2007; Nowacki and Abrams 2008; Fei et al. 2011). For example, although the major forest type in the canopy is still oak–hickory, much of the sub-canopy and understory is dominated by sugar maple (*Acer saccharum*) and other mesophytic species. Today, the rate of reforestation in the state is slowing due to social, economic, and biophysical factors (Evans and Kelly 2008), and the trajectory of forest change is largely a function of the balance between reforestation of rural lands deemed marginal for farming and forest loss from urban development (Moran and Ostrom 2005).

Most forests in the state are now between 50 and 80 years old and occur in parcels that are relatively small in area. No parcels in the northern region exceed 10,000 acres, and only eight patches in the Southern Hills region of Indiana exceed 50,000 acres (Indiana Department of Natural Resources 2010). In addition to affecting wildlife, the fragmentation of Indiana's forests has likely facilitated the invasion of these forests by non-native species, which often prefer disturbances. Over the past several decades, Indiana's forests have become increasingly invaded by non-native woody plants (autumn olive, *Elaeagnus umbellate*; Asian bush honeysuckle, *Lonicera* spp.; and multiflora rose, *Rosa multiflora*), grasses (e.g., Japanese stiltgrass, *Microstegium vimineum*), herbs (e.g., garlic mustard, *Alliaria petiolata*), and vines (e.g., kudzu; *Pueraria montana*). On average, over 50% of Indiana's forests have been invaded by non-native plants (Oswalt et al. 2015). Most of these species form dense thickets in the understory that crowd out native plants, alter tree regeneration, and affect wildlife (DiTomaso 2000; Iannone et al. 2015).

3 Indiana climate projections

Downscaled projections of climate change in Indiana indicate that the state is likely to experience warmer, wetter winters and springs, and hotter and drier summers (see Hamlet et al. 2018 for projected maps). Temperatures in Indiana will increase by ~ 5.6 °C by 2080 under the Representative Concentration Pathways (RCP) 8.5 scenario (a high emission–no mitigation scenario; van Vuuren et al. 2011). In southern Indiana, where most of the state's forests occur, maximum daily temperatures are projected to exceed 35 °C for ~ 100 days per year under the RCP 8.5 scenario by 2080 (Hamlet et al. 2018). Although higher annual precipitation is also predicted to occur across the state under the RCP 8.5 scenario, most of the increases are projected to occur in the winter and spring (25–30% increase) rather than in the summer and fall (1–7% decline), thereby placing extra stress on forests (Hamlet et al. 2018). As such, water stress is likely to be particularly acute for trees in this region. Given the known sensitivities of trees to climate (Francl 2001), the primary climate-related changes to Indiana's forests may be (1) increases in pathogen-related diseases associated with high precipitation in the spring and potential flooding (Bratkovich et al. 1994) and (2) decreases in carbon uptake and forest productivity owing to the greater frequency and severity of droughts during the latter periods of the growing season (D'Orangeville et al. 2018). Moreover, some of these changes may lead to other disturbances. Hotter and drier summers can increase the frequency of natural (i.e., non-intentional) fires, and warmer winters may increase the frequency of ice storms, which tend to occur when air temperatures oscillate just above freezing during the day but below freezing at night. Moreover, changes in climate must be considered in light of other global changes such as nitrogen (N) deposition (wet deposition of ammonium and nitrate in Indiana is the highest in the nation; National Atmospheric Deposition Program 2018) and invasive species, which also pose a significant threat to Indiana forests and their sensitivity to climate change.

4 Specific climate change impacts

4.1 Tree species

Climate change is likely to impact species composition in Indiana forests, with the magnitude of these effects depending on the location and climate forcing. Empirical studies conducted at the regional scale indicate that the impacts of climate change (especially changes in precipitation) on tree species depend in large part on species' traits and evolutionary history (Fei et al. 2017). Notably, under RCP 4.5 (Thomson et al. 2011) and RCP 8.5 (medium and high emission scenarios, respectively) and across all three geographic regions, increases in species suitable habitat (owing to more favorable climate) are predicted to outpace habitat losses (Table 1), which could benefit overall tree species diversity if species are able to capitalize on these gains. Overall, suitable habitat is expected to decline for between 17 and 29% of trees and increase for between 43 and 52% of trees in the state depending on the region and climate prediction scenario. Species projected to experience declines in suitable habitat include American basswood (*Tilia americana*), American beech (*Fagus grandifolia*), bigtooth aspen (*Populus grandidentata*), butternut (*Juglans cinerea*), and eastern white pine (*Pinus strobus*). Species that are predicted to gain suitable habitat include black hickory (*Carya texana*), blackjack oak (*Quercus marilandica*), cedar elm (*Ulmus crassifolia*), loblolly pine (*Pinus taeda*), and water oak (*Quercus nigra*)—many of which are not currently native to Indiana (see Electronic Supplementary Material [ESM] Appendix for species projections).

4.2 Wildlife

Changes in the distribution and abundances of tree species can affect wildlife, as many animal species rely on specific plant species as food sources and habitat. For example, Indiana bats (*Myotis sodalis*) use tree species such as shagbark hickory (*Carya ovata*) for maternity

Table 1 Number of tree species that are projected to change by the year 2100 according to the Climate Change Tree Atlas (Prasad et al. 2014)

Trend	Northern Moraine		Central Till Plains		Southern Hills	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Decrease[a]	9	15	10	11	16	20
No change[b]	17	14	19	21	20	13
Increase[a]	24	22	30	26	33	36
New habitat[c]	17	14	19	21	20	13

RCP, Representative Concentration Pathways model scenario (model 4.5 is a medium emission–no mitigation scenario; model 8.5 is a high emission–no mitigation scenario)

Species-specific projections are detailed in the Electronic Supplementary Material Appendix

[a] "Decrease" and "Increase" refer to the number of tree species whose suitable habitats are projected to change (decrease or increase, respectively) by > 20% under a given climate scenario (RCP 4.5 vs. 8.5) in each physiographic region

[b] "No change" refers to the number of species whose suitable habitat are projected to change by < 20%

[c] "New habitat" refers to the number of tree species not currently present that are projected to gain newly suitable habitat in the region

colonies. If shagbark hickory populations decline, as is projected to occur in the northern and southern regions of the state under RCP 8.5 (ESM Appendix), the impacts on Indiana bats could be detrimental. Similarly, projected increases in suitable habitat for many oak species across the state under RCP 4.5 and RCP 8.5 (ESM Appendix) could benefit wildlife that feed on acorns (e.g., mice, wood rats, and deer). Rising spring temperatures have also been linked to elevated acorn production (Caignard et al. 2017), indicating that the combined effects of more oak trees and greater seed production could increase the populations sizes of wildlife that depend on oaks as their primary food source. Ultimately, the vulnerability of wildlife species to climate change will not only be a function of their habitat requirements and population size, but also of their adaptive capacity (i.e., their ability to associate with new species and disperse into newly suitable habitats; Pearson et al. 2014).

Changes in temperature and precipitation may directly influence the ranges of wildlife species in the state. Wildlife species that were previously constrained by their tolerance for colder winters may find more suitable habitat in Indiana owing to warming temperatures. For example, evening bats (*Nycticeius humeralis*), which have been shifting their distributions across the state to fill vacant niches created by the loss of other bat species to white nose syndrome and wind energy developments, may continue their northward expansion as temperatures rise. However, warming may also enhance overwinter survival for the current population of cave bats (Maher et al. 2012). It is also worth noting that range expansion or contraction owing to climate change may hinge on land use (Oliver and Morecroft 2014). The northern limit of the swamp rabbit (*Sylvilagus aquaticus*), one of Indiana's most endangered mammals, is in southern Indiana. However, swamp rabbits are strongly associated with bottomland forests and rivers (Zollner et al. 2000), and the vast majority of areas that could become suitable habitat are currently in agriculture. Thus, changes in climate may have little impact on the movement of species that have narrowly defined niches.

Changes to phenology owing to climate change may alter resource availability and disrupt wildlife population dynamics. Migrating bird species synchronize their arrival at breeding grounds with pulses of emerging insect prey that they require for successful reproduction (Dunn and Winkler 1999), but under climate change, this synchrony may be disrupted. Mammals, whose populations strongly depend on masting events (e.g., such as woodrats and mice) may have their cycles disrupted by changes in climate, with consequences for other members of the forest community. Mice of the genus *Peromyscus*, which are linked to mast years in oak trees, also strongly impact the prevalence of Lyme disease (Ostfeld et al. 2006).

Finally, increases in the frequency and duration of biotic disturbances (e.g., pests and pathogens) or abiotic disturbances (e.g., floods or droughts or fires) are likely to have strong effects on wildlife, especially if the structural characteristics of the forests are affected and early successional conditions occur. Currently, a majority of Indiana's forests are 50–80 years old, and so increases in age-class diversity owing to the greater frequency and intensity of disturbances could benefit many wildlife species. Moreover, pulses in the number of snags created by invasive insects, such as the emerald ash borer, could increase the quality of summer maternity roosting habitat for bats (Carter and Feldhamer 2005).

4.3 Ecosystem services

Forests provide myriad ecosystems services, many of which are likely to be altered by climate change. Supporting services, such as nutrient recycling, primary production, and soil formation, are likely to be affected. Shifts in forest composition are also likely to impact provisioning services (Walters et al. 2012). Oaks, which are the primary timber and mast-producing species in the state, may not decline with climate change per se, but they have been declining in abundance over the past several decades owing to a lack of regeneration due to management practices that do not create conditions for oak regeneration. The populations of some hickory species, which are also a large component of Indiana's timber industry, are expected to decline, while others increase in habitats, depending on location and scenario. Sugar maple, northern red oak (*Q. rubra*), black cherry (*Prunus serotina*), black walnut (*Juglans nigra*), and yellow-poplar—also important timber species—are projected to decline in the southern parts of the state but may increase in some areas due to the limited oak regeneration. Species that may increase in abundance (Brandt et al. 2014; ESM Appendix) include sweetgum (*Liquidamber styraciflua*), which is used for flooring, furniture, veneers, and other lumber applications and pecan (*Carya illinoinensis*), which is used for pecan nut production.

Christmas tree sales are a \$12.5 million industry in Indiana (Bratkovich et al. 2007), and declines in this sector owing to climate change can be anticipated. Many species of Christmas trees, especially young seedlings, do not tolerate drought or extremely wet conditions, and are also susceptible to diseases from being planted close together in monoculture. Scotch pine (*Pinus sylvestris*) and white pine (*Pinus strobus*) are the predominant Christmas trees grown, and projections suggest that habitat suitability for white pine will be dramatically reduced (Brandt et al. 2014; ESM Appendix).

Another non-timber forest product in Indiana that may be affected by climate change is the \$0.6 million per year maple syrup industry (Matthews and Iverson 2017). While maple trees are predicted to decrease in some parts of the state and increase in others, changes in climate can directly affect sap production. Sap flow is driven by temperatures that fluctuate around the freezing point in the late winter or early spring. As spring temperatures increase, the prime season for syrup production may shift to earlier in the season, and the number of sap flow days could eventually decrease in areas at the southern extent of the species' range (Skinner et al. 2010).

Several regulating ecosystem services are likely to be affected by climate change. The benefits of longer growing season and CO_2 fertilization may be offset by an increase in physical and biological disturbances, leading to increases in carbon storage and sequestration in some areas and decreases in others (Hicke et al. 2011). In this region, mesic hardwood forests, dominated by species such as sugar maple and American beech, tend to be the most carbon dense (i.e., have greater amounts of carbon per acre), so declines in these species may also lead to decreased carbon storage in these forests (Brandt et al. 2014). The majority of forest land in the area is dominated by oak and hickory species, which are projected to persist on the landscape; however, as these trees age (especially oaks) and limited regeneration occurs (due to deer browsing, invasive species, fire suppression, and management inaction), the forest is likely to undergo "mesophication" (sensu Nowacki and Abrams 2008). Thus, in many parts of the state, tulip poplar and sugar maple are poised to become canopy dominants. Both of these species may result in declines in water quality, as the soil bacteria that typically associate with these trees can convert soil nitrogen to its mobile form nitrate (Phillips et al. 2013), which pollutes waterways and groundwater. Moreover, given the lower drought tolerance of these tree species (D'Orangeville et al. 2018), droughts of the future may have larger impacts on forest productivity (Brzostek et al. 2014).

Cultural ecosystem services will almost certainly be affected by climate change, most of which will likely be positive. Warmer springs and falls may improve conditions for outdoor recreation activities, such as camping, boating, and kayaking (Nicholls 2012). Lengthening of the spring and fall recreation seasons may have implications for staffing, especially for recreation-related businesses that rely on student labor that will be unavailable during the school year (Nicholls 2012). A recent study suggests that climate conditions during the summer will become unfavorable for tourism in the region by mid-century under a high emissions scenario (Nicholls 2012). Under that scenario, the number of extremely hot days is projected to increase significantly, which could reduce demand for camping facilities and make outdoor physical activity unpleasant or potentially dangerous to sensitive individuals at the peak of summer. Climate can also have important influences on hunting and fishing. The timing of certain hunting or fishing seasons correspond to seasonal events, which are partially driven by climate. Waterfowl hunting seasons, for example, are designed to correspond to the times when birds are migrating south in the fall.

5 Impacts of changing climate on biological stressors

The degree to which climate change will affect the proliferation of invasive species is poorly known (Simberloff 2000). As with other Midwestern states, Indiana forests have already been widely invaded by exotic species (Oswalt et al. 2015), and climate change can further worsen the invasion problem. For example, even though Japanese stiltgrass reproduction is inhibited during drought years, its large, long-lived seedbank enables it to recover in wetter years (Gibson et al. 2002). In addition, deer herbivory of native vegetation following a drought event can maintain the dominance of stiltgrass (Webster et al. 2008). Other species, such as garlic mustard, are not particularly drought tolerant and may fare worse if summer drying increases (Byers and Quinn 1998).

Changes in climate may allow some invasive plant species to survive farther north than they had previously. For example, kudzu is an invasive vine that has degraded forests in the southeastern USA. Economic damage to managed forests and agricultural land is estimated at $100 to $500 million per year (Blaustein 2001). The current northern distribution of kudzu is limited by winter temperature, and modeling studies suggest kudzu habitat suitability may increase in Indiana with warmer winters (Jarnevich and Stohlgren 2009; Bradley et al. 2010). Privet species (*Ligustrum sinense; L. vulgare*) are invasive shrubs that crowd out native species and form dense thickets. While some populations have already established in Indiana, model projections suggest that the risks for further privet invasion may be even greater than that of kudzu by the end of the century (Bradley et al. 2010). According to this analysis, areas in south-central Indiana are projected to be most susceptible to invasion, based on the predicted increase in suitable habitat. In addition, other currently uncommon invasive species may greatly increase in abundance as more habitats become available under future climate.

Insect pests may benefit from projected climate changes. Many insects and their associated pathogens are exacerbated by drought, including the forest tent caterpillar, hickory bark beetle and its associated canker pathogen, bacterial leaf scorch, and Diplodia shoot blight (U.S. Forest Service 1985; Babin-Fenske and Anand 2011; Park et al. 2013). High spring precipitation has been associated with severe outbreaks of bur oak blight in Iowa (Harrington et al. 2012). Projections of gypsy moth population dynamics under a changing climate suggest substantial increases in the probability of spread in the coming decades, which could put at risk oak species that would otherwise do well under a changing climate (Logan et al. 2007). However, wetter springs could curtail its spread to some extent, as fungal pathogens of the larvae have been shown to reduce populations in years with wet springs (Andreadis and Weseloh 1990). In addition, future northward range expansion attributed to warming temperatures has been projected and documented for southern pine beetle (Ungerer et al. 1999; Lesk et al. 2017), which is likely to become a problem for southern pines, like shortleaf pine, in the region.

Climate changes could also predispose already vulnerable species to further losses from invasive pests. Eastern hemlock (*Tsuga canadensis*), while relatively uncommon in Indiana, occurs in cliffs and canyons around the state where cool, moist conditions prevail. As temperatures rise, these remnant populations may become increasingly stressed and hence vulnerable to pests such as the hemlock woolly adelgid (*Adelges tsugae*). There is no evidence that the adelgid is currently in Indiana, but it has been reported in the neighboring states of Ohio and Kentucky. Given that the woolly adelgid is dispersed by migrating animals and human activities, the potential for populations to move into Indiana is likely. However, predicting how the adelgid and climate change will interact to affect the state's hemlock populations is challenging. Milder winters can provide more suitable conditions for the adelgid (Dukes et al. 2009), whereas hotter summers can provide less suitable conditions (Mech et al. 2018). Thus, the combination of several factors, including adelgid dispersal rates, the degree of climate change, and the size of hemlock populations, will determine the degree to which hemlocks in the state are affected by climate change.

6 Management implications and case study

Changes in climate will create new challenges and exacerbate existing challenges for managing Indiana's forests. Although many forest types in Indiana appear to be adapted to current and future climate, the health of individual stands or species may decline due to changes in temperature and precipitation and the expansion of invasive plants and pests (Brandt et al. 2014). Drier conditions during some seasons and longer summer droughts may increase the potential for wildfire. Natural summer ignitions are quite rare in Indiana, as nearly all summer lightning storms include precipitation (Soula 2009). However, elevated severe droughts may allow more human-caused ignitions, either accidental or deliberate, and would likely lead to larger fires, particularly if ignitions occur in the late summer and early fall when understory vegetation is senescing, thereby increasing forest management cost and difficulty. On the other hand, changes in climate may also affect the timing and opportunities to use prescribed fire as a management tool. Typically, most prescribed burns happen during a narrow window of time in the early spring, when the conditions (primarily moisture content) are best suited for ignition. Increases in spring precipitation (Hamlet et al. 2018) would shorten these burn windows significantly. This could be compounded by restrictions to conducting prescribed burns that pose threats to certain threatened and endangered species, similar to current restrictions on timing and intensity of forest harvesting (Bergeson et al. 2018). Decreases in or absence of snowpack may create opportunities for more prescribed burning during dormant months, but reduced drying time and shorter daylength often keeps fuels too moist to achieve fire prescription goals.

Forest harvesting will become more challenging because harvest windows will also likely become narrower. Currently, winter conditions uncommonly freeze soils deep enough to support heavy harvesting equipment in the southern half the state; projected warmer winters will likely lead to unfrozen soils statewide, at least in some years. Summer harvesting, conversely, may become increasingly limited by restrictions to protect threatened and endangered species (Bergeson et al. 2018). Increased winter harvesting on unfrozen ground and higher frequency of heavy precipitation events across the region will likely increase erosion, especially on steeper slopes (Nearing 2001; Nearing et al. 2004). Increased use of best management practices, such as water bars and other diversion structures, will be necessary on skid trails and forest roads; culvert sizes will likely need to be increased and fords and other stream crossings reinforced for higher stream flows. Unfortunately, many of these voluntary practices will not occur on private lands due to lack of incentives (Indiana Department of Natural Resources 2005).

Nevertheless, potential management strategies and actions can be taken to adapt forests to the effects of climate change (Swanston et al. 2016). Resistance strategies can include protecting refugia and reducing existing environmental stressors. Resilience strategies can include restoring natural disturbance regimes and enhancing structural, age class, species, and genetic diversity. Transition strategies can include favoring tree populations, species, communities, and/or forest types that are likely to be best adapted to future conditions. However, no one approach will be feasible everywhere; it will take a combination of stand-level to landscape-level strategies (see Janowiak et al. 2014) based on the goals and timeframe of the management activities. Nationally, research is ongoing for developing region-specific strategies for forest managers, either by silvicultural treatments increasing ecosystem resistance or resilience to climate change, or actively transitioning the system to a new condition (Nagel et al. 2017).

6.1 Case study: Adapting bottomland hardwood forests to climate change

Here, we present a case study of adaptation to climate change in the Patoka River National Wildlife Refuge (NWR) and Management Area , which was established in 1994. The area currently encompasses 2670 ha (with an ultimate acquisition area of 9200 ha) of wetlands, floodplain forest, and uplands along 48 km of the Patoka River corridor in southwest Indiana. The refuge provides habitat for migratory waterfowl and other wildlife species. Areas along the Patoka river are being restored to bottomland forest and other ecosystems to improve water quality and provide wildlife habitat and recreation opportunities.

In 2015, the Patoka River NWR, along with partners at Ducks Unlimited, the Shawnee National Forest, Illinois Department of National Resources, and the Cypress Creek NWR, came together for a workshop to assess the vulnerabilities of bottomland forests in their region and to appropriately develop adaptation strategies. The workshop was facilitated by the Northern Institute of Applied Climate Science using the Forest Adaptation Resources Adaptation Workbook (Swanston et al. 2016). Information on climate change impacts and vulnerabilities was provided by the Central Hardwoods Ecosystem Vulnerability Assessment and Synthesis (Brandt et al. 2014). The assessment included projected changes in tree habitat by ecological section (Iverson et al. 2008), as well as vulnerability ratings and summaries by ecological community that synthesized multiple model results, observational data, and expert opinion (Brandt et al. 2017; Iverson et al. 2017). A primary concern for the Refuge is increased flood duration and severity from projected increases in heavy rain events during the growing season.

As an outcome of the workshop, Ducks Unlimited applied for and received funding from the Wildlife Conservation Society's Adaptation Fund to adapt bottomland hardwood forest management to changes in climate, including on the Patoka River NWR. The Refuge consulted model projection information from the Climate Change Tree Atlas (Iverson et al. 2008; Prasad et al. 2014) to identify flood-adapted species that could potentially gain habitat in the area. Managers included new potential migrants in approximately 10% of their planting mix, including black oak (*Quercus nigra)* and willow oak (*Quercus phellos)*, two oak species native to the southern USA that are expected to gain new habitat in the area in the coming decades according to model projections. They also included Nuttall oak (*Quercus nuttallii*), which is native to floodplains in southeastern Missouri and areas south. This species did not have projected gains in suitable habitat for Indiana, but had ecological characteristics that suggest it could be a good candidate. In addition to these new species, the Refuge also included species that are native to floodplain forests in Indiana that are likely to tolerate increases in flooding, including bur oak (*Quercus macrocarpa)*, shellbark hickory (*Carya laciniosa*), cherrybark oak (*Quercus pagoda*), swamp chestnut oak (*Quercus michauxii*), and overcup oak (*Quercus lyrata*). Bald cypress (*Taxodium distichum*), which is native to cypress swamps in far southwestern Indiana, was planted in areas expected to experience the most flooding.

The Refuge planted saplings at a density of 500 trees per hectare in an area identified for bottomland hardwood restoration along the Patoka River in summer 2017. In addition to adjusting its planting mix, the Refuge also planted the most flood-tolerant species at higher benches in the floodplain than they had previously. Shortly after planting, the restoration area experienced an uncharacteristic summer flood. Sapling survival following the flood was higher than expected, and the refuge will be monitoring survival over the coming years and replacing saplings as needed.

Refuge managers noted that this was the first time they explicitly incorporated a climate change vulnerability assessment and future habitat suitability projections into their restoration efforts. It allowed them to think differently about species selection and enhance their diversity by including some species that they had not considered previously. Long-term monitoring will be needed in order to determine the long-term survival of newly planted species and other ecological implications of this project.

7 Concluding remarks

Regardless of the emission scenario or geographic region considered, projected climate changes for Indiana—warmer, wetter springs followed by hotter, drier summers—will likely have profound impacts for Indiana's forests. These include direct impacts on forest composition and indirect impacts on wildlife and understory communities. Such impacts, in addition to changes resulting from other human activities (e.g., nitrogen deposition, rising atmospheric CO_2 and ozone, forest fragmentation), threaten to compromise many of the vital ecosystem services that these forests provide. However, isolating and identifying the drivers of change is important, as it will better inform land managers and policy makers on how to slow or halt the most undesirable changes. And while the adoption of proactive management practices may improve the sustainability and resilience of Indiana's forests under these stressors, it is important to acknowledge that such practices can only be made in light of the goals that forest managers are trying to achieve. Thus, there are limits to how much management can counterbalance some of the detrimental ecosystem consequences of climate change.

To enhance our understanding on the direct and indirect impacts of climate change on Indiana's forests, better model projection and monitoring efforts are needed. More specifically, we need comprehensive, adaptive, and more realistic models that incorporate climatic factors and other stressors (e.g., land use change, fire regime shift, and pest outbreaks) with a systems-based approach that integrates across interspecific interactions, inter-trophic level interactions, and above- and below-ground interactions) to better predict the changes in species and community-level vegetation patterns and processes. We also need long-term monitoring efforts that can illuminate how Indiana's forests are responding to climate change and other stressors, and the consequences of these changes for ecosystem services such as water regulation, carbon sequestration, and forest products. Finally, we need more case studies, such as the aforementioned study in the Patoka River NWR and Management Area. Such applied efforts can provide land managers and policy-makers with new strategies and tools that can support adaptive management practices which enhance the resiliency of Indiana forests. Taking these steps will help ensure that the benefits Indiana's forests provide are sustained into the future.

In conclusion, climate change has and will continue to have strong ecological and economic impacts on forest ecosystems in Indiana and beyond. Important potential impacts include but not limited to: (1) acute water stress from spring flooding and growing season drought and (2) reduced climate suitability for key timber species, such as northern red oak, yellow-poplar, and sugar maple. Proactive and adaptive management actions are needed to enhance forest resilience to future climate change.

Acknowledgements We thank guest editor Jeff Dukes and two anonymous reviewers who provided helpful feedback on the manuscript. We also thank Stephen Shifley and many stakeholders for reviewing and commenting on earlier versions. We are indebted to several other members of the Northern Institute of Applied Climate Science, including Matthew Peters, Anantha Prasad, and Steven Matthews, for their assistance in preparing data for this project.

References

Andreadis TG, Weseloh RM (1990) Discovery of *Entomophaga maimaiga* in North American gypsy moth, Lymantria dispar. Proc Natl Acad Sci 87(7):2461–2465

Babin-Fenske J, Anand M (2011) Agent-based simulation of effects of stress on forest tent caterpillar (*Malacosoma disstria* Hubner) population dynamics. Ecol Model 222(14):2561–2569

Badè WF (1924) The life and letters of John Muir, vol I. Houghton Mifflin Company, Boston and New York, 399 pages

Bergeson SM, O'Keefe JM, Haulton GS (2018) Managed forests provide roosting opportunities for Indiana bats in south-central Indiana. For Ecol Manag 427:305–316

Blaustein RJ (2001) Kudzu's invasion into southern United States life and culture. In: McNeeley JA (ed) The great reshuffling: human dimensions of invasive species. IUCN, The World Conservation Union, Gland, pp 55–62

Bradley BA, Wilcove DS, Oppenheimer M (2010) Climate change increases risk of plant invasion in the eastern United States. Biol Invasions 12(6):1855–1872

Brandt L, He H, Iverson L, et al. (2014) Central Hardwoods ecosystem vulnerability assessment and synthesis: a report from the Central Hardwoods Climate Change Response Framework project. Gen. Tech. Rep. NRS-124. USDA Forest Service, Northern Research Station, Newtown Square

Brandt LA, Butler PR, Handler SD, Janowiak MK, Shannon PD, Swanston CW (2017) Integrating Science and Management to Assess Forest Ecosystem Vulnerability to Climate Change. J For 115(3):212–221. https://doi.org/10.5849/jof.15-147

Bratkovich S, Burban L, Katovich S, Locey C, Pokorny J, Wiest R (1993) Flooding and its effect on trees. US Dept. of Agriculture, Forest Service, Northern Area State & Private Forestry, Misc. Publ. Newtown Square, PA

Bratkovich S, Gallion, J, Leatherberry E, Hoover W, Reading W, Durham G (2007) Forests of Indiana: their economic importance. OTHER-NA-TP-02-04 USDA Forest Service, North Central Research Station, the US Department of Commerce, the Indiana Department of Commerce, Indiana Department of Natural Resources-Division of Forestry, and Purdue University

Brzostek ER, Dragoni D, Schmid HP, Rahman AF, Sims D, Wayson CA, Johnson DJ, Phillips RP (2014) Chronic water stress reduces tree growth and the carbon sink of deciduous hardwood forests. Glob Chang Biol 20:2531–2539

Butler AW (1896) Indiana: a century of changes in the aspects of nature. Proc Indiana Acad Sci 5:31–42

Byers DL, Quinn JA (1998) Demographic variation in *Alliaria petiolata* (Brassicaceae) in four contrasting habitats. J Torrey Bot Soc 125(2):138–149

Caignard T, Kremer A, Firmat C, Nicolas M, Venner S, Delzon S (2017) Increasing spring temperatures favor oak seed production in temperate areas. Sci Rep 7:8555

Carter TC, Feldhamer GA (2005) Roost tree use by maternity colonies of Indiana bats and northern longeared bats in southern Illinois. For Ecol Manag 219:259–268

D'Orangeville, L., Maxwell, J., Kneeshaw, D., Pederson, N., Duchesne, L., Logan, T., Houle, D., Arseneault, D., Beier, C.M., Bishop, D.A., ,Druckenbrod, D., Fraver, S., Girard, F., Halman, J., Hansen, C., Hart, J.L., Hartmann, H., Kaye M., Leblanc, D., Manzoni, S., Rayback, S., Rollinson, C., R.P. Phillips (2018) Local climate and drought timing determine the sensitivity of eastern temperate forests to drought. Glob Chang Biol 24: 2339-2351

DiTomaso JM (2000) Invasive weeds in rangelands: species, impacts, and management. Weed Sci 48:255–265

Dukes JS, Pontius J, Orwig D, Garnas JR, Rodgers VL, Brazee N, Cooke B, Theoharides KA, Stange EE, Harrington R, Ehrenfeld J, Gurevitch J, Lerdau M, Stinson K, Wick R, Ayres M (2009) Responses of insect pests, pathogens, and invasive plant species to climate change in the forests of northeastern North America: What can we predict? Can J For Res 39:231–248

Dunn PO, Winkler DW (1999) Climate change has affected the breeding date of tree swallows throughout North America. Proc R Soc Lond Biol 266:2487–2490

Evans TP, Kelley H (2008) Assessing the transition from deforestation to forest regrowth with an agent based model of land cover change for South-Central Indiana (USA). Geoforum 39:819–832

Fei S, Steiner KC (2007) Evidence for increasing red maple abundance in the eastern United States. For Sci 53: 473–477

Fei S, Kong N, Steiner KC, Moser WK, Steiner EB (2011) Change in oak abundance in the eastern United States from 1980 to 2008. For Ecol Manag 262:1370–1377

Fei S, Desprez JM, Potter KM, Jo I, Knott JA, Oswalt CM (2017) Divergence of species response to climate change. Sci Adv 3(5):e1603055

Francl LJ (2001) The disease triangle: a plant pathological paradigm revisited. Plant Health Instructor. https://doi.org/10.1094/PHI-T-2001-0517-01

Gibson DJ, Spyreas G, Benedict J (2002) Life history of *Microstegium vimineum* (*Poaceae*), an invasive grass in southern Illinois. J Torrey Bot Soc 129:207–219

Gormanson DD, Kurtz CM (2017) Forests of Indiana (2016) Resource update FS-127. USDA Forest Service Northern Research Station, Newtown Square. https://doi.org/10.2737/FS-RU-127

Hamlet A, Byun K, Robeson S, Widhalm M, Baldwin M (2018) Impacts of Climate Change on the State of Indiana: Future Projections Based on CMIP5. Clim Chang. [note, this publication is part of the same special issue]

Harrington TC, McNew D, Yun HY (2012) Bur oak blight, a new disease on *Quercus macrocarpa* caused by *Tubakia iowensis* sp. nov. Mycologia 104:79–92

Hicke JA, Allen CD, Desai AR et al. (2011) Effects of biotic disturbances on forest carbon cycling in the United States and Canada. Glob Chang Biol 18(1):7–34

Iannone BV, Oswalt CM, Liebhold AM, et al. (2015) Region-specific patterns and drivers of macroscale forest plant invasions. Divers Distrib 21:1181–1192

Indiana Department of Natural Resources (INDNR) (2005) Indiana logging and forestry best management practices. 2005 BMP field guide. https://www.in.gov/dnr/forestry/2871.htm

Indiana Geological Survey (2001) 2001 Land Cover in Indiana, Derived from the National Land Cover Database (NLCD) (United States Geological Survey, 30-Meter Grid), digital representation by Chris Dintaman, 2007

Iverson LR, Prasad AM, Matthews SN, Peters M (2008) Estimating potential habitat for 134 eastern US tree species under six climate scenarios. For Ecol Manag 254:390–406

Iverson LR, Thompson FR, Matthews S, Peters M, Prasad A, Dijak WD, Fraser J, Wang WJ, Hanberry B, He H, Janowiak M (2017) Multi-model comparison on the effects of climate change on tree species in the eastern US: results from an enhanced niche model and process-based ecosystem and landscape models. Landsc Ecol 32(7):1327–1346

Janowiak MK, Swanston CW, Nagel LM, et al. (2014) A practical approach for translating climate change adaptation principles into forest management actions. J For 112(5):424–433

Jarnevich C, Stohlgren T (2009) Near term climate projections for invasive species distributions. Biol Invasions 11(6):1373–1379

Lesk C, Coffe E, D'Amato AW, Dodds K, Horton R (2017) Threats to North American forests from southern pine beetle with warming winters. Nat Clim Chang 7(10):713
Lindsey AA, Crankshaw WB, Qadir SA (1965) Soil Relations and Distribution Map of the Vegetation of Presettlement Indiana. Bot Gaz 126(3):155–163
Logan JA, Régnière J, Gray DR, Munson AS (2007) Risk assessment in the face of a changing environment: gypsy moth and climate change in Utah. Ecol Appl 17(1):101–117
Maher SP, Kramer AM, Pulliam JT, et al. (2012) Spread of white-nose syndrome on a network regulated by geography and climate. Nat Commun 3:1306
Matthews S, Iverson L (2017) Managing for delicious ecosystem service under climate change: can United States sugar maple (*Acer saccharum*) syrup production be maintained in a warming climate? Int J Biodivers Sci Eco Serv Manag 13(2):40–52
Mech AM, Tobin PC, Teskey RO, Rhea JR, Gandhi KJ (2018) Increases in summer temperatures decrease the survival of an invasive forest insect. Biol Invasions 20:365–374
Moran EF, Ostrom E (2005) Seeing the forest and the trees: human-environment interactions in forest ecosystems. MIT Press, Cambridge
Nagel LM, Palik BJ, Battaglia MA, et al. (2017) Adaptive Silviculture for climate change: a national experiment in manager-scientist partnerships to apply an adaptation framework. J For 115(3):167–178
National Atmospheric Deposition Program (NRSP-3) (2018) NADP Program Office, Wisconsin State Laboratory of Hygiene, Madison. Available at http://www.natureserve.org/explorer. Accessed 11 Feb 2013
Nearing MA (2001) Potential changes in rainfall erosivity in the U.S. with climate change during the 21st century. J Soil Water Conserv 56(3):229–232
Nearing MA, Pruski FF, O'Neal MR (2004) Expected climate change impacts on soil erosion rates: a review. J Soil Water Conserv 59(1):43–50
Nicholls S (2012) Outdoor recreation and tourism. In: Winkler J, Andresen J, Hatfield J, Bidwell D, Brown D (eds) US National Climate Assessment Midwest technical input report. Available at http://glisa.msu.edu/docs/NCA/MTIT_RecTourism.pdf. Accessed 15 May 2013
Nowacki GJ, Abrams MD (2008) The demise of fire and "mesophication" of forests in the eastern United States. BioSci 58(2):123–138
Oliver TH, Morecroft MD (2014) Interactions between climate change and land use change on biodiversity: attribution problems, risks and opportunities. Clim Chang 5:317–335
Ostfeld RS, Canham CD, Oggenfuss K, Winchcombe RJ, Keesing F (2006) Climate, deer, rodents, and acorns as determinants of variation in Lyme-disease risk. PLoS Biol 4(6):0040145
Oswalt CM, Fei S, Guo Q, et al. (2015) A subcontinental view of forest plant invasions. NeoBiota 24:49–54
Park J-H, Juzwik J, Cavender-Bares J (2013) Multiple *Ceratocystis smalleyi* infections associated with reduced stem water transport in bitternut hickory. Phytopathology 103(6):565–574
Parker GR (1997) The wave of settlement. In: Jackson MT (ed) The natural heritage of Indiana. Indiana University Press, Bloomington, pp 369–382
Parker GR, Ruffner CM (2004) Current and historical forest conditions and disturbance regimes in the Hoosier–Shawnee ecological assessment area. In: Thompson, FR III (ed) The Hoosier–Shawnee ecological assessment. Gen. Tech. Rep. NC-244. USDA Forest Service, North Central Research Station, St. Paul, p 23–58
Pearson RG, Stanton JC, Schoemaker KT, (2014) Life history and spatial traits predict extinction risk due to climate change. Nat Clim Chang 4:217–221
Phillips RP, Midgley MG, Brzostek E (2013) The mycorrhizal-associated nutrient economy: A new framework for predicting carbon-nutrient couplings in forests. New Phytol 199:41–51
Prasad AM, Iverson LR, Peters MP, Matthews SN (2014) Climate change tree atlas. Northern Research Station, US Forest Service, Delaware. http://www.nrs.fs.fed.us/atlas
Ridgway R (1972) Notes on the vegetation of the Lower Wabash Valley. Am Nat 6:724–732
Simberloff D (2000) Global climate change and introduced species in United States forests. Sci Total Environ 262:253–261
Skinner CB, DeGaetano AT, Chabot BF (2010) Implications of twenty-first century climate change on northeastern United States maple syrup production: impacts and adaptations. Clim Chang 100(3-4):685–702
Soula S (2009) Lightning and precipitation. In: Betz HD, Schumann U, Laroche P (eds) Lightning: principles, instruments and applications. Springer, Dordrecht
Swanston CW, Janowiak MK, Brandt LA, et al. (2016) Forest adaptation resources: climate change tools and approaches for land managers, 2nd ed. NRS-GTR-87-2. USDA Forest Service, Northern Research Station, Newtown Square. https://doi.org/10.2737/NRS-GTR-87-2
Thomson AM, Calvin KV, Smith SJ, Kyle GP, Volke A, Patel P, Delgado-Arias S, Bond-Lamberty B, Wise MA, Clarke LE (2011) RCP4. 5: a pathway for stabilization of radiative forcing by 2100. Clim Chang 109:77
Ungerer MJ, Ayres MP, Lombardero M (1999) Climate and the northern distribution limits of *Dendroctonus frontalis* Zimmermann (Coleoptera: Scolytidae). J Biogeogr 2:1133–1145

US Department of the Interior, US Fish and Wildlife Service, and US Department of Commerce, US Census Bureau (2011) National survey of rishing, hunting, and wildlife-associated recreation. Available at https://www.census.gov/prod/2013pubs/fhw11-in.pdf. Accessed 22 Feb 2018

US Forest Service (1985) Insects of eastern forests. Misc. Publ. 1426. Washington, DC, USDA Forest Service

US Forest Service (2006) Final environmental impact statement, land and resource management plan Hoosier National Forest. Bedford, Hoosier National Forest

van Vuuren DP, Edmonds J, Kainuma M et al (2011) The representative concentration pathways: an overview. Clim Chang 109:5

Walters BF, Settle J, Piva RJ (2012) Indiana timber industry: an assessment of timber product output and use, 2008. Resour Bull NRS-63. USDA Forest Service, Northern Research Station, Newtown Square

Webster CR, Rock JH, Froese RE, Jenkins MA (2008) Drought–herbivory interaction disrupts competitive displacement of native plants by Microstegium vimineum, 10-year results. Oecologia 157(3):497-508

Zollner PA, Smith WP, Brennan LA (2000) Home range use by swamp rabbits (*Sylvilagus aquaticus*) in a frequently inundated bottomland forest. Am Midl Nat 143:64–69