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Integrating Science and Management to Assess Forest Ecosystem Vulnerability to Climate Change

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We developed the ecosystem vulnerability assessment approach (EVAA) to help inform potential adaptation actions in response to a changing climate. EVAA combines multiple quantitative models and expert elicitation from scientists and land managers. In each of eight assessment areas, a panel of local experts determined potential vulnerability of forest ecosystems to climate change over the next century using EVAA. Vulnerability and uncertainty ratings for forest community types in each assessment area were developed. The vulnerability of individual forest types to climate change varied by region due to regional differences in how climate change is expected to affect system drivers, stressors, and dominant species and the capacity of a forest community to adapt. This assessment process is a straightforward and flexible approach to addressing the key components of vulnerability in a collaborative setting and can easily be applied to a range of forest ecosystems at local to regional scales.

Keywords: climate change vulnerability, climate impact assessment, expert elicitation, adaptive capacity, uncertainty, climate change adaptation

Shifts in global climate are affecting forested ecosystems in the United States and will likely become more severe over the next century (Vose et al. 2012, Grimm et al. 2013). Forest managers in the United States have begun to develop processes that reduce risks and take advantage of opportunities while adapting to climate change (Bosworth et al. 2008, Joyce et al. 2009, Littell et al. 2012, Janowiak et al. 2014b). Climate change adaptation in natural resource management generally involves the identification of climate change impacts on an area, assessment of vulnerability of species or ecosystems to the projected impacts, development of adaptation strategies, and incorporation of adaptation strategies into on-the-ground management (Cross et al. 2012, 2013, Swanston and Janowiak 2012, Stein et al. 2014).

Vulnerability assessments are essential for identifying which species are at risk in a changing climate. Vulnerability is generally defined as the degree to which a system is susceptible to and unable to cope with the adverse effects of climate change (Intergovernmental Panel on Climate Change [IPCC] 2007). A forest ecosystem can be considered vulnerable if it is susceptible to a reduction in health and productivity or a change in species composition that would alter its fundamental identity (Brandt et al. 2014). Climate change vulnerability can be defined as a function of a system's exposure, sensitivity and adaptive capacity (Glick et al. 2011, Stein et al. 2014). Exposure includes the direct and indirect effects of climate change on an area, such as changes in temperature, precipitation, extreme weather, and fire; sensitivity is the extent to which a species or ecosystem responds to those changes (Glick et al. 2011, Stein et al. 2014). Together, exposure and sensitivity can be combined into "impacts." We define impacts as the direct and indirect consequences (either positive or negative) of climate change on systems (Brandt et al. 2014). Def-

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initions of adaptive capacity in the natural resource management community vary widely (Nicotra et al. 2015). We define adaptive capacity as the ability of a species or ecosystem to accommodate or cope with potential climate change impacts with minimal disruption (IPCC 2007), focusing on the ecological and geophysical attributes of the system, such as species and genetic biodiversity, tolerance of disturbance, and connectivity. However, others may include organizational capacity or social or economic factors in their assessment of adaptive capacity (Brown 2009, Johnston and Hesseln 2012).

A variety of frameworks for assessing vulnerability of forests and other terrestrial ecosystems have been developed (for a review, see Staudinger et al. 2015). Some assessment frameworks are complex and rely on quantitative approaches that require a high level of skill for implementation (e.g., Nitschke and Innes 2008, Lexer and Seidl 2009), making them beyond the technical expertise or financial resources of many forest managers. Other frameworks provide simple, highly structured numerical index approaches for assessing vulnerability (e.g., Comer et al. 2012, Manomet Center for Conservation Sciences and the National Wildlife Federation [Manomet and NWF] 2012). These frameworks can be more user-friendly, but the highly structured framework could be a hindrance to some managers who may wish for more flexibility in their assessments.

Involving managers throughout the process is essential to ensuring that the assessment is relevant to management decisions (Stein et al. 2014). Collaboration and stakeholder involvement ensures that assessments address the issues managers are most concerned about and that local expertise that may not be in the peer-reviewed literature is incorporated. However, despite this recognition, most ecosystem-scale assessment frameworks have limited engagement of managers to only parts of the assessment process (Nitschke and Innes 2008, Lexer and Seidl 2009, Comer et al. 2012, Manomet and NWF 2012). This may reduce transparency and thus the likelihood that the framework could be applied by practitioners.

We developed a simple collaborative method for assessing the vulnerability of forest ecosystems to climate change that engages forest managers throughout the process. This method was designed to be flexible enough that it could be applied to multiple locations and scales by forest managers, with the ultimate goal of application to climate change adaptation in forest management. We describe this method and its application to eight geographic areas, totaling 252 million acres, across the Midwestern and Eastern United States.

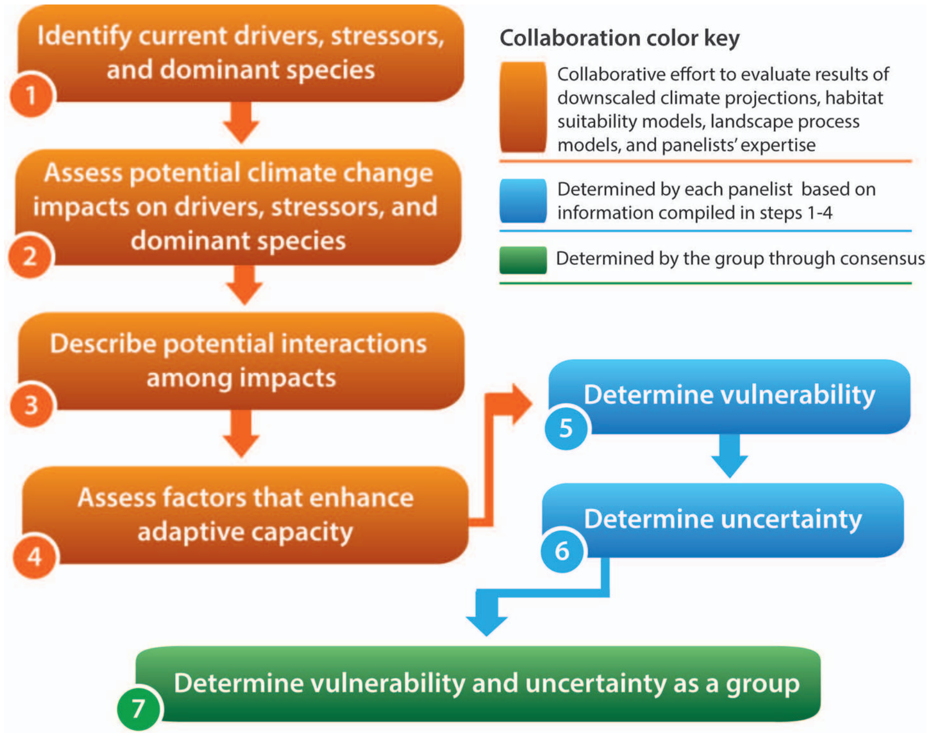

Figure 1. Seven-step vulnerability assessment process. Current conditions and potential impacts are assessed for drivers, stressors, and dominant species, followed by interactions among impacts. The adaptive capacity of each system is assessed. Adaptive capacity factors are combined with impacts to determine vulnerability and then uncertainty by each panelist. The group then determines both vulnerability and uncertainty based on group discussion of individual determinations.

EVAA: Ecosystem Vulnerability Assessment Approach

We developed EVAA (Figure 1), building on lessons learned from a pilot assessment in northern Wisconsin (Swanston et al. 2011). EVAA incorporates elements of the nominal group technique, a structured expert consensus process (Delbecq and Van de Ven 1971, Van de Ven and Delbecq 1974). EVAA consists of 7 steps that are performed in a facilitated group setting using a panel of experts with extensive forest management or research experience in a designated geographic area that can vary in scale, depending on stakeholder preference. The process is performed for each forest or natural community type considered in an assessment.

1. *Identify current drivers, stressors, and dominant species*. For each forest or commu-

Management and Policy Implications

Forest managers can use vulnerability assessments to help understand which species and ecosystems may be at greatest risk in a changing climate. Vulnerability assessments explain what systems are the most (and least) vulnerable, and, more important, why they are vulnerable. We developed the ecosystem vulnerability assessment approach (EVAA) for forest managers and scientists to collaboratively assess forest ecosystem vulnerability. We applied EVAA to eight regions in the Midwest and Northeast totaling 252 million acres. Although we have applied EVAA at the ecoregional scale, it is flexible enough to be used at larger or smaller scales, depending on the needs of managers. Results from assessments using EVAA have been successfully applied to forest management decisions across the Midwest and Northeast by nongovernmental, private, and government forest managers. How this information is applied depends on the specific goals and objectives of different places and ownerships.

nity type, panelists identify current drivers, stressors, and dominant species based on their knowledge of the systems being evaluated. We define drivers as the factors that contribute to the presence of that community or forest type on the landscape. We define stressors as physical, biological, or anthropogenic factors that have been found to be major factors in reducing the long-term viability or productivity of a forest or community type. Dominant species are the canopy species most commonly found in a forest or community type.

2. *Assess the potential climate change impacts on drivers, stressors, and dominant species defined in step 1*. Panelists collaboratively record climate change impacts on drivers, stressors, and dominant tree species for each forest or community type based on locally relevant model projections of climate change and forest impacts. We ask panelists to consider potential impacts that are projected to occur over a defined time frame, given a range of climate model-scenario combinations presented. Changes in species are classified based on whether (and to what extent) models tend to project an increase, decrease, or no change, or there is too much disagreement among climate models to project a direction of change.
3. *Describe potential interactions among impacts defined in step 2*. We define interactions as direct or indirect effects (either positive or negative) of one potential impact on another. Panelists list any potential interactions among these impacts. Potential interactions are largely based on expert knowledge because quantitative modeling results on interactions are generally limited.
4. *Assess factors that enhance adaptive capacity*. Panelists develop a list of attributes for each forest or community type based on the ability of the system to cope with climate change. In our approach, managers are asked to focus specifically on the physical or biological attributes of the ecosystem that may enhance adaptive capacity and not the capacity of the people who manage the system.
5. *Individually determine vulnerability*. Vulnerability is determined based on the balance of potential impacts and adaptive capacity. Panelists independently assess the overall potential impacts on a forest or community type on a continuous scale from positive to negative based on what they described in steps 2 and 3. These ratings are generally based on the overall number of positive versus negative impacts on drivers, stressors, and dominant species, but each expert is allowed to weigh these factors however he or she chooses. Experts evaluate adaptive capacity on a scale from low to high. All individual impact ratings along with a narrative explanation for each panelist's reasoning are recorded in a worksheet by each expert (see the Supplemental Material).[S] Panelists are then instructed to use their impacts and adaptive capacity determinations to indicate their overall vulnerability rating on a figure depicting impacts on the *x*-axis and adaptive capacity on the *y*-axis (Swanston and Janowiak 2012) (Figure 2).
6. *Individually determine uncertainty*. We incorporate the uncertainty framework developed for authors of the IPCC Fifth Assessment Report when dealing with qualitative information (Mastrandrea et al. 2011). Panelists evaluate the level of evidence and agreement supporting each of their vulnerability determinations. Evidence is defined as observational, modeled, or theoretical information that contributes to a vulnerability determination. Evidence is considered robust when multiple observations or models are available as well as established theoretical understanding to support a vulnerability determination. Panelists evaluate agreement based on whether or not theories, observations, and models tend to suggest similar outcomes. Each panelist uses his or her evidence and agreement determinations to indicate their own overall determination of uncertainty in the vulnerability rating in a two-dimensional matrix.
7. *Determine vulnerability and uncertainty as a group*. Panelists indicate their individual vulnerability determinations on a group version of the two-dimensional vulnerability space. Individual ratings are compared and discussed among the group, and the group reaches a determination of vulnerability by consensus. The group vulnerability determination is placed into one of five categories (low, low-moderate, moderate, moderate-high, and high). The group uncertainty determination is made in a fashion similar to that for vulnerability, with ratings for both evidence and agreement falling into one of five categories. The key impact and adaptive capacity factors that contribute to the overall vulnerability and uncertainty determination are synthesized into a 1-page summary based on group discussion of individual responses.

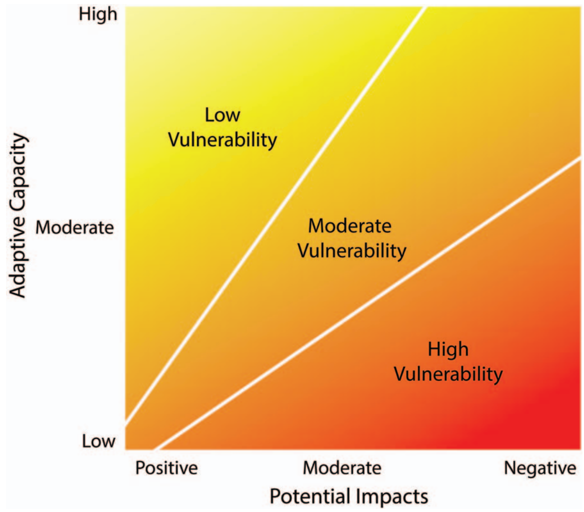

Figure 2. Vulnerability gradient (from Swanston and Janowiak 2012). Negative potential impacts and low adaptive capacity indicate high vulnerability and vice versa.

Application to Eastern US Forests

We applied EVAA to eight regions in the Midwestern and Eastern United States,

[S] Supplementary data are available with this article at http://dx.doi.org/10.5849/jof.15-147.

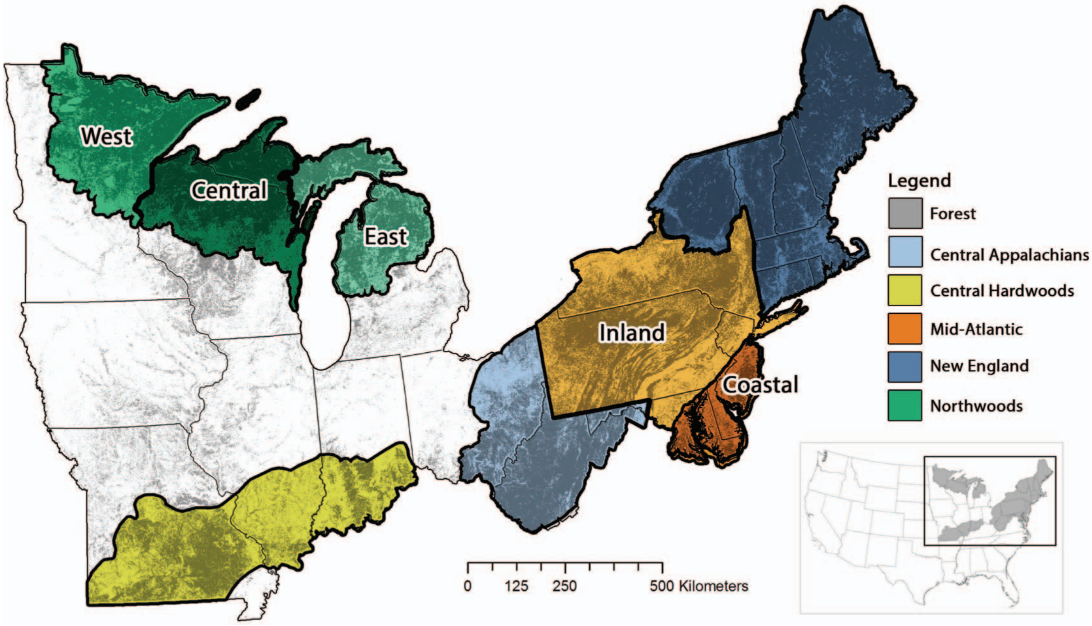

Figure 3. Assessment areas. Central Appalachians, Central Hardwoods, and New England were each assessed as one unit. The Northwoods project area was divided into three assessment areas (West, Central, and East) that roughly corresponded to state boundaries of Minnesota, Wisconsin, and Michigan. The Mid-Atlantic was divided into Coastal and Inland regions.

covering a total of 252 million acres. Results of these assessments were summarized in technical reports designed for a natural resource manager audience (Brandt et al. 2014, Handler et al. 2014a, 2014b, Janowiak et al. 2014a, Butler et al. 2015). These assessments were part of a collaborative, cross-boundary approach among scientists, managers, and landowners to incorporate climate change considerations into natural resource management called the Climate Change Response Framework (Swanston and Janowiak 2012, Janowiak et al. 2014b). We determined boundaries of each assessment area using a combination of ecological and political (state or county) boundaries that were mutually agreed on in initial meetings with Framework participants. Ecological boundaries were based on ecological province and, in some cases, section boundaries of the National Hierarchical Framework of Ecological Units (Cleland et al. 1997). The Northwoods project (66 million acres) was divided into 3 subregions for assessment that approximately followed state boundaries because different groups had completed modeling for each area, there was a larger density of land management organizations, and we wanted to allow wide participation while still keeping the workshop size small. The Mid-Atlantic project (60 million acres) was divided into coastal and interior regions due to differences in climate change impacts and ecosystems between the two areas. The other project areas were each assessed as a whole (Figure 3). The scope of each assessment focused on forest ecosystems. We also included woodlands, savannas, and other terrestrial systems based on target user needs as agreed on by the panel before the workshop.

In each assessment area, we assembled expert panels for 2-day structured workshops that took place between June 2012 and December 2015. Panels were composed of 12–25 members, representing a range of expertise from forest management to forest science. Panelists represented university, government, nongovernmental, tribal, and private organizations within each assessment area (Table 1). Each workshop had a facilitator and recorder that were conversant in ecology, management, and climate change in the assessment area but were not contributing members of the panel.

The types of systems assessed varied by region. Panelists collaboratively selected a system that would best meet the needs of managers in the area before the workshop. Some assessment areas focused on forest type (classified by dominant overstory tree species), and others focused on ecological communities (classified based on structure and ecological characteristics in addition to species composition). In many cases, similar community types were combined based on group discretion to reduce the number of communities to a practical level.

The facilitator provided each panel with information that served as a basis for vulnerability determination. The facilitator summarized the current landscape condition (e.g., current invasive species, pests, diseases, management practices, and land use) from the peer-reviewed and gray literature. Based on the literature review, the facilitator identified specific stressors for each forest or community type. The facilitator also summarized any relevant peer-reviewed or gray literature on the past or projected impacts of climate change to the region.

We also provided panelists with a consistent set of past and projected climate data. We summarized historical climate data from the ClimateWizard Custom Analysis Application (Girvetz et al. 2009) and provided participants with statistically downscaled climate projections (Hayhoe 2010). We chose a consistent set of two model-scenario combinations from the same statistically downscaled data set across all assessment areas to provide a range of plausible futures. GFDL A1FI projects a greater amount of warming and hot, dry summers throughout the region. PCM B1 projects a lesser amount of warming and wetter summers with modest temperature increases in summer (Washington et al. 2000, Delworth et al. 2006). We selected these model-scenario combinations because they had been used previously for projecting changes in habitat suitability for tree species (Iverson et al. 2008). We cre-

Table 1. Panel representation within each assessment area.

Assessment area	Government	Nongovernmental organization	University	Private company	Tribal organization	Total
Central Appalachians	14	5				19
Central Hardwoods	12	4	5			21
Mid-Atlantic Coastal	9	2	1			12
Mid-Atlantic Interior	10	3	3			16
New England	10	2		1	7	20
Northwoods-West	11	1	7	2	1	22
Northwoods-Central	10		6	2	1	19
Northwoods-East	10	4	7	2	2	25

ated maps from these two model-scenario combinations (12-km resolution) showing the differences in temperature and precipitation for the years 2010–2039, 2040–2069, and 2070–2099 compared with a 1971–2000 baseline for each season.

In each assessment area, three forest impact models were used to project climate-induced impacts on selected tree species or forest cover types (Table 2) (Iverson et al. 2016). The logistics, time, effort, and expertise required to model climate impacts within ecoregional analysis areas necessitated working with multiple modeling groups, and thus modeling approaches differed slightly across assessment areas. We were able to use data from the Climate Change Atlas (Iverson et al. 2008, Landscape Change Research Group 2014) in all assessment areas, however, because analysis was carried out at a larger spatial resolution and scale. All models used the same two downscaled model-scenario combinations (described above) as climate inputs. Scientists involved in the development of the model results were part of each panel.

Vulnerability of Forest Ecosystems in the Eastern United States

Impacts

Many major impacts to system drivers and stressors identified by panelists were similar across assessment areas. The impacts that were most frequently identified as contributing to vulnerability of ecosystems in all assessment areas were changes in fire regime, soil moisture, pest and disease outbreaks, and nonnative invasive species. However, the specific pests, diseases, and invasive species varied by region. For example, hemlock wooly adelgid (*Adelges tsugae*) was an issue in the eastern assessment areas, and oak decline was an issue in the western Central Hardwoods region. An increase in summer drought conditions was also a common theme but was listed as a larger concern in the Midwest regions than along the East Coast. Likewise, all assessment areas cited increases in heavy precipitation events as an issue of concern, but this issue had more prominence in the Mid-Atlantic and New England.

Some impacts were specific to certain geographic regions. Most notably, panels for the Coastal assessment region in the Mid-Atlantic and parts of New England were concerned about sea level rise and storm surge, but this was not an issue inland. Disturbance from heavy wind events such as tornadoes and derechos were of more concern in the Northwoods and Central Hardwoods, and changes in tropical storms and hurricanes were highlighted as an issue in the Mid-Atlantic and New England. In the Northwoods and New England where a number of boreal species are at the southern extent of their range, a major concern was the exceedance of temperature thresholds, which may lead to mortality of these species. Several areas also raised the issue of warmer winter temperatures leading to increases in herbivore populations, but species varied by region, with white-tailed deer (*Odocoileus virginianus*) being the major concern in the Northwoods and southern New England, moose (*Alces alces*) in Maine, and nutria (*Myocastor coypus*) in the Mid-Atlantic. In the Central Hardwoods region, where winters tend to be more mild, there was less of a concern about changes in herbivore populations as well as a lower concern overall about changes in winter weather conditions compared with other assessment areas.

Adaptive Capacity

Panels were generally consistent about which factors contributed the most to adaptive capacity. Diversity of species, soil types, landforms, genetic material, and geologic substrates were common themes across all areas. Systems with high diversity of native species in both the understory and the canopy were considered to have high adaptive capacity. Systems distributed on a variety of landforms, soil types, and geologic substrates were also considered to have a higher adaptive capacity because panelists perceived there would be more likelihood that at least some of these locations would remain favorable for that habitat type. Lack of species and genetic diversity was raised as a factor reducing adaptive capacity in plantation forests, such as red pine and aspen stands in the Northwoods.

Past and present land use and management were also common adaptive capacity themes. Systems where past management or land use reduced the diversity of species, ages, or genotypes were generally perceived as having lower adaptive capacity. This issue was the most prominent along the East Coast where systems have been highly altered by European settlement for centuries. Panelists perceived systems where current the fire or flood regime differed dramatically from historic regimes as having lower adaptive capacity. Mesophication of ecosystems, where fire-tolerant oak (*Quercus spp.*) and hickory (*Carya spp.*) species are lost in favor of more mesic species like maple (*Acer spp*) and beech (*Fagus americana*), was raised as a factor reducing adaptive capacity in the Central Hardwoods, Central Appalachians, and parts of the Mid-Atlantic and New England (Nowacki and Abrams 2008). It is important to note that panelists only assessed the current adaptive capacity of the ecosystem itself and not the potential for future management actions as part of their assessments.

Vulnerability

Across all eight assessment areas, 13 ecosystem or forest types (29%) were rated as having high vulnerability and 6 (13%) were rated as having low vulnerability (Table 3). The Central Hardwoods region had the most forest ecosystems that received a "low" vulnerability rating. It is not possible to discern whether this was due to differences in panel composition among regions or because that region did in fact have less negative impacts and higher adaptive capacity. The central hardwoods community type in the New England panel and the woodland/barren/glade community in the Mid-Atlantic panel were also given a "low" rating, indicating a consistency in perceived low vulnerability of these community types

Table 2. Impact models used as informational inputs in each assessment area.

Model	Short description	Climate change inputs	Central Appalachians	Central Hardwoods	Northwoods	Mid-Atlantic	New England
Climate Change Atlas[a]	Statistical model of 134 tree species across the Eastern United States	Monthly minimum, maximum temperature; monthly mean precipitation	X	X	X	X	X
LANDIS-II[b]	Spatially dynamic model that simulates climate change, disturbance, and management effects on forest dynamics	Monthly mean, maximum, and SD temperature; mean monthly and SD precipitation			X		
LANDIS Pro[c]	Spatially dynamic model that simulates management and disturbance effects on forest dynamics based on FIA data	(Uses establishment probabilities from LINKAGES)	X	X		X	X
LINKAGES II[d]	Forest succession and ecosystem dynamics process model that simulates nutrient dynamics and vegetation establishment and growth	Daily maximum, minimum temperature; daily mean precipitation	X	X		X	X
PnET-CN[e]	Ecosystem-level process model that simulates carbon, water, and nitrogen dynamics in forests over time	Mean monthly minimum, maximum temperature; monthly mean precipitation; CO_2 concentration			X		

Northwoods applies to East, Central, and West locations. Mid-Atlantic applies to Coastal and Interior locations.
[a] Data from Iverson et al. (2008) and Landscape Change Research Group (2014).
[b] Data from Scheller et al. (2007) and Duveneck et al. (2014).
[c] Data from Wang et al. (2013) and Dijak (2013).
[d] Data from Wullschleger et al. (2003).
[e] Data from Aber et al. (1997) and Peters et al. (2013).

among the panels. Panelists did not rate any forest ecosystems as having low vulnerability in any of the three assessment areas in the Northwoods or in the Mid-Atlantic Coastal region. In the Northwoods, this was due to the large number of species that were at the southern extent of their range. In the Mid-Atlantic, concerns about storm surges and sea level rise predominated.

Despite differences in classification systems across assessment areas, a few patterns in vulnerability ratings among similar ecological community types emerged. Across all eight assessment areas, upland systems dominated by oak species were generally considered to have relatively low vulnerability. These community types were perceived to have moderate impacts and relatively high adaptive capacity. Boreal and high-elevation community types, which were typically dominated by spruce and fir species, were rated as having higher vulnerability. Finally, community types in floodplains or in areas subject to sea level rise or storm surge also had relatively higher vulnerability ratings.

Uncertainty

The range of uncertainty determinations was lower than the range of vulnerability ratings within and among assessment areas. Most forest or community types (88%) were considered to have limited-medium or medium evidence to support their vulnerability rating. No vulnerability rating for any forest or community type was considered to have robust evidence, and only one system was considered to have limited evidence. Levels of agreement tended to be slightly higher than the degree of evidence, with 19 (37% of communities) receiving a medium-high agreement. Only one community received a low-medium agreement rating and none a low agreement rating, indicating that even when evidence was limited, it tended to support a similar direction of change.

Benefits and Limitations of EVAA

EVAA assesses vulnerability based on impacts and adaptive capacity, which builds on previous frameworks of vulnerability (Glick et al. 2011). To our knowledge, our approach is the first to delineate impacts based on ecosystem drivers, stressors, and dominant tree species, which makes it uniquely suited to forest ecosystems. Exposure and sensitivity were not addressed individually in our approach, but instead combined into our analysis of impacts. Although this simplified the process for managers, it could also have led to some important details related to the relative weight of exposure or sensitivity contributing to a particular impact being lost. This could have important implications for adaptation actions, because different actions may be taken to reduce exposure (e.g., providing shade in riparian areas to reduce stream temperatures) versus sensitivity (e.g., planting future-adapted species). However, our experience working with forest managers indicates that the level of detail provided in our vulnerability summaries is sufficient to develop adaptation actions (Janowiak et al. 2014b).

We found that a key strength in our approach was its collaborative nature. Individual determinations allowed panelists to see where there was more or less agreement on the perceived risk to a particular community or forest type. In most cases, determining vulnerability as a group after the individual determinations did not result in a significantly different vulnerability rating than if the individual determinations had simply been averaged. When there were differences, conversations about these differences helped highlight key issues that may have been important, but overlooked, by some panelists. Thus, sometimes an individual panelist with specific expertise about a community type was able to influence a vulnerability rating that may have been lost by simply averaging. This suggests that the group determination step was valuable and ensured that all panelists were comfortable with the final outcome.

We strived for representation from a variety of organizations, geographies, and backgrounds for each panel to reduce bias.

Table 3. Vulnerability and uncertainty for each forest or community type assessed.

Area	Forest/community type	Vulnerability	Evidence	Agreement
Central Appalachians	Appalachian (Hemlock)-Northern Hardwood Forest	High	Medium	Medium
	Dry Calcareous Forest, Woodland, and Glade	Moderate-high	Limited-medium	Medium
	Dry Oak and Pine Oak Forest and Woodland	Low	Medium	Medium-high
	Dry-Mesic Oak Forest	Low-moderate	Medium	Medium-high
	Large Stream Floodplain and Riparian	High	Medium	Medium
	Mixed Mesophytic and Cove Forest	Moderate	Limited-medium	Medium
	North-Central Interior Maple-Beech Forest	Moderate	Limited-medium	Medium
	Small Stream Riparian	Moderate-high	Medium	Medium
	Spruce-Fir Forest	High	Limited-medium	Medium
Central Hardwoods	Barrens and Savanna	Low	Medium	Medium-high
	Closed Woodland	Low	Limited	Medium
	Dry-Mesic Upland Forest	Low-moderate	Medium	Medium-high
	Flatwoods	Low-moderate	Limited-medium	Medium
	Glade	Low-moderate	Medium	Medium-high
	Mesic Bottomland Forest	Moderate	Medium	Medium
	Mesic Upland Forest	High	Medium	Medium-high
	Open Woodland	Low	Limited-medium	Medium
	Wet Bottomland Forest	Moderate-high	Limited-medium	Medium
Mid-Atlantic Coastal	Coastal Plain Maritime Forest	High	Medium-robust	Medium-high
	Coastal Plain Oak-Pine-Hardwood	Low-moderate	Medium	Medium-high
	Coastal Plain Pine-Oak Barrens	Low-moderate	Medium-robust	Medium-high
	Coastal Plain Swamp	Low-moderate	Medium	Medium
	Coastal Plain Tidal Swamp	Moderate-high	Medium	Medium-high
Mid-Atlantic Interior	Central Oak-Pine	Low-moderate	Medium	Medium-high
	Lowland and Riparian Hardwood	Moderate	Medium-Limited	Medium
	Lowland Conifer	High	Medium	Medium
	Montane Spruce-Fir	High	Medium-robust	High
	Northern Hardwood	Moderate-high	Medium-robust	Medium-high
	Woodland, Glades, and Barrens	Low	Medium	Medium-high
New England	Central Hardwoods	Low	Medium	Medium-high
	Low-Elevation Spruce-Fir	Moderate-high	Medium	Medium
	Lowland and Riparian Hardwood	Moderate	Limited-medium	Medium
	Lowland Conifer and Mixed	Moderate-high	Limited-medium	Medium
	Montane Spruce-Fir	Moderate-high	Medium	Medium
	Northern Hardwoods	Low-moderate	Medium	Medium
	Pitch Pine-Scrub Oak	Low	Medium	Medium
	Transition Hardwoods	Low	Medium	Medium-high
Northwoods-West	Acid Peatland	High	Medium	Medium-high
	Fire-Dependent Forest	Moderate	Medium	Medium
	Floodplain Forest	Low-moderate	Limited-medium	Medium
	Forested Rich Peatland	High	Medium	Medium-high
	Managed Aspen	Moderate-high	Medium	High
	Managed Red Pine	Moderate-high	Medium	Medium
	Mesic Hardwood Forest	Moderate	Medium	Medium
	Wet Forest	High	Limited-medium	Medium
Northwoods-Central	Aspen-Birch	Moderate-high	Medium-robust	Medium-high
	Jack Pine	Moderate	Medium	Medium-high
	Lowland Conifer	High	Medium	Medium-high
	Lowland-Riparian Hardwoods	Moderate-high	Limited-medium	Medium
	Northern Hardwoods	Moderate	Medium-robust	Medium
	Oak Associations	Low-moderate	Medium	Medium-high
	Red Pine	Moderate-high	Medium-robust	Medium
	Upland Spruce-Fir	High	Medium-robust	Medium-high
	White Pine	Low-moderate	Medium-robust	Medium
Northwoods-East	Aspen-Birch	Moderate	Medium	Medium
	Barrens	Low-moderate	Limited-medium	Medium
	Jack Pine (including Pine-Oak)	High-moderate	Medium	Medium-high
	Lowland Conifer	High-moderate	Medium	Medium
	Lowland-Riparian Hardwoods	Moderate	Medium	Low-medium
	Northern Hardwoods	Moderate	Medium	Medium
	Oak Associations	Low-moderate	Medium	Medium
	Red Pine-White Pine	High-moderate	Limited-medium	Medium
	Upland Spruce-Fir	High	Medium-robust	Medium-high

Community or forest types were based on the following classification systems: Central Applachians: NatureServe Ecological Systems (NatureServe 2011); Central Hardwoods: Natural Communities (Nelson 2010); Northwoods-West: Native Plant Communities (Minnesota Department of Natural Resources 2003); Northwoods-Central: Forest Types (Wisconsin Department of Natural Resources 2013); Northwoods-East: Combination of Forest Types and Natural Communities (Kost et al. 2007); Mid-Atlantic and New England: Northeast Habitats (Anderson et al. 2013).

Still, we recognized that the composition of the panel could potentially influence results and took additional steps to try to minimize biases. First, we asked panelists to support statements they made about impacts and adaptive capacity with the best available scientific information. Second, having individual determinations of vulnerability and uncertainty ensured that group members did not simply select the vulnerability determination of the most vocal or outspoken member. After the workshops, we also examined individual responses to see whether participants from a particular organization or academic institution tended to have similar answers, but because of the small sample size, these were not analyzed statistically. Still, no clear patterns emerged from the limited data available. In addition, vulnerability ratings for both the Northwoods-Central and Northwoods-East assessments, which evaluated similar ecosystems and had similar projected climate changes, were generally aligned. This indicates that either panel composition did not influence results or that biases are similar across geographies and organizations.

We developed EVAA to focus on the adaptive capacity of the ecosystems themselves and not of human communities or organizations. This was intentional because the goal of the assessment was to understand which ecosystems were the best able to cope with change if no adaptation actions were taken. In addition, the scale of our assessments spanned multiple ownerships and management units and thus would encompass a range of organizational, technical, social, and economic capacities. We did not feel that social factors were best assessed at the spatial scales we used. If EVAA was applied at finer spatial scales or single ownerships (e.g., within individual county, state, or national forests), additional analysis could be helpful to determine the adaptive capacity of the people that manage and depend on these ecological communities (Brown 2009, Johnston and Hesseln 2012).

We developed EVAA to provide a relatively simple, yet structured, way for translating copious and complex information on the potential effects of climate change for use by natural resource managers. We purposely avoided assigning a numerical score to our assessments of vulnerability or its subcomponents. This differs from some other habitat-level assessment approaches (Comer et al. 2012, Manomet and NWF 2012) and could be perceived as a weakness because it limits the ability to quantitatively rank vulnerability among systems. However, the determination of vulnerability is a primarily qualitative process, and thus we believe that the categorization of vulnerability should also be qualitative. In addition, in the development of more than 150 on-the-ground climate change adaptation demonstration projects, we have found that the summary that identifies the major factors that contribute to the vulnerability of each system is often more useful for making decisions than rating a particular system as more or less vulnerable than another (Janowiak et al. 2014b).

EVAA integrates climate change trends and projections, quantitative data from forest impact models, scientific literature, and expert knowledge and experience. Although EVAA was flexible regarding the specific quantitative models used, we relied heavily on the use of multiple forest impact models and statistically downscaled climate data. This could be a limitation to implementing the approach in other geographic areas or community types within these areas that lack sufficient quantitative model results. In cases in which there is a lower availability of quantitative data, other sources of information such as local expertise on species biology or traditional ecological knowledge may need to be relied on more heavily. This may lower the overall confidence in vulnerability determinations for that area (low evidence rating). However, our approach can still be useful for identifying what systems are at risk (and why) based on the information that is available.

EVAA provided a simple way to communicate uncertainty that combined qualitative and quantitative sources. The IPCC method on which our method is based has been argued to be preferable for characterizing uncertainty when insufficient evidence is available to make a quantitative statement of likelihood (Curry and Webster 2011). This was a preliminary attempt to communicate uncertainty in our rating of the vulnerability of ecosystems. Almost all forest or community types assessed received similar uncertainty ratings in both evidence and agreement, primarily because some vulnerability components had more supporting evidence than others. An alternate approach is to assign a level of uncertainty to each component of adaptive capacity or impacts, which has been used in other habitat-level assessments (Manomet and NWF 2012). This would have provided a more detailed representation of what areas had greater certainty than others, but it would have substantially increased the amount of time needed to assess each forest or community type and may not have been feasible in a group setting.

A key advantage to EVAA is that it we have demonstrated that it can be directly applied to adaptation planning in the forest sector. As part of the Climate Change Response Framework, we have developed more than 150 "adaptation demonstration projects" that show real-world examples of how managers have integrated climate considerations into forest management planning and activities within the eight assessment areas (Janowiak 2014b). Managers have used vulnerability information from these assessments in projects and planning at a variety of scales in both the public and private sector in these demonstration projects. To our knowledge, no other vulnerability assessments have been so widely applied to structured, formalized forest adaptation and implementation.

Conclusions

EVAA is a flexible and collaborative method for assessing the vulnerability of forest ecosystems that incorporates quantitative and qualitative information with local expertise. We have shown that this process can be used in a variety of forest ecosystem types across the eastern United States as a first step in adapting forest management to climate change.

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