Merger of three modeling approaches to assess potential effects of climate change on trees in the eastern United States

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Abstract

Climate change will likely cause impacts that are species specific and significant; modeling is critical to better understand potential changes in suitable habitat. We use empirical, abundance-based habitat models utilizing decision tree-based ensemble methods to explore potential changes of 134 tree species habitats in the eastern United States (http://www.nrs.fs.fed.us/atlas).To help interpret and add value to these outputs, we assigned and calculated Modification Factors for disturbance and biological factors that cannot be specifically assessed with the empirical RandomForest approach. We also use a spatially explicit cellular model, SHIFT, to calculate colonization potentials, based on the abundance of the species, the distances between occupied and unoccupied cells and the fragmented nature of the landscape. By combining results from the three efforts, we are estimating potential impacts that can be used to aid in management decisions under climate change. These tools are demonstrated for one species, black oak (*Quercus velutina*), in northern Wisconsin.

Keywords: Climate Change, RandomForest, Species Distribution Modeling, Eastern United States, Trees

1. Introduction

The ranges of tree species in eastern North America have generally shifted northward as the climate has warmed over the past 14,000+ years since the last ice age (Webb 1992). Evidence is mounting that tree species, along with many other organisms, are continuing this northward movement, some at very high rates (Hoegh-Guldberg et al. 2008). There is also increasing evidence of broad expanses of tree mortality that can be attributed to drier and hotter conditions, often predisposing the forests to insect pest outbreaks (e.g., mountain pine beetle in western North America) (Allen et al. 2010). Habitats for individual species have, and will continue to, shift independently and at different rates, resulting in changing forest community compositions over time (Webb 1992). Such shifts are likely to occur in the coming decades in the eastern United States, so that some species will decline in suitable habitat while others will increase to various degrees. While it is likely that certain habitat will become suitable for some species not currently present, it is less clear how rapidly – or even whether – those species will migrate into the region without active human intervention (Higgins and Harte 2006). Studies on six eastern United States species showed that, at the rate of migration typical of the Holocene period (50 km/century in fully forested condition), less than 15% of the newly suitable habitat has even a remote possibility of being colonized within 100 years (Iverson et al. 2004). The relatively rapid nature of the projected climate shifts, along with the limits on the rate at which trees can migrate over a landscape, especially in the current and future fragmented state of forests, constrain the rate of 'natural' migration.

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We approach modeling impacts of climate change using a combination of statistical species distribution models (DISTRIB), literature-based conceptual models (MODFACs), and cell-based spatially explicit models (SHIFT) to quantify colonization probabilities (Fig. 1). The work presented here is based on modeling the primary individual tree species of the eastern United States, with results focused on the northern Wisconsin region. We briefly describe the methods used and then present a brief evaluation and example of potential changes for one tree species, black oak (*Quercus velutina*), along with several other interpretive measures that complement the models, to assist in further evaluation of vulnerabilities and potential management options.

2. Methodology

2.1 DISTRIB model development

To create the models, current climate variables (1960-1990) are used in statistical model development, and then are swapped with the future climates (~2070-2100) according to several global circulation models (GCMs) and emission scenarios. We used two emission scenarios developed for the Intergovernmental Panel on Climate Change (IPCC): a high level of emissions that assumes a continued high rate of fossil fuel emissions to 2050 (A1fi), and a lower emission scenario that assumes a rapid conversion to conservation and reduced reliance on fossil fuels (B2) (Nakicenovic and al. 2000). The scenarios are also based on the output from two representative GCMs: the HadleyCM3 model (Pope 2000), and the Parallel Climate Model (PCM) (Washington et al. 2000). We present the HadleyCM3 model projections under the high emissions scenario (HadHi) as the most extreme warming case in our analysis, and the PCM model under the low emissions scenario (PCMLo) to represent the case with the least warming.

We use the DISTRIB model, a statistical-empirical approach using decision-tree ensembles to model and to predict changes in the distribution of potential habitats for future climates (Fig. 1) (Prasad et al. 2006), Iverson et al. 2008b). For species information on a total of 134 tree species, we use the USFS Forest Inventory and Analysis (FIA) data to build importance value estimates for each species. We use 38 environmental variables – 7 climate, 9 soil classes, 12 soil characteristics, 5 landscape and fragmentation variables, and 5 elevation variables – to statistically model current species abundance with respect to the environment. Because the processes involved are nonlinear with numerous interactions, we use non-parametric machine-learning approaches using decision-tree ensembles to predict and provide valuable insights into the important predictors influencing species distributions. Specifically we used a 'tri-model' approach: RandomForest for prediction, bagging trees for assessing the stability among individual decision-trees and a single decision tree to assess the main variables affecting the distribution if the stability among trees proved satisfactory (Prasad et al. 2006, Iverson et al. 2008). The result is an estimate of the potential future suitable habitat.

Because models vary in their ability to predict we provide an index of the reliability for each species. For example, species with highly restricted ranges with low sample size often produce less satisfactory models as compared to more common species (Schwartz et al. 2006). This pattern results in quite large differences in the reliability of the predictions among species and highlights the need to consider how the model captures the speceis distribution. The 'tri-model' approach gives us the ability to assess the reliability of the model predictions for each species, classified as high, medium or low depending on the assessment of the stability of the bagged trees and the R^2 in RandomForest. This high rating occurred for 55 of the 134 tree species in our models. Even if the model reliability was medium or low, RandomForest predicts better without overfitting due to its inherent strengths compared to a single decision-tree (Cutler et al. 2007).

2.2 Modification Factors

The DISTRIB model does not address biological or disturbance factors that may influence a species' response to climate change. We conducted a literature assessment of these modifying factors and developed a scoring system to address 9 biological and 12 disturbance modification factors (MODFACs) that influence species distributions. Biological factors we evaluated include the species' capacity to regenerate after fire, regenerate vegetatively, establish as seedlings, disperse, as well as the species' response to competition for light, elevated CO_2 for productivity and water use efficiency, and specificity to specific environmental habitats or edaphic conditions. For distubance factors, we considered the species' response to invasive plants, insects, browse, disease, temperature gradients, fire topkill, wind, ice, pollution, floods, droughts, and harvesting. We also rated their level of uncertainty and future relevance under climate change (e.g., droughts will become more problematic under most future scenarios). These factors, when considered alongside the speces models, can be used to modify how one interprets the potential for increasing or decreasing future importance of a species. Each species is given a set of default scores based on the literature, and each factor can be changed by managers as they consider local conditions. With knowledge of site-specific processes, managers may be better suited to interpret the models after MODFACs have been considered. The MODFACs can then be used to modify the interpretation of the potential suitable habitat models. The goal of this effort is to provide information on the distribution of species under climate change that accounts for the natural processes that influence the final distribution. In addition, this approach encourages decision-makers to be actively involved in managing tree habitats under projected future climatic conditions.

2.3 SHIFT model development

Finally, with SHIFT we are evaluating selected species for their potential migration potentials from where they exist currently to where, of the new suitable habitat to emerge, they may be able to colonize over the next 100 years (Fig. 1). SHIFT calculates colonization potentials based on the abundance of the species, the distances between occupied and unoccupied cells, the quality of the habitat, and the fragmented nature of the landscape. The long distance dispersal, captured by an inverse power function, also depends on stochasticity. By combining output from DISTRIB and SHIFT, we may not only obtain an idea of how the suitable habitat may move, but also some idea on how far the species may move across the fragmented habitats of the region. We calibrate movement at the approximate (generous) migration rate of 50 km per century, according to paleoecological data from the Holocene period (e.g., (Davis 1981). Details of the method (although under revision now because of newly available computing approaches) are presented in several publications (Iverson et al. 1999; 2004; Schwartz et al. 2001).

3. Results and Discussion

3.1 DISTRIB model

Of 134 species modeled in the eastern United States, we found a total of 73 species of interest for the region in northern Wisconsin. Using the estimates of potential changes in suitable habitat, we sorted the species according to their potential to gain, lose, have no change, or enter into the region from outside. As such, we classify them into 8 vulnerability classes which can be influenced by climate change classes ranging from most vulnerable to least vulnerable:

Extirpated (Extirp): These species are in northern Wisconsin currently, but all suitable habitat disappears by 2100. [1 species]; Large Decline (LgDec): Show large declines in suitable habitat , especially under the high emissions scenarios [12 species]; Small Decrease (SmDec): Show smaller declines, mostly apparent in the high emissions scenarios. [6 species]; No Change (NoChg): Show roughly similar suitable habitat now and in the future. [6 species]; Small Increase (SmInc): Have an increased amount of suitable habitat in the future as compared to current, especially with the higher emissions. [4 species]; Large Increase (LgInc): Have much higher estimates of suitable habitat in the future as compared to current, especially with the higher emissions. [17 species]; New Entry Both (NewEntBoth): Have very rarely been currently detected via FIA sampling in northern Wisconsin, but show potential suitable habitat entering the region, even under the low emission scenarios. [11 species]; New Entry High (NewEntHi): Have very rarely been detected via FIA sampling in northern Wisconsin, but show potential suitable habitat entering the region, especially under higher emissions. [16 species]

We chose to select one example species from class 6, large increaser (LgInc), to illustrate the process researchers and managers may pursue to help chart out a range of mangement choices in the face of climate change. Our example species, black oak (*Quercus velutina*), has high model reliability so we can have higher confidence in the modeled expansion of suitable habitat from nearly absent to the entire northern Wisconsin range (Fig. 2a), with an increase in suitable habitat under both low (4-fold increase, Fig. 2b) and high (6-fold increase, Fig. 2c) emission scenarios according to our model.

3.2 Modification Factors

The literature assessment of black oak revealed that it is quite resistant to drought and fire topkill (both projected to increase under climate change), but not so much as compared to many other oaks. It is moderately affected by diseases (which may also increase) and it can succumb to successive defoliations by gypsy moth. It can regenerate quite well from seed or sprouts with the likely increased fire under climate change. And it is rather a generalist with respect to temperatures as well as edaphic and environmental habitats, all of which are advantageous for a species projected to have increased habitat. Overall, both the biological and disturbance modifying factors suggest that the species could do slightly better than modeled from DISTRIB and that it may be well suited for the newly emerging habitats of northern Wisconsin.

3.3 SHIFT model

The preliminary output of 100 repetitive runs of the SHIFT model (1 run = 1% probability of colonization) for black oak shows an expansion of areas with even a small probability of colonization of roughly 120-160 km into the new suitable habitat within 100 years (Fig. 2d). Obviously, variations in colonization probability relate to the current abundance of the species next to the range boundary (Fig. 2d), and the quantity and nature of the forest habitat in the expanding zone (Fig. 2e). The outputs give us a picture of the relatively small and slow expansion of the species, given the constraints of the current habitat and the paleoecologically derived migration rate of 50 km/century. Of course, should humans intervene to assist in the migration, the picture could potentially change dramatically.

4. Conclusions

The combination of these three approaches to assessing the likely impacts of climate change provide a more thorough analysis and, we hope, a tool set that managers can begin to use in the course of their adaptive management decisions in the face of climate change. With DISTRIB, we provide potential changes in individual species' suitable habitat under various climate models and scenarios of human responses to this crisis. With the modifying factors, we assess each species' capacities and vulnerabilities to adapt to various changing conditions and disturbances. And with SHIFT, we provide an indication of the rate of 'natural' migration through the fragmented habitats now existing. We intend to use SHIFT as well to perform 'experiments' of landscape manipulation and assisted migration to assess these potential strategies under climate change.

We also show the vast differential in outcomes between a low carbon future (PCMlo) and high carbon future (HADhi) with respect to habitats for one species (it is the case for most species), and thus the critical need for a global effort to reduce carbon emissions.

References

Allen C., Macaladyb A., Chenchounic H., Bachelet D., McDowell N., Vennetier M., Kitzberger T., Rigling A., Breshear D., Hoggi E., Gonzalezk P., Fensham R., Zhangm Z., Castron J., Demidavao N., Lim J.-H., Allard G., Running S., Semerci A. and Cobb N. 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management* 259: 660-684.

Cutler D.R., Edwards T.C., Beard K.H., Cutler A., Hess K.T., Gibson J. and Lawler J.J. 2007. Random forests for classification in ecology. *Ecology* 88: 2783-2792.

Davis M.B. 1981. Quaternary history and the stability of forest communities. *In* West D. C. and Shugart H. H. (eds.), Forest succession: concepts and application, pp. 132-153. Springer-Verlag, New York.

Hoegh-Guldberg O., Hughes L., McIntyre S., Lindenmayer D.B., Parmesan C., Possingham H.P. and Thomas C.D. 2008. Assisted colonization and rapid climate change. *Science* 321: 345 - 346.

Iverson L.R., Prasad A.M., Matthews S.N. and Peters M. 2008. Estimating potential habitat for 134 eastern US tree species under six climate scenarios. *Forest Ecology and Management* 254: 390-406.

Iverson L.R., Prasad, A.M. and Schwartz M.W. 1999. Modeling potential future individual tree-species distributions in the Eastern United States under a climate change scenario: a case study with *Pinus virginiana*. *Ecological Modelling* 115: 77-93.

Iverson L.R., Schwartz M.W. and Prasad A.M. 2004. Potential colonization of new available tree species habitat under climate change: an analysis for five eastern US species. *Landscape Ecology* 19: 787-799.

Nakicenovic N. and others. 2000. IPCC special report on emissions scenarios. Cambridge University Press, Cambridge, UK.

Pope V.D. 2000. The impact of new physical parametrizations in the Hadley Centre climate model -- HadCM3. *Climate Dynamics* 16, 123-46. 16: 123-146.

Prasad A.M., Iverson L.R. and Liaw A. 2006. Newer classification and regression tree techniques: bagging and random forests for ecological prediction. *Ecosystems* 9: 181-199.

Schwartz M.W., Iverson L.R. and Prasad A.M. 2001. Predicting the potential future distribution of four tree species in Ohio, USA, using current habitat availability and climatic forcing. *Ecosystems* 4: 568-581.

Schwartz M.W., Iverson L.R., Prasad A.M., Matthews S.N., O and Connor R.J. 2006. Predicting extinctions as a result of climate change. *Ecology* 87: 1611-1615.

Washington W.M., Weatherly J.W., Meehl G.A., Semtner Jr. A.J., Bettge, T.W., Craig A.P., Strand Jr. W.G., Arblaster J.M., Wayland V.B., James R. and Zhang Y. 2000. Parallel climate model (PCM) control and transient simulations. *Climate Dynamics* 16, 755-74. 16: 755-774.

Webb T.I. 1992. Past changes in vegetation and climate: lessons for the future. *In* Peters R. L. and Lovejoy T. E. (eds.), Global warming and biological diversity, pp. 59-75. Yale University Press, New Haven, CT.

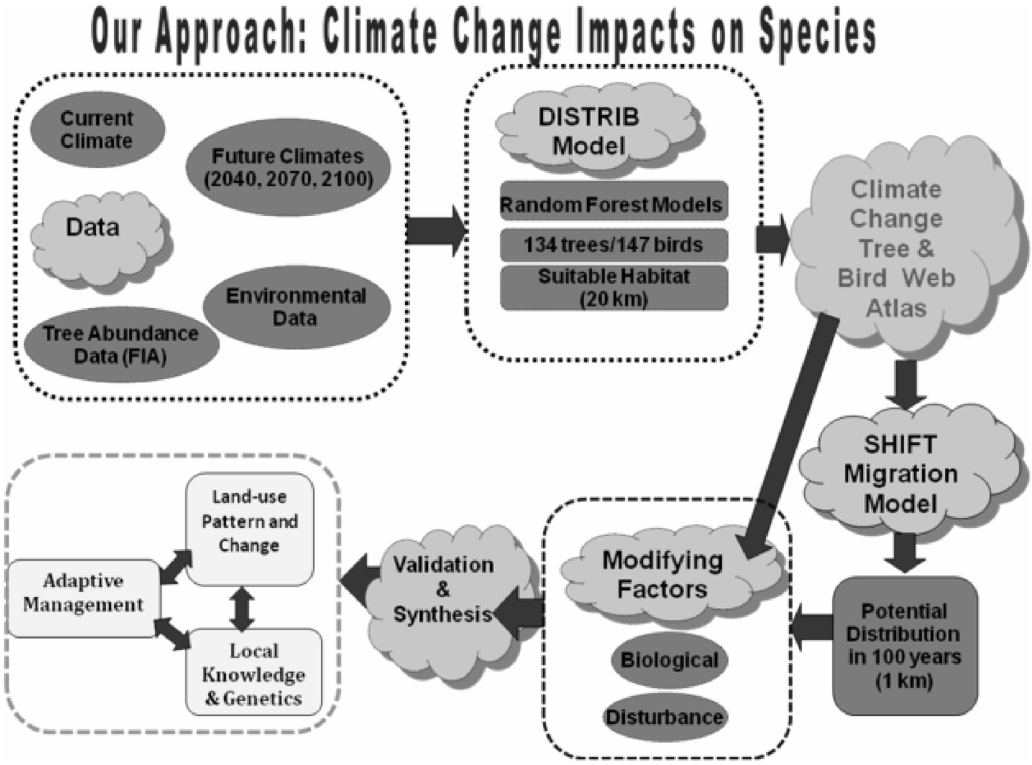

Fig. 1. Schematic showing approach to modeling potential impacts of climate change on trees and birds in the Eastern United States.

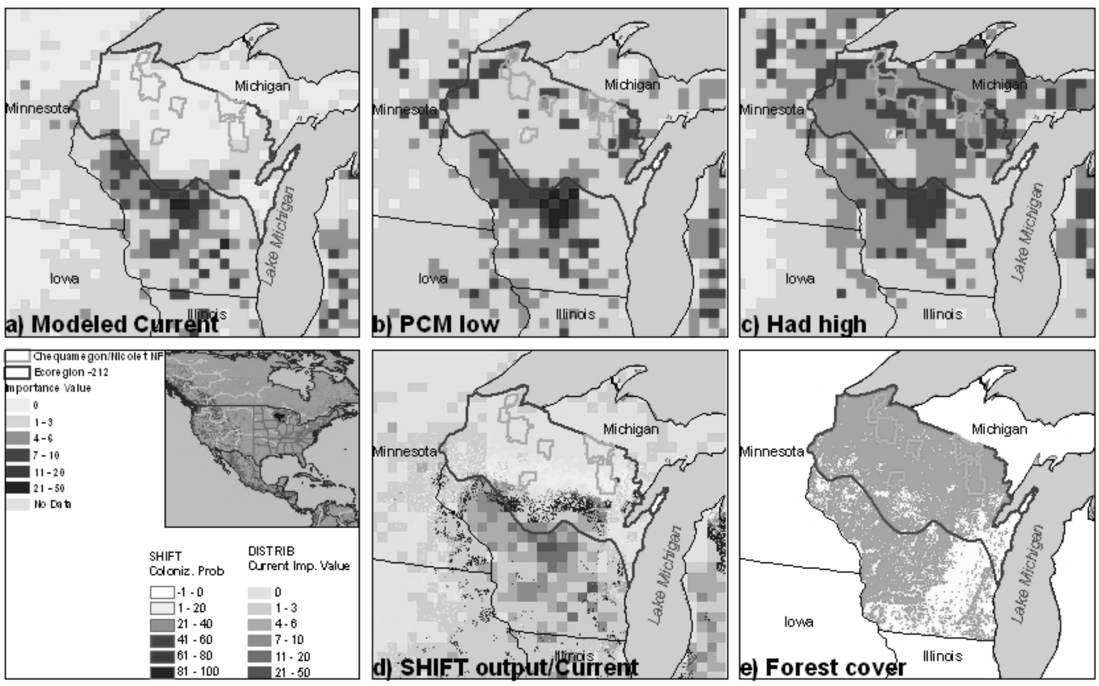

Fig. 2. Potential habitat changes for black oak; a) current distribution; b) future habitat under PCM low (humans track low carbon emissions); c) future habitat under Had high (humans continue to expand carbon usage); d) SHIFT colonization probability on current distribution; e) forest cover of Wisconsin region (gray=forest).

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