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

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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 forests 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 find 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 biotic communities of the past or present. Overall, suitable habitat is expected to decline for 17-29 percent of tree species and increase for 43-52 percent 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 forests resources and products (both timber and non-timber). 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.

Keywords: Indiana, climate change, species shift, Tree Atlas, forest composition, forest ecosystem services

I. Introduction

Forests provide food and habitat to a rich assemblage of animals and microorganisms, and 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 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 2016). The vast majority of the forest (~84%) is privately owned, with the remaining forest ownership split between local, state, and Federal government government (Goramson 2016). 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 GDP; 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 - 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.

II. 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 18th and 19th centuries. Nearly 90% of Indiana was 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; **Figure 1**). This 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 20th 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) 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 it to 160 to 200 ft. (Ridgway, 1872).

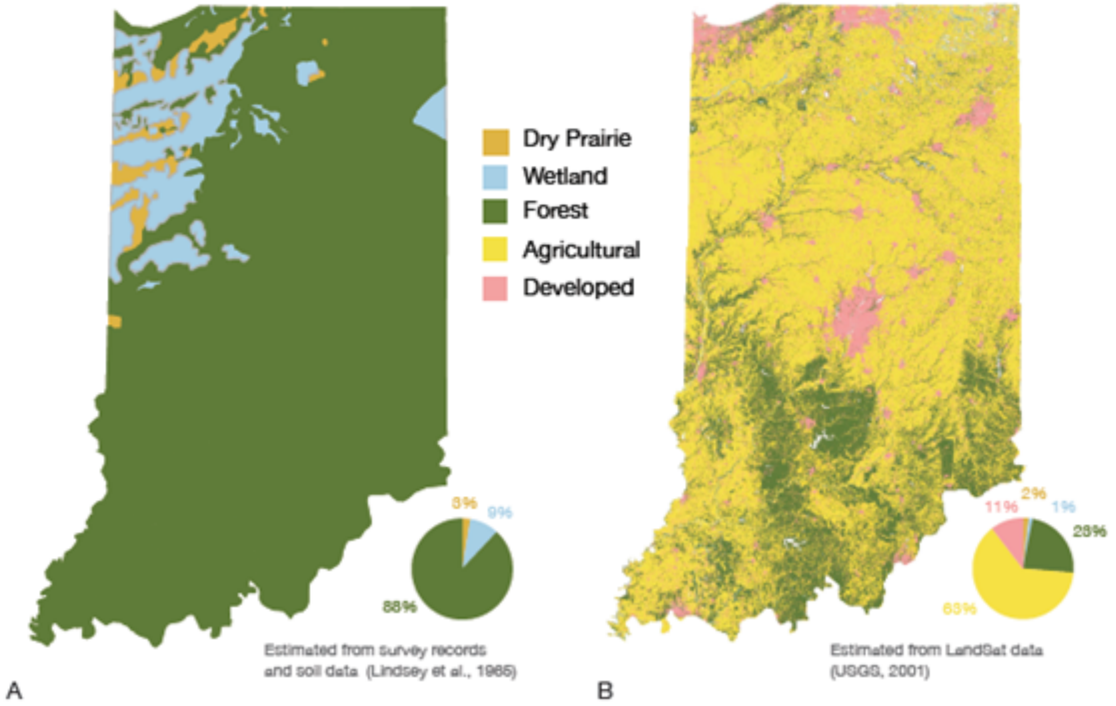

Figure 1. Indiana vegetation cover, then and now. A. Major biome cover as it would have been in approximately 1820 reconstructed from analysis of land survey office records and associated soil types (Lindsey *et al.*, 1965). Wetlands in the northwest were associated with prairie vegetation and those 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).

As land clearing and widespread burning became less common by the mid-20th century, much of the abandoned agricultural land reverted back to forest naturally (U.S. Forest Service 2006). During the early to mid 20th 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 Ostrum 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 Statewide Forest Assessment, 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 high light environments. 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 percent 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.

III. 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 RCP 8.5 scenario (a high emission-no mitigation scenario; Riahi 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 winter and spring (25-30% increase), rather than in 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 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 spring precipitation and 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.

IV. Specific climate change impacts

Tree Species

Climate change is likely to impact species composition in Indiana forests, with the magnitude of these effects depending on 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), whereas the impacts of droughts depend on site factors and drought timing (D'Orangeville et al. 2018). 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 percent of trees and increase for between 43 and 52 percent 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 cinera*) 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 Appendix for species projections).

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). "Decrease" and "Increase" refer to the number of tree species whose suitable habitats are projected to change (decrease or increase) by more than 20% under a given climate scenario (RCP 4.5 vs. 8.5) in each physiographic region. "No change" refers to the number of species whose suitable habitat are projected to change by less than 20%. "New habitat" refers to the number of tree species not currently present that are projected to gain newly suitable habitat in the region; Species-specific projections are detailed in Appendix 1.

	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	9	15	10	11	16	20
No change	17	14	19	21	20	13
Increase	24	22	30	26	33	36
New habitat	17	14	19	21	20	13

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 species such as shagbark hickory (*Carya ovata*) for maternity colonies. If shagbark hickory populations decline, as is projected to occur in the northern and southern regions of the state under RCP 8.5 (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 (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 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's 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 (Ostefeld 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 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 like emerald ash borer could increase the quality of summer maternity roosting habitat for bats (Carter and Feldhamer 2005).

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. 2008). Oaks, which are the primary timber and mast-producing species in the state, may not decline with climate change *per se*, but have been declining in abundance over the past several decades owing to lack of regeneration due to fire suppression and management practices that don't create conditions for oak regeneration. Some hickory species, which are also a large component of Indiana's timber industry, are expected to decline, while others increase in habitat depending on location and scenario. Sugar maple, 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, 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 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, 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. 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 like 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 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.

V. 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 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 United States. 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 ((Bradley et al. 2010; Jarnevich and Stohlgren 2009). 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 were projected to be most susceptible to invasion, based on the predicted increase in suitable habitat.

Insect pests may benefit from projected climate changes. Many insects and their associated pathogens are exacerbated by drought including forest tent caterpillar, hickory bark beetle and its associated canker pathogen, bacterial leaf scorch, and Diplodia shoot blight (Babin-Fenske and Anand 2011, Park et al. 2013, U.S. Forest Service 1985). 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 establishment in the coming decades (Logan et al. 2003). The spread of the gypsy moth could put at risk oak species that would otherwise do well under a changing climate. 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, 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 how the degree to which hemlocks in the state are affected by climate change.

VI. 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). Additional resources may be required to prevent the spread of invasive species into new areas and control them if they do invade. Consequently, management costs could increase considerably as foresters are forced to control higher abundances of invasive species and use artificial regeneration to enrich severely impacted and depauperate sites.

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, longer, more 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, increasing forest management cost and difficulty. On the other hand, changes in climate may also affect 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 are best suited for igniting biomass. 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 day-length often keeps fuels too moist to achieve fire prescription goals.

Forest harvesting will become more challenging, not only for the reasons mentioned above, but because harvest windows will 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 (BMPs), 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 crossing reinforced for higher stream flows. Unfortunately, many of these practices will not occur on private lands for lack of incentives (INDNR 2005).

Nevertheless, potential adaptation strategies 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 treatments increasing ecosystem resistance or resilience to climate change, or actively transitioning the system to a new condition (Nagel et al. 2017).

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 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 develop suitable 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 National Wildlife Refuge. 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 percent of their planting mix, including black oak (*Quercus nigra)* and willow oak (*Quercus phellos),* two oak species that are native to the southern United States 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 hadn't 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.

VII. 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. Given the dynamic nature of forest ecosystems, it will always be difficult to attribute specific changes to a single driver such as climate change. 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's 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 intrgates 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 study in the Patoka River National Wildlife Refuge and Management Area. Such applied efforts can provide land managers and policy makers with new strategies and tools that can support adaptive management practices that enhance the resiliency of Indiana forests. Taking these steps will help ensure that the benefits Indiana's forests provide are sustained into the future.

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