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RESEARCH ARTICLE

Assessing and comparing risk to climate changes among forested locations: implications for ecosystem services

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Abstract Forests provide key ecosystem services (ES) and the extent to which the ES are realized varies spatially, with forest composition and cultural context, and in breadth, depending on the dominant tree species inhabiting an area. We address the question of how climate change may impact ES within the temperate and diverse forests of the eastern United States. We quantify the vulnerability to changes in forest habitat by 2100, based on the overall pressures of community change from an aggregation of current and potential future habitats for 134 tree species at each of 149 US Department of Defense installations. To do so, we derive an index, Forest-Related Index of Climate Vulnerability, composed of several indicators of vulnerability for each site. Further, a risk matrix (likelihood × consequences) provides a visual cue to compare vulnerabilities among species (example from Pennsylvania) or among sites [example for *Acer saccharum* (sugar maple) in Vermont vs. Kentucky]. Potential changes in specific ES can then be qualitatively examined. For example in Pennsylvania, the loss of the provisioning services (wood products) of *Prunus serotina* (black cherry) and *Fraxinus americana* (white ash) habitat projected for the future will not likely be compensated for by concomitant increases in *Juniperus virginiana* (redcedar) and *Pinus echinata* (shortleaf pine) habitat. Taken together, this approach provides a conceptual framework that allows for consideration of how potential changes in tree species habitats, as impacted by climate change, can be combined to explore relative changes in important ES that forests provide.

Keywords Climate change · Ecosystem services · Trees · Eastern United States · Forest composition · Prediction

Introduction

Forests provide key ecosystem services (ES) and are unquestionably linked to sustaining human well-being (MEA 2005; Bonan 2008). The importance of forests is clear from the perspective of multiple forms of ES: supporting, provisioning, cultural, and regulating (MEA 2005). Yet, forests in many parts of the world have shown marked declines (Anderegg et al. 2013; Liu et al. 2013) and transformations, especially in recent times (Ciccarese et al. 2012). The global pressures placed on trees and the forests they make up are as diverse as the multitude of services they provide (Bonan 2008).

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Climatic conditions serve as a fundamental backdrop upon which the patterns of vegetation occupy the globe; for example across North America, the underlying mechanisms that regulate the transition from barren to grassland to shrublands to forest are driven by climate (Woodward 1992). Vegetative patterns have always changed over time along with the climate (Williams et al. 2004). However, the current rate at which the climate is changing and the likely further intensification of these climate shifts will place increasing stress on forest systems. Therefore given that we rely on forests to provide ES, we must consider how these changes may unfold. As climates begin to show significant and sustained departures from long-term normals, vegetative responses are becoming more evident [e.g., changes in arctic ecosystems (Soja et al. 2007; Post et al. 2009; Allen et al. 2010) or drought-induced mortality (Allen et al. 2010)]. There is thus a need to consider how climate change induced effects can impact certain ES (Embrey et al. 2012).

In many respects, the challenge for conserving ecosystem function in the face of global change pressures is to be able to simultaneously capture how future changes to the forest ecosystems may unfold in relation to the important ES functions they provide (Perrings et al. 2010). Thus a key component of defining and evaluating ES is a thorough understanding of the ecosystem functions that will drive the supporting services of vegetation (Diaz et al. 2007). Some of the most compelling accounting of how ES, at a regional scale, may be impacted by climate change focuses on a specific service that can be quantified and projected into the future. Evaluating the risk of floods as induced by changes in vegetation (Verburg et al. 2012) or the potential for altering pest control by European birds (Civantos et al. 2012) are two such examples that aim to evaluate these risks spatially. In addition, forests are essential with regard to water regulation and carbon storage, and while these services will readily be impacted by climate change, they are also key elements in climate mitigation strategies (Deal et al. 2010). Part of ensuring that ecosystem functions are preserved relies on having the broadest functional diversity present (Hooper et al. 2005).

Yet there is also a need to consider a more complete spectrum of services that may be provided within a given location, especially when trying to inform management decisions that must balance many objectives, as the real drivers producing ES occur at a finer resolution and are place-based (Turner et al. 2013). Smith et al. (2011) showed that accounting for the ES provided in a management unit requires a thorough accounting of the activities and objectives that fall under that management unit. For example in many locations, forests provide a strong sense of place where cultural services are tightly tied to the well-being of the residents, making it essential to have a transparent prioritization of tradeoffs for services and to identify when and where they can be translocated, or in some cases, abandoned (Breshears et al. 2010). This reality suggests that forest ES will vary strongly spatially with different forest communities as well as temporally (Seppelt et al. 2011). Changes are likely to be quite subtle due to the long-lived nature of trees, as changes in abiotic and species interactions, and eventually composition, may occur. Hence the ES provided may change slowly over time or be accelerated by disturbance events such as those directly or indirectly associated with a changing climate (He et al. 2002). With such uncertainty, we must develop tools and adaptive strategies which will allow us to quantify vulnerabilities of forests to climate change, and from here we can develop a view of how relative ES may be impacted.

Therefore, to identify potential threats to ES, we must evaluate how both forest communities and individual tree species may be impacted by climate change. In doing so, we can focus on how these changes relate to specific ES that forests provide and how this profile may vary across a broad geographic region. Fortunately, for some time we have been engaged in detailed vulnerability assessments with a purpose to assess each of 134 tree species within several regions of the Northern and Midwestern US for potential gains or losses in suitable habitat in response to expected changes in climate (e.g., Swanston et al. 2011). These projects identify vulnerabilities and provide initial guidance on managing the forests under climate change. The purpose of this paper is to take the next step, i.e., to evaluate potential changes in light of the ES these changing forests provide now and into the future. To do so, we first expanded the footprint of these vulnerability assessments to the entire eastern United States by assessing the land in and around 149 US Department of Defense installations within the region, and then quantified the vulnerability to changes in forest habitat in response to projected climate changes. Our approach was to summarize how these relative changes can inform the potential for impacting forest-related ES, how changes in tree species habitat may influence the maintenance of ecosystem processes, and how contemporary views of production and cultural services may be impacted by climate change.

Methods

Climate change vulnerability

The foundation for this new analysis builds on species distribution models for 134 tree species east of the 100th meridian in the United States at a 20 × 20 km pixel resolution, and are presented in a web atlas (www.nrs.fs.fed.us/atlas). These data and modeling approaches have been the focus of several key papers (Iverson et al. 2008, 2011), and only briefly outlined here to articulate how they align with the current objectives of the study. The response variable of importance value (IV) by species was derived from US Forest Service Forest Inventory and Analysis data (www.fs.fed.us/fia; Woudenberg et al. 2010) from over 100,000 plots across the eastern US. These plots provide a robust sample size, and a continuous metric of importance value (IV, a metric that combines basal area and number of stems for each species within a plot relative to all species, see Iverson et al. 2008 for details) that captures the distributional extent of each species within the study region. The predictor data set included 38 variables that incorporate patterns of temperature, precipitation, soils, elevation, and landscape composition. Models of current species distributions were elucidated using decision tree ensemble models, with the RandomForest technique providing a robust assessment of the environmental associates within and across a species' distribution (Prasad et al. 2006; Cutler et al. 2007). The model reliability for each species was assessed based on fit and stability (Iverson et al. 2008) and then projected onto several global circulation models (GCMs, see below for details) to provide estimates of changes in suitable habitat under various potential climate conditions for 2070–2099 (i.e., end of century). From these outputs, metrics were generated to rapidly screen multiple locations based on their current tree species composition, and evaluate the relative climate change vulnerabilities based on potential changes in habitat suitability. We can then begin to highlight how ES may be impacted with shifts in species habitats.

In this example, we used 149 Department of Defense installations across the eastern US to provide a spatially distributed array of locations representing all forest types of the region (Fig. 1). There was also a need for the installations to be assessed for their overall vulnerability to climate change (US Department of Defense 2010). Because the installations are small relative to the coarse scale of our distribution model (20 × 20 km cells), we buffered each installation by 50 km to generate a focal area of at least 25 cells to ensure that our comparisons were not anomalies to model outputs from only a few cells.

Next, we evaluated all tree species within each location to quantify the individual and cumulative contribution to overall tree species importance, and to identify how these species' habitats change under four climate change simulations (2 GCMs-HadleyCM3 and PCM × 2 emission scenarios-A1FI = high emissions and B1 = low emissions to result in combinations: hereafter referred to as Hadhi, Hadlo, PCMhi, and PCMlo). Based on the cumulative evidence, we evaluated the potential for each species to decline at least 20 % in importance, remain within 20 % of current status, or increase at least 20 % in habitat in response to climate change. Assignment to these categories was based on declines being a ratio of future IV to current of less than 0.80, no change from 0.8 to 1.2, and gains with a future to current ratio of greater than 1.2. These categories were based on the average projected habitat change from each GCM-emission scenario combination to provide an ensemble perspective, yet we also tracked whether group assignment varied between emission scenarios. We also identified if there was potential for new species, generally from the south, to move poleward given the species' projected change in habitat. In contrast to species currently present and gaining habitat, these new migrants were not used in the metric calculations below. Next, we derived several metrics that were combined into an overall climate change vulnerably index called the Forest-Related Index of Climate Vulnerability (FRICV). The FRICV is composed of five components, each with unique contributions towards the overall vulnerability of the site. The loss pressure (L) considers all species at the site which are projected to lose >20 % of habitat (IV_l), and is the

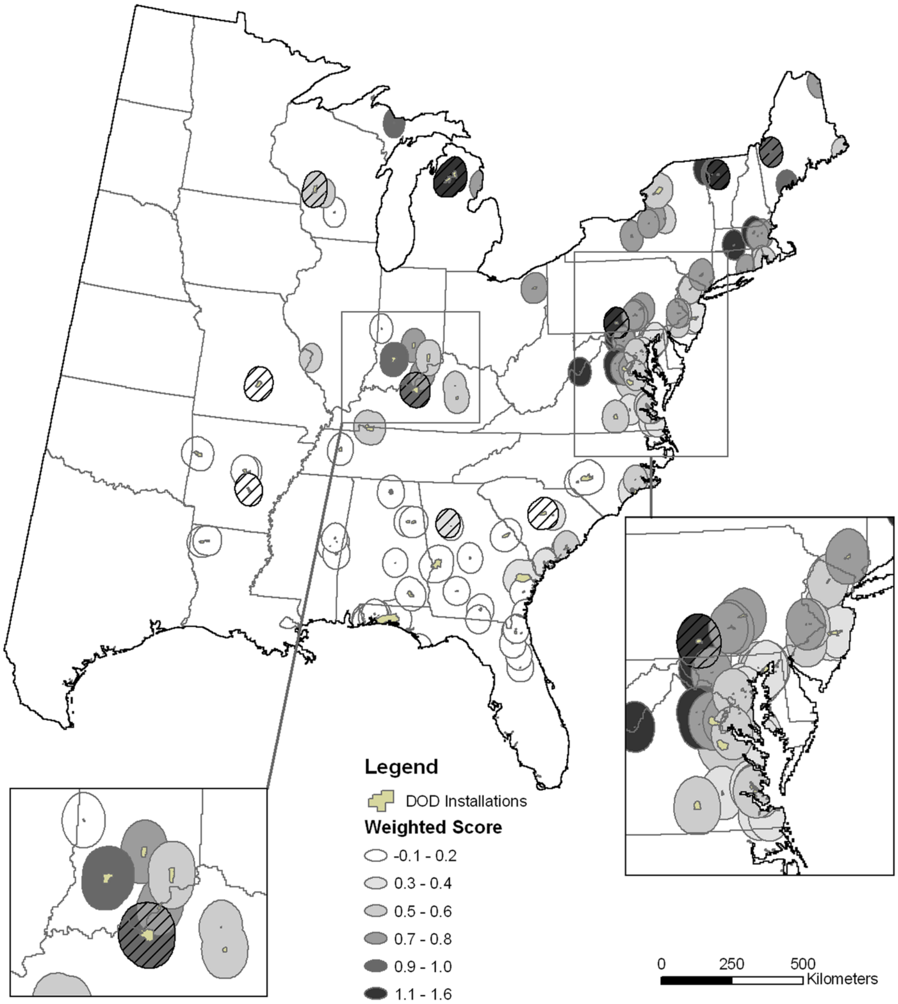

Fig. 1 Forest-Related Index of Climate Vulnerability (FRICV) scores of climate change impacts on tree species habitats for the 149 eastern US Department of Defense installations and 50 km buffered perimeter that serve as the background for this analysis (eastern seaboard inline map $n = 55$ locations). The *heavier shading* indicated greater vulnerability and the hatch line installations capture the ten focal areas

ratio of the sum of the current importance value of those species to total current IV (IV_T) for all species. The focus on the potential for losses captures the reality that for changes to occur, the suitability of habitat for those species currently occupying a location should decline to create opportunities for those niches to be filled.

$$L = \sum IV_l \Big/ \sum IV_T$$

The stability of gains to losses (s) is captured by the absolute value of the natural log of the ratio of summed IV of species which are projected to gain habitat (IV_g) to the summed IV of species projected to lose habitat (IV_l). The natural log transformation allows a compression of the range in ratios across very different levels of IV. The possible range of values was 0–3 with those near zero representing greater synchrony between gains and losses, and the highest values (truncated at a maximum of 3) representing high levels of asynchrony.

$$s = \left| \ln\left(\sum IV_g \Big/ \sum IV_l \right) \right|$$

The total IV change potential (T) is the ratio of the mean total IV, summed for all tree species from the 4 (n) modeled GCM/scenarios combinations (IV_i for PCMlo, PCMhi, Hadlo, and Hadhi) to the sum of the current importance value (IV_T), to capture the overall increases or decreases of cumulative IV. In the final index for T, we subtract from 1 to align the directionality of the metric (i.e., subtracting 1 will result in a larger T values consistent with the direction of greater vulnerability as portrayed in the other metrics).

$$T = \left(\sum \frac{\sum_i IV_i}{n}\right) \Big/ \sum IV_T$$

Examining the top 5 species in terms of IV within an area, we calculated the proportion of these species in a loss category, where (D) is the number of species with a >20 % loss of IV among the top 5 species at a location; it accounts for the importance of the most dominant tree species in the region, as their potential shifts in habitat will be key drivers to the system.

$$D = \text{Number of 5 most important species expected to lose habitat}/5$$

The proportion of forest at the site (F) is the proportion of 30-m pixels, derived from the National Land Cover Data (Fry et al. 2011), that are forested within the total area of the buffered location. This term weights the index by the proportion of forest within the location, as our goal is to identify those areas with the greatest forest vulnerability.

$$F = \text{Area forested/total area}$$

The FRICV, then, is simply a compilation of these five components in the following formula

$$FRICV = (L \times s + (1 - T) + D) \times F$$

where the index is related to the total loss of species habitat as captured by the magnitude of the loss potential, the ratio of gaining species to losing species, the total change in community importance value, and the potential loss of dominant species, all equally weighted in the metric and then multiplied by the forested proportion of the focal location. FRICV integrates some key features to identify the potential for change at any location, while simultaneously providing a mechanism to compare across locations; it captures both the potential for biome shifts as comprised by the cumulative pressures of forest change as well as the weighting of those tree species that are currently most important in the focal location. The focus on the distribution of current conditions, and with the partitioning of these values based on cumulative GCM habitat projections, is to reduce uncertainty as to the capacity for forests to change and the lag time involved.

Linking to ecosystem services

Once the relative vulnerability was derived, the tree species composition and individual risks were explored to highlight how ES may be influenced by changing habitats. Specifically, we focus on the coarse potential for changes in forest communities and diversity, as this provides direct evidence to the relationship that forest ES can provide (Quijas et al. 2012). A risk matrix framework that incorporated both the likelihood and consequence of climate change for individual species, and provided a location-specific assessment of the immediacy to develop management strategies (Iverson et al. 2012), was applied to species with high importance in terms of relevance to ES as well as how common they are on the landscape. The likelihood is derived from the potential change in habitat as provided from the species distribution models, while the consequence incorporates the potential adaptive capacity of the species. The adaptive capacity was obtained from the multi-criteria framework (Modfacs) that captures many of the un-modeled determinants (based on 9 biological characteristics and 12 life history traits related to disturbance tolerances) that will likely influence a species' ability to respond to climate change (Matthews et al. 2011). These data were then used to explore potential relative impacts for supporting services based on the i-Tree Species Selector program to identify, for each location (e.g., nearest city to installation), the species that were in the top 10 % (standard output of the software) at providing selective supporting services (Nowak et al. 2008). Because we were more interested in metrics relative to broad forest function, we equally weighted carbon storage and water regulation as the focal services. Further, we also demonstrate that through robust projections of potential climate change risk for tree species habitat, we can evaluate provisioning, and even cultural services by combining these data with location-specific characteristics.

Results

Climate change vulnerability

Using the 149 Department of Defense installations as a spatially distributed sample across the eastern US, the potential for climate change vulnerability was strongly influenced by the geographic position of the installation (Fig. 1) and reflects greater vulnerability when the installation lies in or just north of a forest transition zone of tree species communities (e.g., see forest type

Table 1 Vulnerability metrics for the 10 primary locations as well as summary for all 149 installation vulnerability scores distributed across the eastern United States

Installation	State	Current # of species	Prop. of top 5 species IV to total cur IV	Loss pressure (L)	Stability of gains to losses (s)	Total IV change potential (T)	Prop. of top 5 species with loss (D)	Prop. of forest land (F)	Forest-Related Index Of Climate Vulnerability (FRICV)
Fort Jackson	South Carolina	58	0.46	0.18	0.24	1.15	0.2	0.39	0.03
Pine Bluff Arsenal	Arkansas	56	0.56	0.08	1.68	1.17	0.2	0.31	0.05
Fort Leonard Wood Military Reservation	Missouri	45	0.46	0.3	0.13	1.09	0.2	0.61	0.09
Fort McPherson	Georgia	48	0.46	0.33	0.58	1.09	0.6	0.47	0.33
Fort McCoy	Wisconsin	49	0.63	0.53	0.54	1.08	0.8	0.43	0.43
Fort Knox	Kentucky	63	0.68	0.65	1.48	1.1	0.8	0.49	0.81
U.S. Naval Training Facility	Maine	41	0.46	0.5	1.4	0.91	0.4	0.76	0.9
Letterkenny Army Depot	Pennsylvania	59	0.63	0.63	1.68	0.99	0.8	0.54	1.01
Camp Grayling Military Reservation	Michigan	50	0.55	0.67	1.71	0.87	0.8	0.52	1.09
Fort Ethan Allen Military Reservation	Vermont	61	0.55	0.6	1.65	1.03	0.6	0.79	1.22
All 149 installation median (IQR)		58 (6.5)	0.53 (0.08)	0.58 (0.19)	1.24 (0.30)	1.08 (0.06)	0.60 (0.40)	0.36 (0.08)	0.41 (0.26)

The individual scores are derived from the pool of 134 tree species and summarized based on the projected habitat changes under four GCM/scenarios combinations of climate change maps, www.nrs.fs.fed.us/atlas). For example, of the installations that show high FRICV scores (Table 1), those in Vermont and Michigan have a northern latitude and could face increased pressure from oak forests to the south, while those in Kentucky and Pennsylvania are at middle latitudes and may incur increases in habitat for oak and southern pine forest types. While the overall FRICV score provides a sense of the broad range of vulnerabilities (e.g., the Inter Quartile Range of FRICV is 0.26, Table 1) as well as information related to the accumulation of the 'pressure' for species composition to change, considering the individual components of FRICV allows a more complete picture of vulnerabilities for any given location (Table 1). For example, when the loss pressure component *L* was averaged (median) across installations, over half of the total species IV occurred from species projected to lose >20 % of their current habitat; this value, along with relatively high levels of instability ($s =$ median 1.24), provides a more comprehensive picture of the potential for forest community changes across the eastern United States. These two metrics, while sharing some common attributes by being based on total species aggregations for an installation, are not strongly associated ($r_s = 0.13$, $p < 0.05$). They capture some unique qualities of vulnerability, as one metric evaluates overall directional change while the other metric assesses variability. The total change value (T) indicates that overall cumulative IV remains near current levels with slightly higher suitability for the median (1.08), but in some cases, there is a projected reduction in the suitability of the site for tree species (e.g., Michigan at 0.87 of total IV). Finally, with a median of 3 out of top 5 species projected to lose habitat across the 149 locations there is clear evidence for the potential turnover of communities as these dominant trees cope with future stressors. Thus, overall the FRICV is an indicator of which locations have the greatest vulnerability to climate change and its computation is an essential first step towards assessing coarse and relative ES impacts.

Coarse-level ecosystem services: from the forest community perspective

To identify ES vulnerabilities from this coarse perspective relative to climate change, a closer examination of site-level data is required. We selected a sample of 10 installations (hereafter 'primary installations'), representing a range of both location, forest types, and vulnerability, to facilitate a more detailed look at the patterns resulting from the overall scores (Table 1; Fig. 2). The diversity of tree species represented in these locations reflects the diversity of eastern forests, with a median of 58 species at all 149 installations and 53 species at the primary installations (Table 1). For the primary installations showing the greatest vulnerability, over 60 % of the species' total current IV is contained in species that are projected to decline in habitat by >20 % (*L*, Table 1; Fig. 2) and, in many cases, individual species show a much larger decline in habitat. Furthermore, the installations in Michigan and Maine had a projected decline in total IV (*T*, Table 1), indicating a generally poorer habitat across the entire suite of available species, which was surprising given that the model projections of future habitat don't include limiting growth factors. On the other hand, the installation in central Arkansas had a greater projected future importance value than current conditions suggest. From a forest community perspective, some of the best information that can be provided on changes to the essential ES provided by forests under climate change can be captured in the potential change in the diversity of tree species occupying specific locations.

Ecosystem services: from the species perspective

Despite the high species richness across all sites, the contribution to the cumulative current IV at any given primary location was dominated by a few species, with 46–68 % of the total IV captured in the top five species (Table 1). Based on current conditions, only 27 out of the 134 tree species occurred as a top five species in the 10 primary locations and only five new species are added to this total when we consider the climate change projections (Table 2). Importantly, in each case the species most influential at these locations had high or medium model reliability, providing confidence in the projected habitat values. Of these species, *Acer rubrum* (red maple) occurred in 7 installations (though the top in only two), while *Pinus taeda* (loblolly pine) occurred in the top position at three of the primary locations (Table 2). Looking more closely at the species making large contributions to overall importance at a primary location, we see that declining habitats in Pennsylvania and Michigan ($L > 0.6$) point

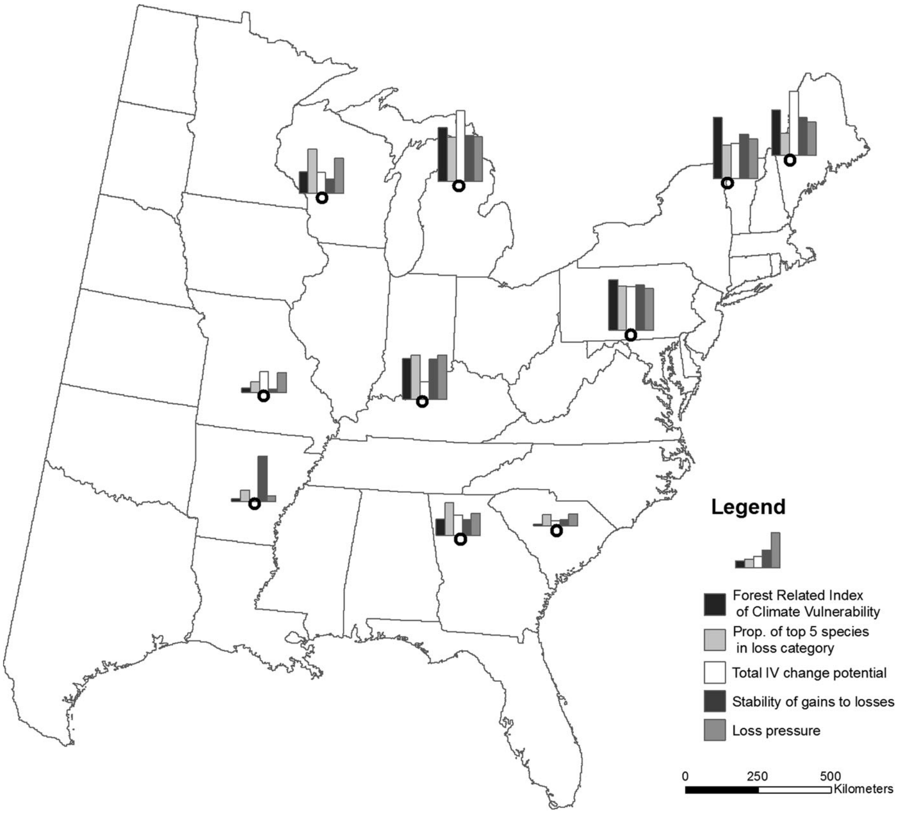

Fig. 2 The individual metric components making up the Forest-Related Index of Climate Vulnerability (FRICV) scores for the 10 primary locations. Each component is standardized to facilitate comparison across installations

to potentially destabilizing scenarios for those locations ($s > 1.5$) and result in higher overall FRICV scores (Table 1). In contrast, the relatively smaller projected change in Georgia, where *P. taeda* has a current importance value 1.7× that of the next species (*Liquidambar styraciflua*, sweetgum), and with its projected habitat to change little, the overall forest is likely to remain in a similar condition ($L = 0.33$, $s = 0.58$), thus reflecting a likely stabilizing effect for that location which also lowers the FRICV score (Table 1). It is important to note that this analysis is only considering the state of forested communities and is not able to evaluate changes from forests to other ecosystem types. Additionally, the relatively lower FRICV of southern installations is likely biased low as other analyses show that novel climate conditions are even more likely to emerge in southern US locations (sensu Williams et al. 2007; Matthews et al. 2011).

Further, the cumulative results, when paired with the i-Tree Species Selector results of a given installation, can provide key indicators of relative changes in specific ES (Table 3). In the states of Wisconsin, Pennsylvania, and Kentucky, the decline of many of the currently dominant trees that drive the supporting services show the potential to be replaced by species with contrasting life histories (Table 3). For example in Wisconsin, the potential declines in habitat for two key supporting service providers of *A. rubrum* and *Betula papyrifera* (paper birch) could be compensated by a comparable increase in *Ulmus americana* (American elm) and *Prunus serotina* (black cherry); in this case, there certainly could be a shift in the ES profile.

Aligning species risk to specific ecosystem services

We next provide two examples using these broad-based results, one species-specific and one location based, to demonstrate how provisioning and cultural services may or may not see increased vulnerability to climate change by century's end.

First, we evaluate *Acer saccharum* (sugar maple) in Kentucky and Vermont, with Vermont ~7° higher in latitude (Fig. 2). Based only on the potential for change in habitat and adaptability, we see that in both

Table 2 Current and projected top five species (rank order of species provided) from the 10 primary locations (pooled) and corresponding species distribution model reliability value and adaptability score (Iverson et al. 2012)

Common name	Scientific Name	Model reliability	Relative adaptability	R1	R2	R3	R4	R5	Total
Red maple	*Acer rubrum*	High	8.49	2	2	–	2	1	7
White oak	*Quercus alba*	High	6.14	–	–	3	1	1	5
Sugar maple	*Acer saccharum*	High	5.81	2	1	–	1	–	4
Loblolly pine	*Pinus taeda*	High	3.42	3	–	–	–	–	3
Sweetgum	*Liquidambar styraciflua*	High	4.1	–	3	–	–	–	3
Balsam fir	*Abies balsamea*	High	2.65	1	–	–	1	–	2
Eastern redcedar	*Juniperus virginiana*	Medium	3.87	–	1	–	1	–	2
Flowering dogwood	*Cornus florida*	High	5	–	–	–	1	1	2
American beech	*Fagus grandifolia*	High	3.56	–	–	1	–	1	2
Quaking aspen	*Populus tremuloides*	High	4.66	–	1	1	–	–	2
Northern red oak	*Quercus rubra*	High	5.39	1	–	–	1	–	2
Red spruce	*Picea rubens*	High	2.94	–	–	1	–	–	1
Jack pine	*Pinus banksiana*	High	5.18	–	–	–	1	–	1
Shortleaf pine	*Pinus echinata*	High	3.62	–	–	–	–	1	1
Longleaf pine	*Pinus palustris*	High	4.16	–	–	–	–	1	1
Red pine	*Pinus resinosa*	Medium	2.99	–	–	–	–	1	1
Eastern hemlock	*Tsuga canadensis*	High	2.69	–	–	–	–	1	1
Paper birch	*Betula papyrifera*	High	3.43	–	–	–	–	1	1
White ash	*Fraxinus americana*	High	2.65	–	–	–	1	–	1
Green ash	*Fraxinus pennsylvanica*	Medium	3.97	–	–	1	–	–	1
Yellow-poplar	*Liriodendron tulipifera*	High	5.29	–	–	1	–	–	1
Black cherry	*Prunus serotina*	High	3.04	–	–	1	–	–	1
Blackjack oak	*Quercus marilandica*	Medium	5.58	–	–	–	–	1	1
Water oak	*Quercus nigra*	High	3.72	–	–	1	–	–	1
Chestnut oak	*Quercus prinus*	High	6.14	–	1	–	–	–	1
Post oak	*Quercus stellata*	High	5.7	–	1	–	–	–	1
Black oak	*Quercus velutina*	High	4.9	1	–	–	–	–	1
Slash pine	*Pinus elliottii*	High	4.35	–	–	–	–	–	–
Boxelder	*Acer negundo*	Medium	7.39	–	–	–	–	–	–
Bur oak	*Quercus macrocarpa*	Medium	6.43	–	–	–	–	–	–
Winged elm	*Ulmus alata*	High	3.63	–	–	–	–	–	–
American elm	*Ulmus americana*	Medium	3.97	–	–	–	–	–	–

Note the last five species, while reaching top five status under projected habitat changes, are not currently ranked as having high importance value at these locations

locations, there is an increased risk of a decline in *A. saccharum* habitat being realized throughout the century (Fig. 3A), but with Kentucky under relatively greater urgency to develop strategies. However, Vermont produces over 30 % of the total US maple syrup market, while Kentucky forest managers have a negligible syrup market (Farrell and Chabot 2012). This ES dimension to sugar maple's importance in Vermont should be added to the interpretation of the weightings shown in the matrix, where the climate change risk for a species is described in two dimensional space of likelihood of a habitat response and the consequence of a species' potential adaptability to climate change (Fig. 3A).

We also evaluated the potential for change across species at a given location of interest. The projections

Table 3 List of the top five tree species, in rank order, within each installation based on current modeled distribution and top species after models are projected onto high (Hadhi) and low (PCMlo) climate change storylines

Rank	South Carolina	Arkansas	Missouri	Georgia	Wisconsin	Kentucky	Maine	Pennsylvania	Michigan	Vermont
Cur										
1	Loblolly pine	Loblolly pine	Black oak	Loblolly pine	Northern red oak	Sugar maple	Balsam fir	Red maple	Red maple	Sugar maple
2	Sweetgum	Sweetgum	Post oak	Sweetgum	Quaking aspen	Eastern red cedar	Red maple	Chestnut oak	Sugar maple	Red maple
3	Water oak	Green ash	White oak	Yellow poplar	White oak	White oak	Red spruce	Black cherry	Quaking aspen	Am. beech
4	Red maple	White oak	Eastern red cedar	Flowering dogwood	Red maple	White ash	Sugar maple	Northern red oak	Jack pine	Balsam fir
5	Longleaf pine	Shortleaf pine	Blackjack oak	Red maple	Paper birch	Flowering dogwood	Am. beech	White oak	Red pine	Eastern hemlock
HADhi										
1	Loblolly pine	Loblolly pine	Post oak	Loblolly pine	Am. elm	Loblolly pine	Red maple	Post oak	Eastern red cedar	Post oak
2	Slash pine	Sweetgum	Black oak	Sweetgum	Bur oak	Post oak	Eastern red cedar	Winged elm	Am. elm	Red maple
3	Sweetgum	Post oak	Shortleaf pine	Post oak	Boxelder	Winged elm	Sugar maple	Shortleaf pine	Red maple	White oak
4	Water oak	Shortleaf pine	Loblolly pine	Shortleaf pine	Black oak	Sweetgum	White oak	Loblolly pine	Black oak	Eastern red cedar
5	Longleaf pine	Winged elm	Blackjack oak	Water oak	Eastern red cedar	Shortleaf pine	Northern red oak	Black oak	White oak	Black oak
PCMlo										
1	Loblolly pine	Loblolly pine	Post oak	Loblolly pine	Am. elm	Post oak	Red maple	Red maple	Red maple	Red maple
2	Sweetgum	Sweetgum	Black oak	Sweetgum	White oak	Eastern red cedar	Balsam fir	Chestnut oak	Northern red oak	Sugar maple
3	Water oak	Post oak	White oak	Post oak	Black cherry	Winged elm	Sugar maple	White oak	Black cherry	Eastern hemlock
4	Slash pine	Winged elm	Blackjack oak	Water oak	Northern red oak	White oak	Am. beech	Black oak	Sugar maple	Am. beech
5	Post oak	Shortleaf pine	Shortleaf pine	Shortleaf pine	Black oak	Flowering dogwood	Eastern hemlock	Northern red oak	White oak	White ash

Shading corresponds to those species that were identified as being in the top 10 % of ecosystem services based on carbon storage and water regulation from I-tree's Species program. The darkest shade indicates a species that is currently a dominant species and remains so in at least one of the climate change scenarios, the middle shade indicates the species is dominant only in the current setting, and the lightest shade indicates the species' habitat potential would increase to the top five status by century's end (for scientific names see Table 2)

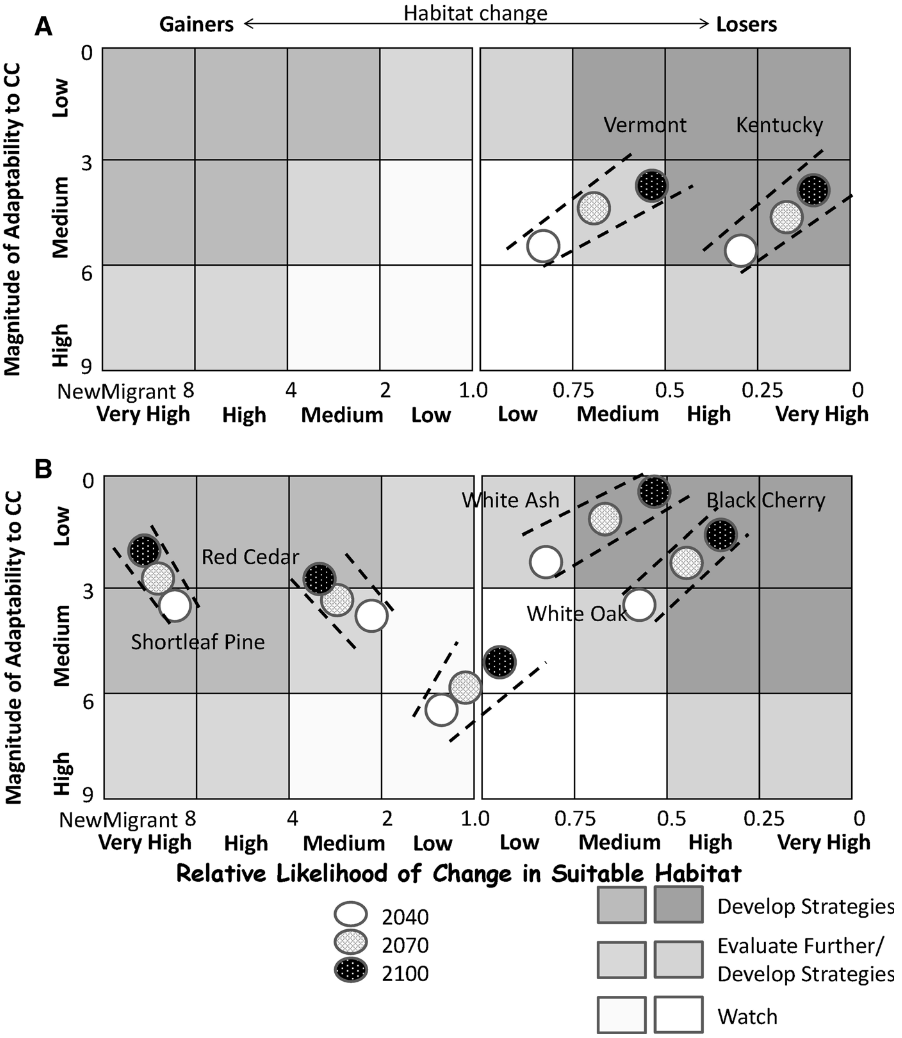

Fig. 3 **A** Risk matrix for *Acer saccharum* (sugar maple) in Vermont and Kentucky to illustrate variability in climate change vulnerability within a species, and **B** risk matrix for Pennsylvania illustrating the interplay between climate change risk and the need to develop management actions for five species both currently important and one with the potential to have increases in suitable habitat by 2100. *Dashed lines* reflect the range of the projected habitat changes based on PCMlo and Hadhi, while *circles* capture the mean change in relative risk

for Pennsylvania suggest that under Hadhi (greater climate sensitivity scenario), the increase in potential for southern pines that barely extends into the region at present, could increase in habitat, with a concomitant decline in some hardwood species of the region (Fig. 3B). Most notably, *P. serotina*, an extremely high value and currently common timber species, is projected to decline to only 38 % of its current value—a large impact on this important provisioning service of wood production as well as providing wildlife food resources. While adaptation strategies need to be developed for potential declining species, the same must be considered for species showing marked increases. The potential increase of *Pinus echinata* would need to be placed alongside how the other provisioning services may change, but clearly these data suggest a high potential for a stark shift in the aesthetic and economic nature of the forest. As we begin to concentrate on specific important tree species of an area, it becomes possible to conduct an enhanced assessment of risk to climate change vulnerability on forest systems.

Discussion

Understanding both the current state of ES and how the habitat of the trees that make up these communities may respond to climate change will be important to planning and policy. Our reliance on forests to sustain human well-being clearly requires that we account for the realities that changing climate conditions and associated stressors will continually shape the forest attributes related to ES (Bonan 2008). By exploring multiple locations across a broad geographic extent, we can quickly gain a perspective that climate change vulnerabilities will present location-specific opportunities and challenges to facilitate climate change adaptation. The information contained within FRICV, with a focus on forest communities and important individual trees, lends itself to many avenues to explore the ways in which ES may be affected by climate change. Yet it is important to stress that these data, derived from species distribution models, carry many assumptions which preclude accurate predictions of how these changes will finally unfold (Wiens et al. 2009); hence our focus on how suitable habitats may change (Matthews et al. 2011). It is important to consider these assumptions while also considering that the outputs do provide important information on the capacity that species have to respond to change, essential for planning (Wiens et al. 2009). In the end, we can evaluate how these shifts might be realized, with a focus on the management decisions needed to facilitate or guard against disruptions of these ecosystems and the services they provide.

Ecosystem services and sense of place

In building the habitat models, we first use a macroecological approach, by incorporating all distributional data for each species and corresponding environmental data, within the entire region, so that the bounds and correlating variables can be established (Kerr et al. 2007). Then, by zeroing in on specific locations, we can begin to evaluate the individual combinations of species composition and the set of geographic characteristics that set the stage for the current forest conditions. This embedded focal area perspective also aligns with the need to understand the balance of the ES being provided in an area (Smith et al. 2011) before we consider how such changes may impact it. The assessment of installation vulnerability (FRICV), when overlaid with a perspective of ES, provides a framework for comparing among locations as well as a starting place to explore more in-depth characterizations of a particular location. In order to further evaluate the potential consequences that climate change may impose on specific services, one must undertake a study of the finer scale processes operating within the current, but also changing, heterogeneous landscapes to generate and evaluate appropriate and specific management options (Turner et al. 2013). Though beyond the scope of this paper, there are examples of such fine-scale efforts within this special issue.

Relative services from a forest community perspective

One of the challenges of evaluating how ES may change in light of perturbations like climate change is the (in)ability to evaluate what a change in composition might mean to the services provided. The focus on maintaining ecosystem function certainly resonates with preserving vital supporting functions on the landscape (Lavorel and Grigulis 2012). A key component to preserving a broad array of functions is to also maintain and promote a broad diversity of plants within the system (Kremen 2005; Bastian 2013). Fortunately, the diversity within the forests represented in this study is quite high, with tree species richness among the 149 sites ranging from 33 to 79 (median = 58; Table 1). This relatively high diversity of trees results in part from the wide variety of climatic conditions that currently exist and are likely to continue (though in different forms), resulting in landscapes that are likely to remain forested (though also in different forms) into the future. This is in contrast to the Mediterranean, where forest landcover types are projected to be replaced by more drought and heat-tolerant plant functional types (Diaz et al. 2007), or the transition in the arctic where forests are encroaching on tundra (MacDonald et al. 2008).

For many locations within the eastern US, though there may be a high diversity of tree species, often times only a few dominant species tend to govern the ecological system so that changes in habitat to those few species could result in rather high consequences with respect to ES. With a median of 53 % of the total importance value contained within the top five species of a given installation (Table 1), changes in habitat for those species would have the potential to disproportionally influence the services provided. For example, if a site had projected high losses in habitat coupled with relatively lesser amounts of gains in habitat, the site would have an increased probability for other destabilizing events such as plant invasions. To fully account for the interplay between gains and losses, one would need to address the time lags both for incoming and outgoing species, which this work does not address (but see Iverson et al. (2004) and Prasad et al. (2013) for incorporating migration over 100 years). For outgoing species, the changes may occur over long time periods as trees generally have long lives, or they could occur relatively quickly should the location undergo a serious disturbance such as fire (e.g., Liu et al. 2010), insects (Paradis et al. 2007), or disease (Pautasso et al. 2012).

Focus on individual species and the ecosystem services they provide

The concepts of ES often rely on considering species both collectively as well as individually, as each species has its own capacity to provide specific functions (Hooper et al. 2005). For example, the habitat loss of *Tsuga canadensis* (Eastern Hemlock) projected for most locations along with a serious insect pest (hemlock wooly adelgid, *Adelges tsugae*) killing vast numbers of trees, will lead to a disproportionate impact on water resources (Brantley et al. 2013). By considering the unique individual contributions of species, we can conceptualize how shifts in species will impact some ES. Therefore, by considering both the projected habitat changes and the adaptability of each species at a given location, it is possible to accumulate evidence on how great the potential for ES changes within a given location may be. In the example of the Letterkenny Army Depot installation in Pennsylvania, the results suggest a potential change in the underlying forest types from northern hardwood and oak-hickory to a greater increase of pine (Table 1). This change would suggest a fundamental shift in how the landscape provides its diverse services. For example, the projected decline in habitat and ES for *P. serotina* and *Fraxinus americana* (white ash), two species that have high economic and cultural benefits, may far exceed the concomitant new services provided by the increasing species (Fig. 3). Both species have high quality hardwoods that are established iconic products of the region (e.g., cherry wood for solid wood products and veneer and white ash for baseball bats), and both species not only face projected losses in habitat, but their life history traits will also likely challenge their adaptability to climate change. Furthermore, *F. americana*, with its so-far unchecked decimation from emerald ash borer (EAB, www.emeraldashborer.info), serves as a pointed reminder that the potential climate change impact can be dwarfed in time by emerging direct threats to mortality. Coupling these losses of hardwood species habitat with gains in habitat for *Juniperus virginiana* (eastern redcedar), *P. echinata* and *P. taeda* suggest opportunities for very different production services, depending on local community infrastructure and capacities (e.g., does this increase the likelihood of pulp wood production?).

Finally, by examining individual species across locations, we can see another perspective on how variation in the vulnerability to climate change enters into the resulting ES (Fig. 3A). *A. saccharum* is projected to decline across much of its range (Iverson et al. 2008), a continuation of current trends in maple decline (Long et al. 2009). That, along with evidence of altered maple sap production as a response to current and potential future climate, clearly raises concerns for this iconic species of eastern North America and its billion dollar industry (Duchesne et al. 2009).

Of the ten focal locations presented here, *A. saccharum* was the top species at Fort Ethan Allen, Vermont and Fort Knox, Kentucky. Both locations will likely have forest community changes as a result of the decline in *A. saccharum* habitat (Fig. 3A), but since Kentucky is closer to its southern range limit, it is projected to lose a greater proportion of its habitat. Yet these locations have very different production values for maple syrup, with Vermont accounting for over a third of the US production and Kentucky without any major industrial capacity (Farrell and Chabot 2012). So in this case, even though the Kentucky location is projected to lose relatively more habitat, there will be a greater loss in Vermont of the services that sugar maple provides in terms of monetary and cultural value (Groffman et al. 2012), and these will not be readily transferable to other species.

The matrix outputs for five species in Pennsylvania and for sugar maple in Vermont vs. Kentucky provide a visual representation of the current and future risk associated with the species, by combining both likelihood of change (either gain or loss of suitable habitat) with the capacity of the species to adapt to expected conditions under climate change. When coupled with socio-economic importance related to the services provided, new insights are gained into the future of the ES these forest communities provide.

Conclusions

This paper presents a means to address the potential impacts to ES associated with forest community vulnerability to climate change across the eastern United States, as exemplified using 149 US Department of Defense installations for an overall perspective, and with 10 representative installations to derive finer-scale metrics for evaluation. This broad perspective, not common in the ES literature, provides a perspective of regional factors influencing ES; these factors include climate variables most prominently, but also variations in edaphic and physiognomic conditions. The analysis of the 10 installations provides a more detailed understanding of the role that geographic variation among species and site conditions play in estimates of vulnerability and changes in ES under a changing climate. In addition to contemporary and locally derived information concerning ES, we believe the additional inputs of potential future species habitats, and the derived vulnerabilities to climate change, add an important dimension to the evaluation of ES. The newly derived index, FRICV, and the variables from which it is calculated, provide tools to compare vulnerabilities to climate change among locations as well as provide indicators that lend themselves to specific elements of key supporting (e.g., carbon and nutrient cycling), provisioning (e.g., maple syrup, building materials, and wildlife habitat), regulating (e.g., water retention and purification, erosion control), and cultural (e.g., recreation, traditional uses) services. Land managers and policy makers are dealt a set of difficult choices when prioritizing among a plethora of desired outcomes, especially in the context and uncertainty of climate change. Knowledge of specific species vulnerabilities and the ES profiles that current and projected future forest community types provide could be important to such decisions. Cost-benefit analyses of various adaptation strategies to climate change (i.e., resistance, resilience, response; Millar and Stephenson 2007) will be contingent also on the ES profile, which will necessarily require place-based decisions in part because of the kinds of spatial variations in vulnerabilities and ES discussed in this paper.

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