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Development of risk matrices for evaluating climatic change responses of forested habitats

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Abstract We present an approach to assess and compare risk from climate change among multiple species through a risk matrix, in which managers can quickly prioritize for species that need to have strategies developed, evaluated further, or watched. We base the matrix upon earlier work towards the National Climate Assessment for potential damage to infrastructures from climate change. Risk is defined here as the product of the likelihood of an event occurring and the consequences or impact of that event. In the context of species habitats, the likelihood component is related to the potential changes in suitable habitat modeled at various times during this century. Consequences are related to the adaptability of the species to cope with the changes, especially the increasing intensity and/or frequency of disturbance events that are projected. We derived consequence scores from nine biological and 12 disturbance characteristics that were pulled from literature for each species. All data were generated from an atlas of climate change for 134 trees of the eastern United States (www.nrs.fs.fed.us/atlas). We show examples which depict a wide range of risk for tree species of northern Wisconsin, including species that may gain substantial habitat as well as lose substantial habitat, both of which will require the development of strategies to help the ecosystems adapt to such changes.

1 Introduction

The world's climate communities (e.g., policy, research, and social societies) have begun to adopt a risk-based approach to thinking about how to cope with a changing climate. This fact

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became evident when the Summary for Policymakers of the Synthesis Report of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) included the following unanimously approved language (word by word approval): "Responding to climate change involves an *iterative risk management* process that includes both adaptation and mitigation and takes into account climate change damages, *co-benefits, sustainability, equity* and attitudes to risk (Intergovernmental Panel on Climate Change 2007, pg 22, italics emphasis ours)." Since then, all four of the Panel Reports of *America's Climate Choices* (ACC), plus the report of the Committee on America's Climate Choices (National Research Council 2010a, b, c, d, 2011), have made similar statements, as did the New York (City) Panel on Climate Change (NPCC) and its associated Adaptation Task Force (New York City Panel on Climate Change 2009). The National Climate Assessment (2011) also has 'risk' embedded in its vision statement several times, to assess, communicate, analyze and reduce risk due to climate change.

An important challenge is to make a risk-based perspective operational in the climate change context, but we do not have to start from the very beginning. All risk management techniques are, to begin with, fundamentally rooted in the same statistical definition of risk—the probability that an event will occur multiplied by a measure of its consequences (e.g., Raiffa and Schlaiffer 2000). Many decision makers already favor risk-based approaches in multiple contexts because they are generally derived from sound economic theory *and* because they can be applied to situations characterized by significant uncertainty. Finance directors, government officials, and infrastructure managers, all of whom deal with risk and associated best practices on a daily basis, understand that (1) focusing attention on the sources of risk (through both the likelihoods and the consequences) can improve social and/or private welfare and (2) risk-based decisions can be drawn rigorously from either the strict quantification of both components *or* even qualitative representations that at least speak to both.

Thus the challenge is to find ways to use these dual components, likelihood X consequences, within the climate science and ecosystem science communities to express the climate change impacts in ways that speak to those of the decision-makers' risk-based concerns. This brief paper offers a proof of concept application of the risk-matrix approach designed by the NPCC (2009) to support adaptation and to protect infrastructure that can be applied widely–to consider, for example, ecosystems for which the economic value is not necessarily well established but for which the services provided to humans can be calibrated. The key is to recognize as noted above that risk is the product of likelihood and consequence; but as always, understanding the details is critical. A measure of consequence, or impact, can be calibrated in a variety of metrics ranging from physical impacts to vulnerability where vulnerability depends on exposure and sensitivity and can be modified by the exercise of adaptive capacity. It is more complicated when calibration of any of these factors takes account of multiple stressors, as we attempt to do in this paper with information gleaned from the literature. It follows that the consequences may have synergies and/or conflicts with other policy objectives which may be particularly important. Meanwhile, likelihood depends on climate sensitivity, and a host of associated factors that influence the association between climate variability and variables that influence human welfare.

In this paper, we demonstrate the development and application of the risk-matrix approach to the forested habitats of northern Wisconsin. This area is the focus of an 'all-lands' approach to vulnerability assessment and the associated management strategies for both adaptation and mitigation (Swanston et al. 2011; Swanston and Janowiak 2012). In assessing 73 tree species in the region (both presently and potentially occurring in the future) for both their vulnerability and adaptability to climate change, we provide the key components for presenting the risk matrix for comparing among species.

2 Defining a practical tool for risk assessment

The fundamental definition of risk from Raiffa and Schlaiffer (2000) and others before them makes it clear that analysts and decision-makers who focus their attention on uncertain futures should organize their thoughts around its dual components–likelihood and consequence(s), calibrated with respect to whatever metric(s) the decision-maker takes to be important. This was the approach NPCC (2009) adopted in New York City when they created a fixed (a priori) shading system within a risk matrix, with darker shading indicating higher qualitative and functional levels of risk, corresponding to the categories of (1) watch–relatively low risk but be diligent; (2) evaluate further and perhaps develop strategies–middle level of risk; and (3) develop strategies to cope with the risk–highest level of risk (Fig. 1a).

Using this two-dimensional framework, an example for potential future flooding on infrastructure in New York City was prepared by Yohe and colleagues (Yohe 2010; Yohe and Leichenko 2010, Fig. 1b). They provide qualitative judgments about both the magnitude of vulnerability and the likelihood of flooding exposure at specific points in time. The matrix portrays the fundamental nature of the risk (the product of likelihood and consequence) to specific types of infrastructure, which can be placed in the matrix for specific points in the future. This example displays a representative illustration of changes in risk (e.g., potential number of buildings damaged or destroyed) over time generated by the implications of sea level rise on the return time of what is now the 100 year storm and what is now the 10 year storm.

The point of creating the matrix was not that anybody would make a policy decision on the basis of this representation; it was that this representation, with judgments defended before

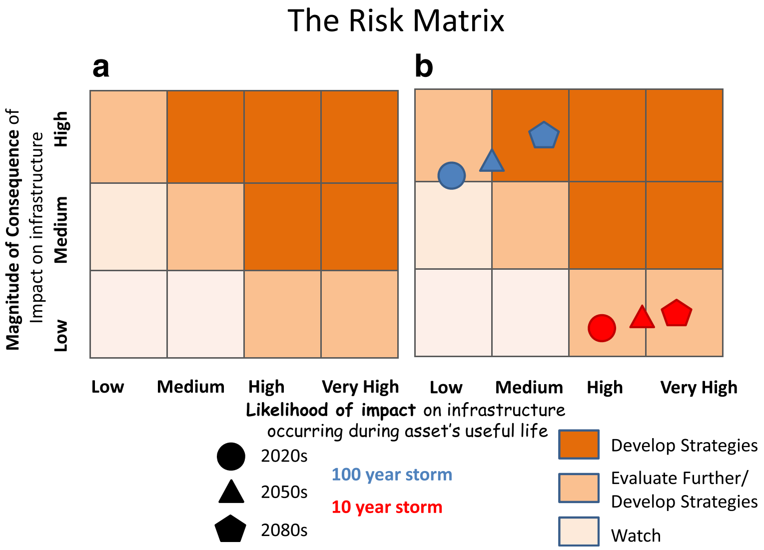


Fig. 1 **a** This two-dimensional risk matrix displays qualitative judgments about both the magnitude of vulnerability and the likelihood of exposure at specific points in time. The *shading in the box* indicates differences in qualitative judgments about risk levels and the need for response. Source: Figure 5 in Appendix B of NPCC (2009) and Fig. 4.2 in NRC (2010b). **b** NPCC (2009) reports that the return time for the current 100-year storm falls to 65–85, 35–55, and 15–35 years on average (low moving to medium likelihood) years on average during the 2020's, 2050's and 2080's, respectively along high and low emissions scenarios. The return time for the current 10-year storm falls to 8–10, 3–6, and 1–3 years for the same cases (high to very high likelihood). NPCC (2009) also reports that consequences climb over time because of the anticipated increases in the value and/or number and/or size of the buildings affected

peers, would organize individuals' and governmental thinking about near and far-term risk around both likelihood and consequence. This example is intended to show that the thought process of locating risk within such a matrix works not only for infrastructure as in the New York City application, but also for organizing thoughts around risks that are anticipated for ecosystems, which we now demonstrate for Northern Wisconsin exposure to climate change.

3 Application

3.1 Vegetation, land use, and climate of northern Wisconsin forests

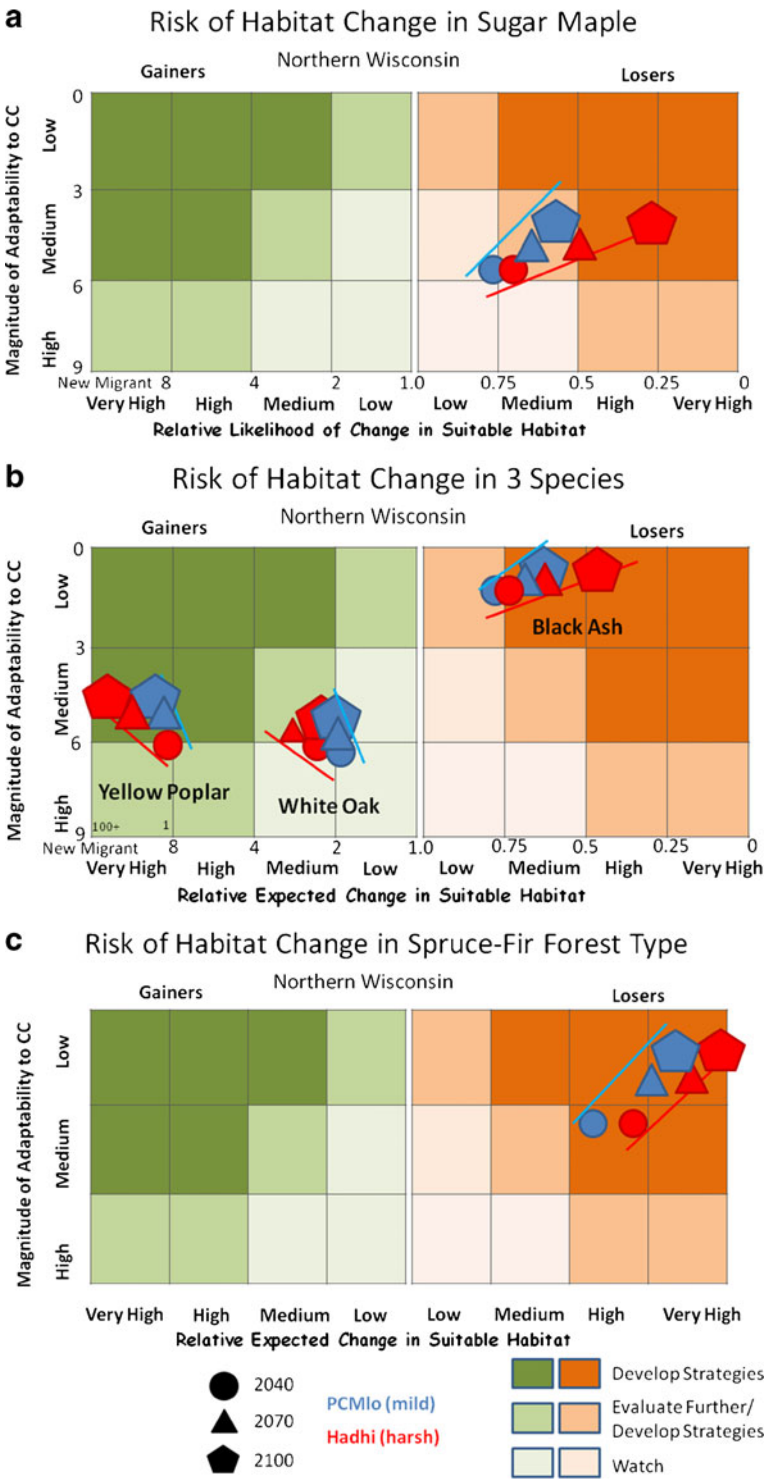
A logical location to apply the risk matrix approach in an ecosystem context is in ecological province 212j of northern Wisconsin, where work is ongoing to assess vulnerabilities and adaptation strategies (Swanston et al. 2011; Swanston and Janowiak 2012). This area is fully described in these cited documents, but summaries of vegetation, land use, and the climate are presented in Online Resource 1. Suffice it to say that each of these ecological forces has undergone radical change over the past 100 years, and that the threats and vulnerabilities to many species and forest types have been changing. Many of these changes are directly or indirectly tied to the changes underway with climate, which is projected to change even more. By 2100, May–September temperatures in this region may increase by 2.2–7.6°C, according to the Parallel Climate Model, B1 scenario (PCMlo = mild scenario; Washington et al. 2000) and the Hadley CM3 model, A1fi scenario (Hadhi = harsh scenario; Pope 2000), respectively (Swanston et al. 2011). These scenarios, used in the risk matrices presented below, represent the full range of possibility according to models and emission storylines projected by the Intergovernmental Panel on Climate Change (IPCC 2007; Nakicenovic et al. 2000).

3.2 Indices for likelihood and consequences for trees of the eastern United States

3.2.1 Bases for the risk matrix for tree species habitats

We modified the matrix structure presented for New York City to replicate the likelihood of exposure by magnitude of vulnerability (or consequences) matrix, and demonstrated for sugar maple (*Acer saccharum*) in northern Wisconsin (Fig. 2a). Because in the case of changes in species habitats, a decrease *or* increase may pose additional management

Fig. 2 **a** Risk matrix for sugar maple, a potential loser of habitat in northern Wisconsin, especially under the Hadhi scenario of climate change. The 'Gainers' section in greens is the mirror image of the 'Losers' section in browns in that the species gaining habitat may also merit the development of management strategies. The numbers on the x axis are based on future:current ratios of suitable habitat for the species, so that a 0 indicates complete loss of habitat, a 1.0 indicates no change, and an 8 represents an 8-fold increase in suitable habitat. Increasing projected change away from 1.0 in either direction indicates additional care managers need to take with regard to managing the species. The numbers on the y axis are based on the average scores of the 12 disturbance and 9 biological modification characteristics; a higher number means more adaptability of the species towards climate change. The increasing symbol sizes of the three dates of 2040, 2070, and 2100 indicate conditions are expected to get more unfavorable for the species as time proceeds in this century. **b** Risk matrix for three tree species, representing a species expected to lose habitat (*black ash*), gain habitat (*white oak*), and become a potential new migrant because of newly appearing habitat (*yellow poplar*). Because the new migrant is not currently present in northern Wisconsin, the future:current ratio has a 0 devisor, so we added 1 to each value to calculate the ratios ranging 1–100. The potential migrant species would require special attention to assess the biological and sociological realities associated with migrating into the zone of study. **c** Risk matrix for the spruce-fir forest type, based on a combination of potential changes in suitable habitat for black spruce and balsam fir. The axes are quantified the same as in **a**) and **b**), but are not labeled with the numbers ▶


a
Risk of Habitat Change in Sugar Maple
Northern Wisconsin
Gainers
Losers
Magnitude of Adaptability to CC
Low
Medium
High
0
3
6
9
New Migrant 8
4
2
1.0
0.75
0.5
0.25
0
Very High
High
Medium
Low
Low
Medium
High
Very High
Relative Likelihood of Change in Suitable Habitat
b
Risk of Habitat Change in 3 Species
Northern Wisconsin
Gainers
Losers
Black Ash
Yellow Poplar
White Oak
100+
1
Magnitude of Adaptability to CC
Low
Medium
High
0
3
6
9
New Migrant
8
4
2
1.0
0.75
0.5
0.25
0
Very High
High
Medium
Low
Low
Medium
High
Very High
Relative Expected Change in Suitable Habitat
c
Risk of Habitat Change in Spruce-Fir Forest Type
Northern Wisconsin
Gainers
Losers
Magnitude of Adaptability to CC
Low
Medium
High
Very High
High
Medium
Low
Low
Medium
High
Very High
Relative Expected Change in Suitable Habitat
● 2040
▲ 2070
⬟ 2100
PCMlo (mild)
Hadhi (harsh)
Develop Strategies
Evaluate Further/ Develop Strategies
Watch

challenges, another modification was the creation of a mirror image of the matrix in order to capture also those species or forest types that are projected to increase in suitable habitat into the future (the 'gainers', Fig. 2a).

Data used for these risk matrices are based on a long history of statistical habitat modeling (using the model DISTRIB) and species vulnerability assessments, for 134 tree species across the eastern United States (described in Online Resource 2, and in Iverson et al. 2008, 2011). Suitable habitat was defined as those climatic, edaphic, and physiognomic conditions suitable for a particular species to occur, and modeled using 38 predictors including 7 climate, 5 elevation, 9 soil class, 12 soil property, and 5 land use and fragmentation variables. The metric used for quantifying suitable habitat was summed importance values (IV) for northern Wisconsin. Thus, the area and the abundance of the species are accounted for, both now and potentially in the future. Key outputs from this work are the ratios, for any particular species, of quantified suitable habitat in the future (for 30-year periods ending in 2040, 2070 and 2100) under Hadhi and PCMlo climate scenarios to suitable habitat present now. These ratios form the basis of the X axis—the likelihood axis.

Modeling the responses of a comprehensive suite of biological and disturbance characteristics with a myriad of interactions is extremely difficult–irrespective of whether statistical or process-based mechanistic models are used. We therefore recently adopted a literature-based scoring system, called Modification Factors, to capture the species' response to changes in climate (Matthews et al. 2011b) that cannot be adequately captured by our habitat modeling. This literature-based approach was used to assess the capacity for each species to adapt to 12 disturbance types, and to assess nine different biological characteristics related to the species adaptability (described in Online Resource 3, and Matthews et al. 2011b). To score each characteristic for each species, key, summarized literature was reviewed and scored according to specific criteria to arrive at a modification factor score ranging from −3 to +3 (very negative to very positive influence in dealing with expected climate change and associated disturbance impacts). We also scored each of the characteristics for their future climate relevance (e.g., will the changing climate potentially increase the risk of this disturbance?), with scores ranging in increasing relevance from 1 to 4. For species that have very little information available, we used information from related species or use 'default' values derived from all other species. Further explanations, definitions, default values, and examples of the scoring system are provided in Online Resource 3 as well as Matthews et al. (2011b). The resulting values are related to the adaptability of the species to climate change, and are used to construct Y axis values in the risk matrix.

By combining key species, we can also prepare data for the risk matrices for a particular forest type. As described in Online Resource 4, we have done this for the spruce-fir type for northern Wisconsin.

3.2.2 Likelihood: based on current and potential future importance values

The ratios of summed importance values in the future (2040, 2070, 2100) to summed modeled importance values currently are the key values for the likelihood (X) axis in the risk matrix. These ratios are presented for sugar maple in Table 1, and which also provide the data on the X axis (e.g., likelihood) of the risk matrix (Fig. 2a).

'Likelihood' in this context would be, for any point in time, the potential that a section of forest within a specified region would have suitable habitat for the selected species or forest type, *relative to its current amount of suitable habitat*. The axis is based on the difference in suitable habitat between current and three future time intervals ending around 2040, 2070, and 2100. In this exercise, we contrast two widely differing scenarios of modeled climate

Table 1 Data to quantify the values for sugar maple in the risk matrix

Scenario[a]	Year[b]	Future:current[c]	ModFac[d]	Future relevance[e]	Future ModFac[f]
Hadhi	2040	0.68	5.81	1	5.81
Hadhi	2070	0.50	5.81	0.86	5.00
Hadhi	2100	0.32	5.81	0.72	4.19
PCMlo	2040	0.77	5.81	1	5.81
PCMlo	2070	0.69	5.81	0.86	5.00
PCMlo	2100	0.67	5.81	0.72	4.19

[a] Scenario of climate model and emissions

[b] Year ending 30-year average: 2040 = average of 2010–2040; 2070-average of 2040–2070; 2100 = average of 2070–2100

[c] X axis:Ratio of habitat importance value for sugar maple in northern Wisconsin at future year relative to current (1960–1990)

[d] Modification factor score related to both disturbance and biological characteristics (see text)

[e] Future relevance score is determined by proportion of disturbance score resulting from disturbances likely to be increasing because of climate change

[f] Y axis:Future ModFac score is product of the disturbance ModFacs*Future Relevance, thus a measure of increasing impacts through time

change, PCMlo and Hadhi, to extract a range of possibility of risk associated with the IPCC-projected future climates.

We view the Future IV:Current IV ratio as a function related to likelihood of impact on the amount of suitable habitat—the greater the potential change in IV, the greater likelihood of impact. For species showing loss of habitat (i.e., reduction in Future IV relative to current), the X-axis ranges from +1 (no change in habitat with time) to 0 (complete loss of habitat over time) (Fig. 2a). For sugar maple, the values range from 0.32 to 0.77, depending on year and scenario (Table 1, Fig. 2a). The models show that for sugar maple, the largest reduction of suitable habitat (only a third of remaining habitat) would be present by 2100 if we follow the high emissions track and if the Hadley GCM is accurate. However, if humans adopt a strict energy conservation track (and the PCM GCM is more accurate), roughly two-thirds of the suitable habitat for sugar maple would remain from northern Wisconsin by 2100 (Table 1). For species showing gains in habitat (i.e., increase in Future IV relative to current), the range in this demonstration is +1 to +8, and is exemplified by white oak (*Quercus alba*) in Fig. 2b, which is modeled to show 2–3x increases of habitat by 2100. For newly entering migrants, the range is confined to the leftmost column of the graph and ranges from 1 to 100+, exemplified by yellow poplar (*Lireodendron tulipifera*) in northern Wisconsin (Fig. 2b). In this case, because current IV is zero (indivisible), we simply add 1 to both current and future scores, and then divide (1 to 108 for yellow poplar). It is important to understand that these numbers themselves are not directly the scale of 'likelihood', but rather scales of the Future IV:Current IV, and are only plotted on Fig. 2a and b to show the quantitative linkages.

3.2.3 Consequences: based on modification factors

'Consequences' in this context would be related to the species or forest type's adaptability under climate change, based on a literature assessment of the species' biological traits and capacity to respond to disturbance which are occurring or likely to occur within this century, and as compounded (or not) by climate change. In this case, we score the adaptability of the species to cope with climate change; the lower the capacity to cope, the greater risk for habitat loss and greater the consequences from climate change.

We build this component of the risk matrix from the modification factors as described in Online Resource 3 and Matthews et al. (2011b), using the nine biological and 12 disturbance characteristics, scored individually from −3 to +3 (rescaled 0–6) as an indication of the adaptability of the species to climate change. The mean, rescaled values for biological and disturbance characteristics were plotted to form two sides of a right triangle; the hypotenuse was then a combination (disturbance and biological characteristics) metric, ranging from 0 to 8.5, and used as the Y axis of the risk matrix (Table 1, Fig. 2a). Relative to many other species, sugar maple is fairly adaptable, with a score of 5.81 (Table 1). Other species' scores reported in this paper range from 6.14 for white oak to 1.69 for black ash (*Fraxinus nigra*) (Fig. 2b). Black ash scores very low in part because 6 of 12 disturbance characteristics score at least a −2, with a clear overriding threat from the emerald ash borer (*Agrilus planipennis* Fairmaire) (Poland and McCullough 2006).

It is important to note that the 'consequences' axis does not include socio-economic consequences. Obviously, these are important but are not considered here. For example, a decline in sugar maple habitat can be linked to loss in the maple syrup industry. A loss of black ash is very important to certain Native American tribes that depend on the species for their basket-making livelihood.

3.2.4 Future relevance in risk of disturbances

So far, we have derived the 'likelihood X axis' from potential changes in suitable habitat at three future times this century (2040, 2070, 2100), and a 'consequences Y axis' from the adaptability scores derived from the biological and disturbance modification factors. These numbers form the basis for the first interval (2040). For sugar maple, it results in X values of 0.68 (PCMlo) to 0.77 (Hadhi), and a Y value of 5.81 from Modification Factors (Table 1, Fig. 2a). However, these two components do not account for the increasing likelihood that certain disturbances will occur in the decades following 2040. Virtually all GCM models suggest that the hydrologic cycle will become more vigorous as warming of the atmosphere continues; thus we will witness increasing floods, droughts, wind, ice, etc., directly, and with the indirect result of increasing outbreaks of pests and pathogens as well as fires. Therefore, we derived a means to represent this potential for increasing climate-related disturbances for the periods ending in 2070 and 2100.

As previously mentioned, we estimated the 'future relevance', ranging from 1 to 4, as well as assigned a literature-based score, ranging from −3 to +3, for each of the 12 disturbance characteristics, (see also Matthews et al. 2011b). The sum of the 12 products of these two scores (−20 for sugar maple), divided by the minimum possible sum of products (−144) yielded an estimate of the relative influence these disturbances may have in the future. For sugar maple, this calculation results in a 14% reduction in adaptability by, we assume, the year 2070 (shown as a 0.86 multiplier in Table 1). To generate the multiplier for the 2100 date, we arbitrarily calculated it as twice the 2070 multiplier, so that for sugar maple, there would be a 28% reduction in adaptability (0.72 multiplier in Table 1).

4 Results

A risk matrix for sugar maple (*Acer saccharum*) shows the level of risk of losing suitable habitat varying from relatively low to high, depending on the model/scenario and time into this century (Fig. 2a). Because of the very high projected increase in temperature for this region by 2100, especially under Hadhi with a projected ~7.5°C increase in growing season temperature for northern Wisconsin, the species shows substantially more risk by then. According to the class boxes on the matrix, it would be quite important to develop strategies for dealing with this outcome. In contrast, with the mild scenario of PCM, the expectation would be that the urgency to develop strategies is lessened (e.g., evaluate further and perhaps develop strategies). The red (top) and blue (bottom) lines form a range of potentials according to our models and the IPCC scenarios of harshest to mildest.

In Fig. 2b, we present a risk matrix for three species, a 'loser' species, black ash (*Fraxinus nigra*), a 'gainer' species, white oak (*Quercus alba*), and a 'new migrant' species, yellow poplar (*Liriodendron tulipifera*). Black ash carries more risk because, among other disadvantageous traits, it has low adaptability to the emerald ash borer, which is carrying great risk to all ash species in North America (Prasad et al. 2010). White oak is expected to gain habitat in northern Wisconsin, and it is quite well adapted to many of the expected conditions in the future. Relative to many other species, there is not as much change projected with time or scenario for this species. Yellow poplar is currently not recorded in northern Wisconsin, according to forest inventory information of the US Forest Service. As a potential new migrant into the region, it is confined to the left-most column of boxes on the risk matrix, and this species may actually provide new opportunities for habitat or wood products, but will require managers to evaluate actual migration and colonization potentials, and develop strategies related to promoting the species (or not).

The spruce-fir forest type is the simplest of the forest types in the eastern United States, in that we plot a combination of just two species, balsam fir (*Abies balsamea*) and black spruce (*Picea mariana*), and these two species are similar both in X and Y axis traits (large losers of habitat, low level of adaptability) (Fig. 2c). To arrive at the axes scores, we took the total (summed) ratio of importance values of future:current for the X axis, and the averages of the two species for the adaptability and future relevance estimates. As shown, this forest type is in great danger of having nearly its entire suitable habitat moving north into Canada where it came from about 6,000 years ago (DeHayes et al. 2000). Developing coping and adaptation strategies to deal with these eventual changes, such as resistance, resilience, or response, are important for this forest type. Carrying this methodology forward with a) more general forest types (e.g., oak-hickory) or b) across large regions (e.g., the eastern United States), would be more difficult because there will often be a group of losing species and a group of gaining species which would tend to cancel each other out in the summations.

5 Discussion

The purpose of this paper is to show how we can combine a statistical modeling framework (DISTRIB) with a decision support scoring system (Modification Factors) to provide a means to compare among species for key risks in changes in habitats associated with climate change. As such, the approach reveals a process which may allow deliberations on potential adaptation strategies for maximum efficiencies and value added. The examples provided reveal various insights about species and how they may fare in facing key risks associated with climate change. This tool could potentially be used in public vetting to, for example, organize thinking of a planning team on a national forest as they work to include climate change into the Forest Plan, or for various stakeholder groups to respond to proposed projects while considering climate change. We anticipate developing a tool that will automatically create these matrices so that land managers, scientists, policy makers, and other interested parties could readily compare among species for likelihood of habitat change and their adaptability to a changing climate on their particular piece of ground. Those species needing attention could then be in focus for further studies and the development of coping strategies. However, managers and policy makers obviously have multiple objectives and constraints in their management of ecosystems; we provide the risk matrices as one tool in the decision framework.

We know that species have always been moving about the landscape (e.g., Davis and Shaw 2001; Davis and Zabinski 1992; Webb 1992), and that in recent decades, evidence is building that species are moving even faster than in historic times (e.g., Chen et al. 2011; Dobrowski et al. 2011; Parmesan and Yohe 2003). Here, we attempt to evaluate the risk for species' habitats to move over the remainder of this century (not necessarily the species moving, but rather their habitats, as significant lags times to movement occur with trees). The risk matrices demonstrated here provide a data-driven, consistent approach to assessing forms of both 'likelihood' and 'consequences' related to potential tree species changes in suitable habitat, over time, with climate change. They provide the potential range of possibility within the last Intergovernmental Panel on Climate Change tested models (IPCC 2007), including emissions trajectories (Nakicenovic et al. 2000). While direct quantitative risk cannot be drawn, a mechanism to evaluate species in a clearly defined relative risk manner is supported, given the volume of data available for tree species. We show that, besides the substantial uncertainty associated with the selection of GCM, there is a great importance with respect to outcomes of risk due to the decisions humans make regarding emissions, especially later in the century. Though the matrices are built from methods, data, and metrics that have been peer-reviewed and published, there are many assumptions and caveats associated with the outputs. The risk matrices show the spread of risk, and uncertainty, increasing with time, with estimated changes between the 'red' and 'blue' lines. We could produce these matrices for any of 134 tree species in the eastern U.S. (see our web site for the list (www.nrs.fs.fed.us/atlas), Prasad et al. 2009). Though we focus on data from our 134 tree species, other data sources could be used to generate the risk matrices. For example, efforts are underway to combine potential changes in suitable habitat for selected birds (again, from our website, Matthews et al. 2011a), with vulnerability assessments from the System for Assessing Vulnerability of Species (SAVS) system of Bagne et al. (2011), to derive a similar matrix. Similarly, elsewhere in the forestry sector, efforts are underway to construct such matrices for fire, carbon, and water.

The unique setting of applying risk matrices to ecological systems requires that the interconnected nature of these systems be represented. One basic feature of ecosystems is the multitude of competitive forces which drive species persistence, and as species habitat suitability changes, we must consider both losing and gaining species. Because many species also gain habitat (mostly as they move habitat north), there is also risk associated with these movements that managers must consider. Decisions will need to be made as to the desirability, value, and migration and colonization realities associated with potential new migrants, as compared to the need to secure the original species which are now facing new levels of competition. Here the adaptation framework will be invoked, considering resistance, resilience, or response (Millar and Stephenson 2007). Perhaps assisted migration is desired, or migration corridor management, or alternatively, a defensive strategy to prevent or slow the incursion of new species. Perhaps competition from the gainers will add stress to the species presently there and potentially decreasing in habitat. These all require attention from managers, hence "developing strategies" will be as relevant for species gaining habitat as those projected to lose habitat.

Socio-economic impacts are not included in these matrices and thus there is a large gap related to the 'consequences' of the changing habitats. For many species, one would expect a correlation between value(s) of particular species to society and the positive or negative changes in habitat portrayed here, but that would not always be expected. Of course, societal values also vary by population groups. Perhaps one approach towards including these impacts here would be to frame the discussion within the context of ecosystem services, as provided in one form by the Millennium Ecosystem Assessment (MEA 2005). The ecosystem services of our forests include high levels of supporting (e.g., primary production, nutrient cycling, soil formation), provisioning (e.g., food, fresh water, wood and fiber, fuel), regulating (e.g., regulation of climate, floods, disease, water purification), and cultural (e.g., aesthetic, spiritual, educational, recreational) services. These services, in turn, provide many of the constituents of well-being (security, basic material for good life, health, good social relations, freedom of choice and action). Forests changing as a result of global change will also result in changes in ecosystem services and thus the constituents of well-being–but for some species and for some people in some places, these changes are not always negative. Thus we can use ecosystem services to link to the socio-economic side from the biophysical side.

6 Summary

We present these ideas as a “proof of concept” paper for “organizing thoughts” to inform an approach for risk management challenges in forestry to address climate change impacts. Our example risk matrices allow for comparison among forest tree species with respect to likelihood and consequences of habitat change due to climate change. We suggest these types of approaches can be applied across a wide variety of impacts ongoing or expected from climate change. Although the metrics may not be derived from the same methodologies, the capacity to rate one species against another, or one location against another, will be helpful in developing a consistent approach to risk management from impacts of climate change.

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References

Bagne KE, Friggens MM, Finch DM (2011) A System for Assessing Vulnerability of Species (SAVS) to climate change. Gen. Tech. Rep. RMRS-GTR-257. U.S. Department of Agriculture, Forest Service, Rockey Mountain Research Station, Ft. Collins, p 28

Chen I-C, Hill JK, Ohlemüller R, Roy DB, Thomas CD (2011) Rapid range shifts of species associated with high levels of climate warming. Science 333:1024–1026

Davis MB, Shaw RG (2001) Range shifts and adaptive responses to quaternary climate change. Science 292:673–679

Davis MB, Zabinski C (1992) Changes in geographical range resulting from greenhouse warming: effects on biodiversity in forests. In: Peters RL, Lovejoy TE (eds) Global warming and biological diversity. Yale University Press, New Haven, pp 297–308

DeHayes DH, Jacobson GL, Schaber PG, Bongarten B, Iverson LR, Dieffenbacker-Krall A (2000) Forest responses to changing climate: lessons from the past and uncertainty for the future. In: Mickler RA, Birdsey RA, Hom JL (eds) Responses of northern forests to environmental change. Springer-Verlag, Ecological Studies Series, New York, pp 495–540

Dobrowski SZ, Thorne JH, Greenberg JA, Safford HD, Mynsberge AR, Crimmins SM, Swanson AK (2011) Modeling plant ranges over 75 years of climate change in California, USA: temporal transferability and species traits. Ecol Monogr 81:241–257

Intergovernmental Panel on Climate Change (IPCC) (2007) Climate change 2007: synthesis report. Cambridge University Press, Cambridge

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

Iverson L, Prasad AM, Matthews S, Peters M (2011) Lessons learned while integrating habitat, dispersal, disturbance, and life-history traits into species habitat models under climate change. Ecosystems 14:1005–1020

Matthews SN, Iverson LR, Prasad AM, Peters MP (2011a) Potential habitat changes of 147 North American bird species to redistribution of vegetation and climate following predicted climate change. Ecography. doi:10.1111/j.1600-0587.2011.06803.x

Matthews SN, Iverson LR, Prasad AM, Peters MP, Rodewald PG (2011b) Modifying climate change habitat models using tree species-specific assessments of model uncertainty and life history factors. For Ecol Manag 262:1460–1472

MEA (2005) Ecosystems and human well-being: synthesis. Island, Washington

Millar C, Stephenson NL (2007) Climate change and forests of the future: managing in the face of uncertainty. Ecol Appl 17:2145–2151

Nakicenovic N, Alcamo J, Davis G, de Vries B, Fenhann J, Gaffin S, Gregory K, Grübler A, Jung TY, Kram T, Lebre La Rovere E, Michaelis L, Mori S, Morita T, Pepper W, Pitcher H, Price L, Riahi K, Roehrl A, Rogner H, Sankovski A, Schlesinger M, Shukla P, Smith S, Swart R, van Rooijen S, Victor N, Dadi Z (2000) IPCC special report on emissions scenarios. Cambridge University Press, Cambridge

National Climate Assessment (NCA) (2011) Strategic plan, http://globalchange.gov

National Research Council (NRC) (2010a) Adapting to the impacts of climate change: report of the panel on advancing the science climate change. America's Climate Choices, National Academy of Sciences Press, Washington, DC. http://www.nas.edu

National Research Council (NRC) (2010b) Advancing the science of climate change: report of the panel on advancing the science climate change. America's climate choices, National Academy of Sciences Press, Washington, DC. http://www.nas.edu

National Research Council (NRC) (2010c) Informing decisions on climate change: report of the panel on advancing the science climate change. America's Climate Choices, National Academy of Sciences Press, Washington, DC. http://www.nas.edu

National Research Council (NRC) (2010d) Limiting the magnitude of future climate change: report of the panel on advancing the science climate change. America's Climate Choices, National Academy of Sciences Press, Washington, DC. http://www.nas.edu

National Research Council (NRC) (2011) Report of the committee on Americas climate choices. America's climate choices, National Academy of Sciences Press, Washington, DC. http://www.nas.edu

New York City Panel on Climate Change(NPCC) (2009) Climate change adaptation in New York city: building a risk management response. In: Rosenzweig C, Solecki W (eds) Prepared for use by the New York City Climate Change Adaptation Task Force, Annals of the New York Academy of Sciences, New York, NY, pp. 349, http://www.nyas.org

Parmesan C, Yohe G (2003) A globally coherent fingerprint of climate change impacts across natural systems. Nature 421:37–42

Poland TM, McCullough DG (2006) Emerald Ash Borer: invasion of the urban forest and the threat to North America's ash resource. J Forest 104:118–124

Pope VD (2000) The impact of new physical parameterizations in the Hadley Centre climate model–HadCM3. Clim Dyn 16:123–146

Prasad AP, Iverson LR, Matthews SN, Peters MP (2009) Atlases of tree and bird species habitats for current and future climates. Ecol Restor 27:260–263

Prasad A, Iverson L, Peters M, Bossenbroek J, Matthews SN, Sydnor D, Schwartz M (2010) Modeling the invasive emerald ash borer risk of spread using a spatially explicit cellular model. Landsc Ecol 25:353–369

Raiffa H, Schlaiffer R (2000) Applied statistical decision theory. Wiley Classics, New York

Swanston CW, Janowiak MK (eds) (2012) Forest adaptation resources: climate change tools and approaches for land managers. Gen. Tech. Rep. NRS-XX. U.S. Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, p 108

Swanston C, Janowiak M, Iverson L, Parker L, Mladenoff D, Brandt L, Butler P, St. Pierre M, Prasad AM, Matthews S, Peters M, Higgins D (2011) Ecosystem vulnerability assessment and synthesis: a report from the climate change response framework project in northern Wisconsin. U.S. Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, p 142

Washington WM, Weatherly JW, Meehl GA, Semtner A Jr, Bettge TW, Craig AP, Strand WG Jr, Arblaster JM, Wayland VB, James R, Zhang Y (2000) Parallel climate model (PCM) control and transient simulations. Clim Dyn 16:755–774

Webb TI (1992) Past changes in vegetation and climate: lessons for the future. In: Peters RL, Lovejoy TE (eds) Global warming and biological diversity. Yale University Press, New Haven, pp 59–75

Yohe G (2010) Risk assessment and risk management for infrastructure planning and investment. The Bridge Fall: 14–21

Yohe G, Leichenko R (2010) Adopting a risk-based approach. Ann N Y Acad Sci 1196:29–40