Chapter 2
Climate as an agent of change in forest landscapes

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Abstract Climate is the primary force that controls forest composition and the broad-scale distribution of forests. The climate has always been changing, but the changes now underway are different—they are faster and they are intermingled with other disturbances promoted by increasing human pressures. The projected climate change during the twenty-first century will alter forest habitats—dramatically for some species. These pressures will simultaneously affect the survival, growth, and regeneration of a species. Here, we present an approach to visualizing the risk to individual tree species created by climate change by plotting the likelihood of habitat change and the adaptability of trees to those changes. How will the forests actually respond? Many factors play into the final outcomes, including the vital attributes and abundance of a species, its migration potential, the fragmented nature of the habitats in the landscape into which the species must move, and other factors. Our research is attempting to address each of these factors to inform a more realistic picture of the possible outcomes by the end of the century. We describe three programs that have been developed to support this analysis: DISTRIB, which empirically models the distribution of suitable future habitats under various climate-change scenarios; SHIFT, which is a cell-based spatial model that simulates species migration across fragmented landscapes; and ModFacs, which accounts for the impacts of 9 biological traits and 12 disturbance factors on final species fates. We conclude with a discussion of research needs and how humans can potentially assist forests in their adaptation to climate change.

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2.1 Climate change

The climate has always been changing. However, our increased use of fossil fuels has made the anthropogenic component more prominent than ever before, and unusually rapid change is projected to occur by the end of the twenty-first century (IPCC 2007). Globally, temperatures (and especially nighttime minimums) have risen, while many places are getting wetter, albeit as a result of more frequent extreme events (Alexander et al. 2006). A recent study by the Berkeley Earth Surface Temperature Project (http://www.berkeleyearth.org; Fig. 2.1) has provided reliable evidence of a rise in the average global land temperature by approximately 1 °C since the mid-1950s (Rohde et al. 2012).

IPCC (2007) has determined that climate change is accelerating and that changes will continue. Many institutions have been modeling future climates, and all

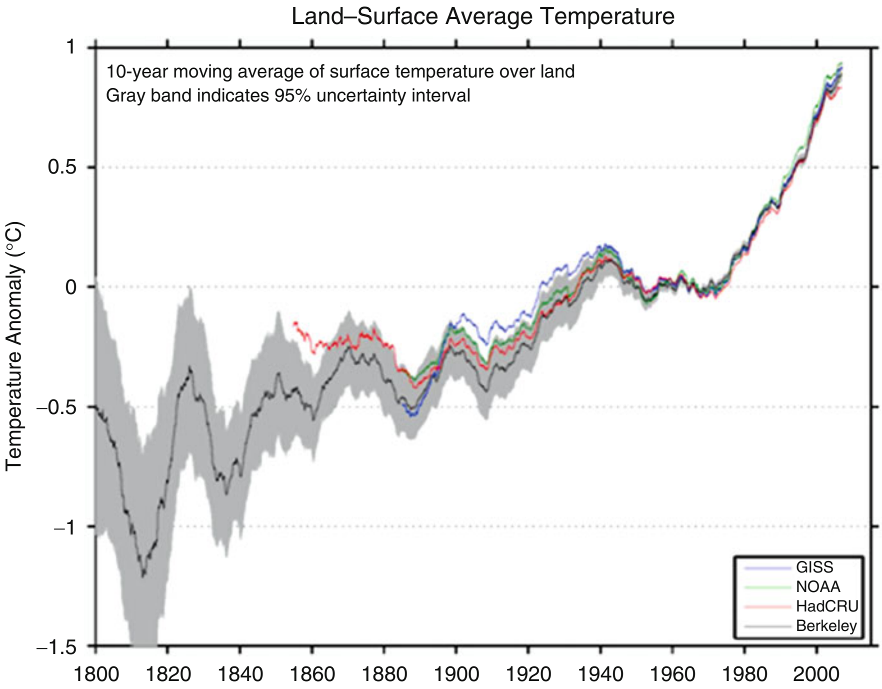

Figure 2.1 Changes in land-surface temperatures since 1800. Reprinted with permission from the Berkeley Earth Surface Temperature Project (2012, http://berkeleyearth.org/analysis/). The graph shows the global mean annual land-surface temperature using a 10-year moving average. Anomalies are expressed relative to the mean from January 1950 to December 1979; positive values represent a temperature increase. The *grey band* indicates the 95 % confidence interval. GISS, Goddard Institute for Space Studies; NOAA, National Oceanic and Atmospheric Administration; HadCRU, Hadley Centre of the U.K. Meteorological Office; Berkeley, Berkeley Earth Surface Temperature Study

scenarios predict a warmer world in the coming decades, particularly in the latter part of this century (IPCC 2007). Future precipitation patterns are less consistent, with some parts of the globe showing net increases and others showing net decreases. What is consistently projected, though, is a more vigorous hydrologic cycle because of the greater heat energy in the atmosphere. Thus, it is projected that heavy precipitation events (storms) will increasingly provide a larger proportion of the total annual precipitation, resulting in more runoff and floods (Lenderink and van Meijgaard 2008, Milly et al. 2002), but also more and longer periods without rain and droughts (Burke et al. 2006, IPCC 2007, Seidel et al. 2008). Indeed, a recent study showed strong evidence linking the extraordinary number and impact of disastrous heat and precipitation events that occurred between 2000 and 2011 to the human influence on climate (Coumou and Rahmstorf 2012). Another study pointed to the amplified heating of the Arctic as a key factor responsible for the elevated number of extreme events in the northern hemisphere (Seminov 2012). Coumou and Rahmstorf (2012) clearly describe how we might think about this pattern:

"Many climate scientists (including ourselves) routinely answer media calls after extreme events with the phrase that a particular event cannot be directly attributed to global warming. This is often misunderstood by the public to mean that the event is not linked to global warming, even though that may be the case—we just can't be certain. If a loaded dice [sic] rolls a six, we cannot say that this particular outcome was due to the manipulation—the question is ill-posed. What we can say is that the number of sixes rolled is greater with the loaded dice (perhaps even much greater). Likewise, the odds for certain types of weather extremes increase in a warming climate (perhaps very much so). Attribution is not a 'yes or no' issue as the media might prefer, it is an issue of probability."

2.2 Forests and a changing climate

At a coarse scale, climate is the primary driving force for the location, composition, and productivity of forests (Shugart and Urban 1989, Woodward and Williams 1987). Therefore, changes in climate will yield changes in forests. These changes have also always occurred in response to climate change (e.g., Davis and Zabinski 1992, Delcourt and Delcourt 1987), and the combination of species that comprise a forest also changes through time (Webb 1992). A mounting number of studies provide evidence that such changes continue to occur (Bolte et al. 2010, Woodall et al. 2009). Although there is empirical evidence of tree species moving to higher altitudes (Beckage et al. 2008, Holzinger et al. 2008, Lenoir et al. 2008), there is minimal evidence documenting a progression of tree species in a poleward direction in this century (Zhu et al. 2012). However, some case studies have shown changes in species composition over time, with more recently arrived species arriving from lower latitudes (Schuster et al. 2008, Treyger and Nowak 2011). In addition, meta-analyses have provided increasing evidence of species movements from a large suite of taxa (Chen et al. 2011, Parmesan and Yohe 2003). The mean extinction risk across all taxa and regions has been estimated at 10 to 14 % by about 2100 (Maclean and Wilson 2011) despite the “Quaternary conundrum”, which relates to a lower-than-expected rate of extinction during the Quaternary ice ages (Botkin et al. 2007).

The paleoecological record shows a remarkable change in tree distributions. In eastern North America, for example, the pollen record shows massive migrations since the last glaciation (ca. 18 000 years before the present). These migrations have been matched to concomitant changes in temperature (Davis 1981). Spruce (*Picea* spp.) and fir (*Abies* spp.) in the northeastern United States have shown particularly great changes in their distribution during the last 6000 years and appear to be destined to retreat northwards back into Canada as the climate warms (DeHays et al. 2000). The same phenomenon has been observed in Europe, where the glacial history and climate have acted as key controls on tree distribution and species richness (Svenning and Skov 2005, 2007).

Thus, suitable habitats for tree species appear to be changing, but many models predict that these changes are likely to accelerate throughout this century. The models of several groups show these potential trends (Crookston et al. 2010; Delbarrio et al. 2006; Dobrowski et al. 2011; Iverson et al. 2008b; Keith et al. 2008; McKenney et al. 2007, 2011; Morin et al. 2008; Ravenscroft et al. 2010; Scheller and Mladenoff 2008), and a recent report suggests these studies may be underestimating the actual change (Wolkovich et al. 2012). Uncertainty and extraordinary challenges will continue to confront species modeling (Araújo and Guisan 2006, Pearson et al. 2006, Thuiller et al. 2008, Xu et al. 2009), although multiple approaches are being developed in attempts to improve projections (Araújo and Luoto 2007, Elith et al. 2010, Franklin 2010, Iverson et al. 2011, Matthews et al. 2011, Morin and Thuiller 2009).

2.3 Climate-related drivers for forests and forest changes

Climate constraints interact with the physiological and ecological attributes of trees to produce the broad-scale characteristics of forest composition and productivity. These forces, along with broad-scale land-use and management manipulations, are the primary determinants of the forests we see today. At a finer scale, topography, local climate, and soil conditions play a primary role in determining forest characteristics, and many features such as species composition, productivity, and regeneration success are strongly determined by slope position and aspect along with the soil’s water-holding capacity (Iverson et al. 1997, Kabrick et al. 2008, McNab 1996). Thus, scale is important, especially in climate and climate impact models. The spatial resolution of the original general circulation models was coarse, with cells spanning 1° to 4° (Tabor and Williams 2010). Thus, downscaling of these data is required, and though such efforts will be very helpful, they will by their nature be imprecise at a fine scale (Tabor and Williams 2010).

Many drivers of forest change are also related to climate, either directly or indirectly. Obviously, land-use change, management or mismanagement, herbivory, pest outbreaks, and other impacts are critically important forces of change at certain times and places, but climate provides the overall conditions that create constraints on a forest's characteristics. Climate change creates two primary, and interrelated, categories of impacts for trees: *maladaptation* and *disturbance* (Johnston 2009). Maladaptation refers to a situation in which the local conditions to which a species is adapted begin to change faster than the species can move or adapt. Examples include a reduction of moisture availability, the CO_2 fertilization effect, permafrost melting, drying or creation of wetlands, and changes in snow depth. Disturbance refers to the suite of biotic and abiotic onslaughts that occur as a result of climate change or that are in some way encouraged by climate change. Many disturbance regimes that directly alter forests are expected to increase in frequency, intensity, or both as a result of climate change (Dale et al. 2001). Evidence is mounting that such climate-linked disturbances are increasing, including an increase in fire frequency in the western United States and elsewhere (Littell et al. 2009, Liu et al. 2010, Westerling 2006), an increased northward prevalence of mountain pine beetle (*Dendroctonus ponderosae*) outbreaks in western North America (Bentz et al. 2010, Hicke et al. 2006, Kurz et al. 2008, Sambaraju et al. 2012), an increasing risk from invasive species (Dale et al. 2009, Dukes et al. 2009, Hellmann et al. 2008, Jarnevich and Stohlgren 2009, Mainka and Howard 2010), and an increasing evidence of drought-induced mortality (Adams et al. 2012, Allen et al. 2010, Hanson and Weltzin 2000, Peng et al. 2011).

Although some of the disturbance characteristics may be subtle, they may eventually reach a "tipping point" at which the change is enough to shift the competitive balance between species or to overwhelm a forest's compensatory mechanisms, leading to a change in the forest's composition. For example, an insect species may be able to overwinter just enough that its population levels gradually increase until they become sufficient to kill trees that were not previously at risk. This phenomenon has been shown for the mountain pine beetle in whitebark pine (*Pinus albicaulis*) forests in the Greater Yellowstone Ecosystem (Logan et al. 2010), the southern pine beetle (*Dendroctonus frontalis*) in the New Jersey pine barrens (Tran et al. 2007), and the hemlock woolly adelgid (*Adelges tsugae*) on hemlocks (*Tsuga* spp.) of the eastern United States (Fitzpatrick et al. 2012, Paradis et al. 2008). Some of these climate-induced or climate-enhanced factors have been shown to quickly alter forest characteristics, but even when the impact is more gradual, these factors can still greatly alter the biodiversity of an area. Though few or no single events can be attributed to climate change, the overall trend tends to support the hypothesis that the impacts of climate change are increasing.

2.4 Forest adaptation to climate change

Uncertainties abound in forest management, even in the absence of climate change (Bolte et al. 2009, Long 2009, Seidl et al. 2011). Most of the large uncertainties associated with climate change will remain, regardless of research progress, owing to the impossibility of predicting the impact of the next major pest, of the next hurricane, or of the series of climatic events needed to create a “perfect storm” for fire or drought mortality at a location where such events had rarely occurred or had not previously occurred. It is known, though, that one of the primary outcomes of climate change is a more vigorous hydrologic cycle and that extreme events with direct and indirect impacts on forests will therefore become more likely (Solomon et al. 2007). This increase in extreme events is already occurring, and their frequency is expected to increase substantially in the future (Coumou and Rahmstorf 2012, Huber and Gulledge 2011). Therefore, the direct and indirect risks to forests are expected to increase throughout the century. We therefore need methods to evaluate changes in the risk for a given species over time and to evaluate and implement policies and procedures that would allow or promote adaptation to the new climate and disturbance regimes. Essentially, any tree species whose microclimate changes enough for it to be growing outside its preferred niche has three options: move, adapt, or be extirpated (Aitken et al. 2008). In the rest of this chapter, we address the first two options after evaluating the concept of risk.

2.4.1 Strategic assessment of species adaptation requirements through risk matrices

To help forest species adapt to changing conditions, where this is appropriate, it is first necessary to evaluate the risk and develop appropriate strategies that respond to that risk (Millar and Stephenson 2007, Yohe and Leichenko 2010). Increasing a forest’s resistance to climate change and its resilience is a key elements of adaptation, but triage may be necessary if a species cannot be protected in situ without incurring a cost that society is unwilling to bear.

We developed a visual tool called a *risk matrix* to assess risk and compare risks among species and among locations to “organize thoughts” around risk and forest adaptability for a particular region (Iverson et al. 2012). The tool was developed for the United States National Climate Assessment and is intended to provide an easily understood visual tool for focusing the conversation on management strategies at all levels. The intention is to use the tool for areas small enough that they do not have major disjoint habitats or species that gain and lose from climate change simultaneously within the same region, but not so small that they have too few cells for analysis. First, we defined “risk” as the product of the likelihood of an event happening and the consequences if it happens. We then categorized the matrix into three zones: (1) *watch*, which involves a relatively low risk but the need to remain vigilant; (2) *evaluate further and perhaps develop strategies*, which involves an intermediate level of risk; and (3) *develop strategies to cope with the risk*, which involves the highest level of risk (Yohe and Leichenko 2010). For forest trees, we interpret this risk (likelihood) as a potential for change based on the adaptability or resistance of the species to the impacts of climate change (consequences), and in this chapter, we will demonstrate this form of analysis for a species whose habitat is likely to

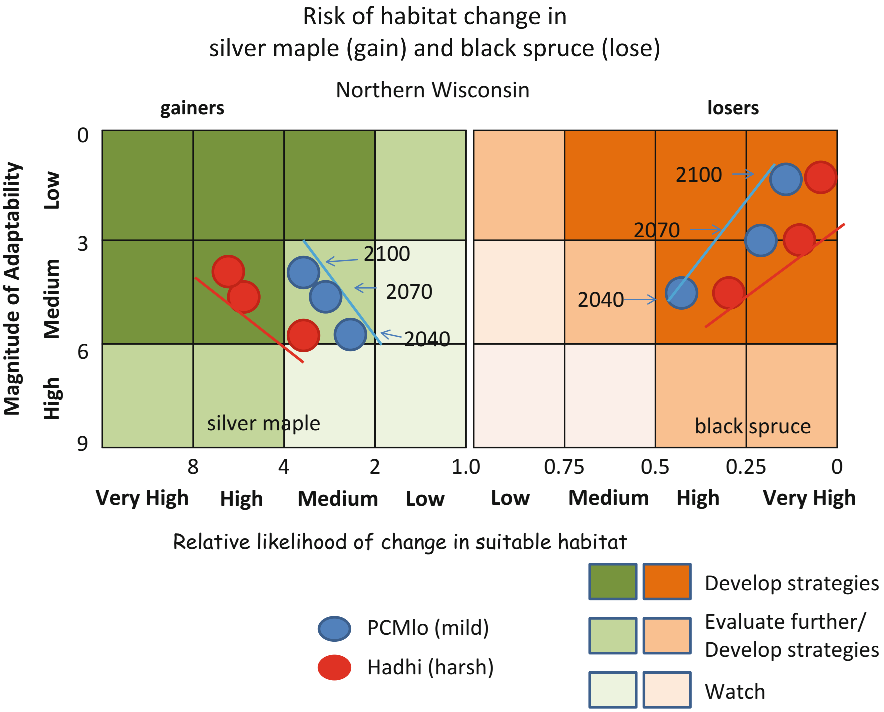

Figure 2.2 A risk matrix for a species whose habitat is likely to decrease (black spruce, *Picea mariana*) and a species whose habitat is likely to increase (silver maple, *Acer saccharinum*). The analysis is conducted for northern Wisconsin (United States). The trend lines are hand-drawn to approximate the trends modeled throughout the twenty-first century. PCMlo represents the PCM B1 scenario and Hadhi represents the Hadley A1fi scenario (IPCC 2007). Relative likelihood represents the ratio of future habitat in a given year to the current habitat

decrease, black spruce (*Picea mariana*), and for a species whose habitat is likely to increase, silver maple (*Acer saccharinum*). We conducted the analysis for northern Wisconsin (United States) between now and 2100 (Fig. 2.2).

In the context of changes in the amount of suitable habitat in response to climate change, we modeled the potential for an area to have suitable habitat for the selected species in the future relative to its current amount of suitable habitat. The *x*-axis is thus based on the difference in suitable habitat (i.e., the sum of importance values for all 20 × 20 km cells within the region of interest) between the current date and three future time intervals, which end around 2040, 2070, and 2100. In addition to these three dates, we also include predictions based on two widely differing scenarios for modeled climate change, PCM B1 and Hadley A1fi, to extract a range of potential risks associated with the IPCC projections of future climates (IPCC 2007, Nakicenovic et al. 2000). We view the ratio of future habitat to current habitat as being related to the likelihood of an impact on the amount of suitable habitat—the greater the potential change in habitat, the greater the likelihood of an impact.

For species that show a loss of habitat, the *x*-axis ranges from +1 (no change in habitat with time) to 0 (complete loss of habitat over time). In this analysis, black spruce shows a substantial future habitat loss by 2100, especially under the more severe Hadley A1fi scenario, and the species thus has a large likelihood of change on the "loser" side of the risk matrix (Fig. 2.2). On the other hand, silver maple shows a positive ratio of future to current habitat and is therefore in the "gainer" section of the risk matrix.

The *y*-axis is related to the adaptability of the species under climate change, based on a literature review to assess the biological traits of the species and its capacity to respond to various disturbances that may increase in frequency or severity in the coming century, compounded (or not) by climate change. We thus scored the adaptability of the species to cope with climate change; the lower the capacity to cope, the greater the risk of habitat loss and the greater the consequences of this loss. The data for this species-level analysis comes from an evaluation of the literature for 12 disturbance factors and 9 biological factors (Matthews et al. 2011). Relative scores were averaged for the biological and disturbance factors, then plotted to yield a composite modification factor score that was also modified for plotting on the *y*-axis in 2070 and 2100 based on the disturbance factors that were estimated to increase throughout the century. Further details are provided by Iverson et al. (2012).

In summary, we quantified the estimated risk for each species using the bounds of a harsh (Hadley A1fi) and a mild (PCM B1) scenario for the future climate and extrapolated the trends to 2040, 2070, and 2100 (Fig. 2.2). The matrix shows contrasting trends for the two species, but in both cases, managers will increasingly be required to develop strategies to cope with the risks created by the climate change that is currently underway—one set of strategies for silver maple, a species that may or may not need to be encouraged to become established, and one for black spruce, for which it may be necessary to establish protected refugia, enhance or maintain corridors that will permit poleward migration, or possibly even assist in this migration.

2.4.2 *The need for species migration*

Migration of species will be necessary over the long term as species reshuffle their distribution to adapt to their new climatic niches. Most species-distribution models show that the habitats for many species will often move large distances by 2100 (Iverson et al. 2008b, McKenney et al. 2011). Based on studies of pollen distributions during the Pleistocene, when forest cover was nearly complete across eastern North America, migration rates per century appear to range from 10 km (McLachlan et al. 2005) to 50 km (Davis 1981, Huntley 1991). With the modern fragmentation of forested land, estimates of migration rates are generally much lower (Schwartz 1993). Thus, there is little evidence to support the belief that migration by natural means will be able to keep up with the expected rate of change in habitats.

In one study, less than 15 % of new suitable habitat would have even a remote chance of being colonized by 2100 (Iverson et al. 2004b).

Various aspects of forest management will therefore become important to assist migration or encourage an increased rate of migration. Two primary modes include increasing the connectivity of forested land (i.e., to provide migration corridors) and assisting in the migration (e.g., by artificial distribution of seeds and other propagules). In addition to facilitating species movements, forest management can also play a large role in adaptation through techniques that increase the resistance of the current forest stands to environmental and other stresses, thereby increasing their resilience.

2.4.3 Enhancing adaptation through stand and landscape manipulation

On their own, the extent to which tree populations will be able to adapt to a changing climate depends upon the amount of phenotypic and genotypic variation, the natural selection intensity, fecundity, degree of interspecific competition, and a range of biotic interactions (Aitken et al. 2008). We may be able to intervene in the latter three via silvicultural management. There have been several publications that thoroughly describe the suite of possibilities to enhance adaptation through stand- and landscape-level management (e.g., FAO 2012, Johnston 2009, Spies et al. 2010). For example, Spies et al. (2010), working in the Pacific Northwest of the United States, provided the following ideas to enhance adaptation at the stand and landscape levels:

1. To promote resilience and vigor and to promote diversity of species and stand structures, use variable-density thinning in dense young stands to provide more resources to the surviving individuals.
2. Maintain mature stands where possible, because older, well-established individuals (at least before senescence begins) are usually more resistant and resilient to disturbances and climate change.
3. Increase the proportion of the landscape devoted to providing critical habitats and resilient ecosystem types, so that any single disturbance event has a decreased probability of destroying the habitat.
4. Manage wildfire to protect habitats or species that are at risk by suppressing fire where critical habitats exist, treating stands to reduce fuel loads, increasing spatial heterogeneity to create more resilience against fire or pests, or implementing tactical treatments that create fire breaks. (However, these interventions will have trade-offs with the requirements of some species. For example, some boreal species such as jack pine (*Pinus banksiana*) require periodic high-intensity fires to ensure their persistence within a landscape; Rohde et al. 2012.)

5. Alter the landscape structure to facilitate migration of species, to impede the spread of fire and pathogens, or a combination of the two. (Again, this may lead to mutually exclusive outcomes for some species.) Here, it is helpful to identify "pinch points" where species movement is constrained by the landscape, so that managers can alter the landscape structure accordingly and most efficiently. Tools to assist in this landscape analysis include Conefor Sensinode (Saura and Rubio 2010) and Circuitscape (McRae and Shah 2011).

2.4.4 Enhancing adaptation through managed relocation

Spies et al. (2010) proposed an additional idea to encourage adaptation to climate change: "Establish new genotypes and species to create communities that are adapted to current and future climates"—in other words, to assist species migration, which is also referred to as "managed relocation" or "assisted colonization". Here, we will use the definition presented by Hoegh-Guldberg et al. (2008): *intentionally moving species to sites where they do not occur or have not been known to occur in recent history*. The use of assisted migration has elicited controversy within conservation circles and must be used with caution because of potentially serious tradeoffs (Hoegh-Guldberg et al. 2008, Richardson et al. 2009). Opponents cite many cases in which intentional relocations resulted in myriad environmental issues (Davidson and Simkanin 2008, Ricciardi and Simberloff 2009, Seddon et al. 2009) because of unanticipated risks, such as runaway invasions, that surface only after it is too late to turn back. Proponents point out that assisted migration is a key option that must remain available in the face of unprecedented global change (Minteer and Collins 2010, Sax et al. 2009, Schwartz et al. 2009, Vitt et al. 2010). Several groups have developed frameworks to evaluate the risks and benefits of assisted migration so that decisionmakers have solid approaches they can use (Hoegh-Guldberg et al. 2008, Lawler and Olden 2011, Richardson et al. 2009, Seddon 2010).

When the discussion shifts to common trees, rather than endangered species such as *Torreya taxifolia* (Schwartz 2005), the discussion changes. Trees have been planted in places where they previously did not occur for centuries. In the context of commercial forestry operations, managed relocation has been proposed as a means to maintain forest productivity, health, and ecosystem services under a rapidly changing climate (Gray et al. 2011, Kreyling et al. 2011). Pedlar et al. (2012) thus distinguish forestry-assisted migration from rescue-assisted migration (the latter being the context of much of the debate) based on the intended outcomes, target species, movement logistics, potential risks, science-based feasibility, scope, cost, and practice. We believe that if practiced cautiously and with the focus on moving species within their current broadly defined range to encourage "filling in" at the margins where a species is less common, forestry-assisted migration holds promise as a relatively low-risk tool for adaptation to climate change.

2.5 Putting it all together: a case study of potential forest responses to climate change in the eastern United States

In this section, we present a case study that attempts to capture the key aspects of the discussion thus far in this chapter—specifically, we describe the results of our last 17 years of research, which has been devoted to understanding and modeling potential changes in forests of the eastern United States in the face of a changing climate. Though details on these efforts have been published, we will present a brief synopsis accompanied by links to representative papers for readers who want to learn more. Figure 2.3 provides a flow chart of the overall process.

We have used a series of species-distribution models to assess habitat suitability for 134 tree species across the eastern United States, under both current environmental conditions and predicted future conditions. The methods used in these models, which were created with DISTRIB, have been published (e.g., Iverson et al. 2008a, 2008b, 2011; Prasad et al. 2007, 2009). In summary, the procedure is as follows: (1) collect data on the forests using more than 100 000 forest inventory and analysis plots (Miles et al. 2001) and data on 38 predictors, including soil, climate, and landscape variables; (2) aggregate all data to a 20 × 20 km grid across the eastern United States, including estimates of the importance of a species based on the numbers and sizes of individuals of the 134 tree species; (3) use a decision-tree ensemble method of statistical modeling (including regression-tree analysis, bagging, and random forests) to establish contemporary relationships between the 38 predictor variables and the importance values determined in step (2), and then use the model to create

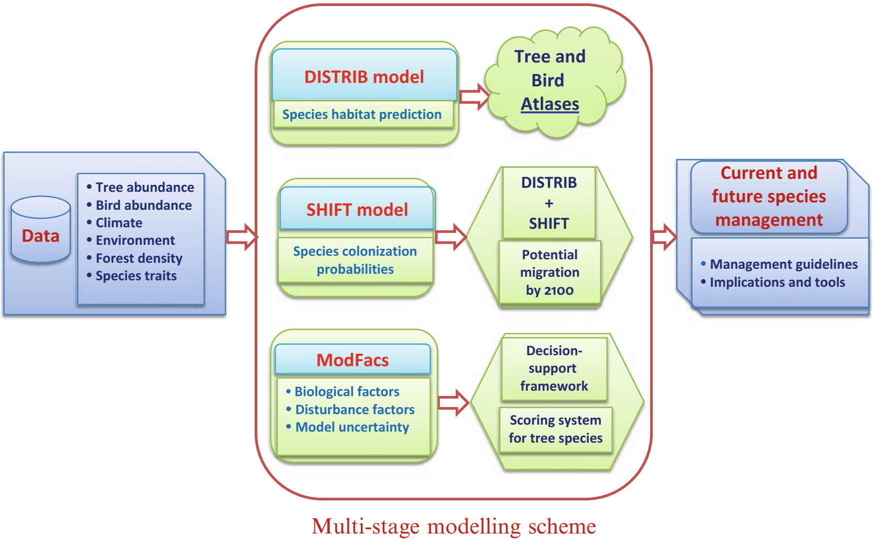

Figure 2.3 Flow diagram for the approach used to model potential responses of forests and tree species to climate change

a wall-to-wall map of importance values that resembles the current situation (Prasad et al. 2006); (4) use a series of future climate scenarios, varying according to greenhouse-gas emission scenarios and general circulation models, to replace current values of the seven key climate variables used by the models with their potential values at each of the three future time steps; and (5) map, chart, and tabulate the outputs. The outputs, consisting of more than 20 maps, 11 charts, and 4 tables for each of 134 tree species, are available in our Climate Change Tree Atlas (http://www.nrs.fs.fed.us/atlas/tree/tree_atlas.html). The atlas provides a suite of landscape-scale ecological information for each species under both current and future conditions, including details on the current species–environment relationships, maps of species abundance, life-history information, relative importance of the 38 predictors, potential habitat changes according to three general circulation models and two emission scenarios, and tables of potential changes by ecoregion, state, national park, or national forest (Prasad et al. 2009).

One feature of advanced data mining and modeling procedures such as those used in this analysis is that some distinction of scale can be made for key drivers of the model through the model outputs. For example, in our model for white ash (*Fraxinus americana*), we used a regression-tree tool, "random forest" (Prasad et al. 2006), to show that at the distribution level (i.e., the range of the species), climate variables such as the January temperature were most relevant for this species, whereas soil permeability was the single most important variable for identifying the most suitable habitat within white ash's distribution. For most species, though importantly, not for all species, we can discern the scale of influence for each driver and distinguish differences among drivers by means of the regression-tree analyses. For example, we often see a distinction between climate-level versus landscape-level drivers, such that initial, broad-scale variables (often climate) fall out at the top of the regression tree, whereas fine-scale (often edaphic) variables fall out farther down in the tree's structure (Iverson et al. 2011). Thus, these tools provide additional detail about the workings of the models and insights into why species occur where they do.

We then used the SHIFT model (Fig. 2.3) in conjunction with the outputs of DISTRIB to model the possible colonization of new suitable habitats within the next 100 years (Iverson et al. 1999, 2004a, 2004b; Prasad et al. 2013; Schwartz et al. 2001). SHIFT is a spatially explicit simulation model based on 1 × 1 km cells that simulates the dispersal of individual species propagules as a function of the current abundance of suitable habitats in surrounding cells, the proportion of the land covered by forest in the region to which the species is migrating, and the probability of long-distance dispersal using an inverse-power function of distance (so that long-distance dispersal also occurs occasionally). The rate of dispersal was calibrated to approximately 50 km per century through unfragmented areas of forest, which is towards the high end of the Holocene migration rates. Even so, the "advancing front" of the migrating species is likely to be concentrated near the boundary of the current distribution of the species and is not likely to keep pace with projected rates of warming and changes in habitat availability (Iverson et al. 2004a).

Another important interpretation of these SHIFT outputs is that the source strength (i.e., the abundance of a species near the boundary of its distribution) appears to be more important for migration than the sink strength (the proportion of forest cover in the destination cells). The combination of SHIFT with DISTRIB therefore predicts how much of the newly suitable habitat may be colonized over a 100-year period (in the absence of human-assisted migration); typically, this is only a small fraction of the available habitat.

Because of scale issues, it is difficult to translate the potential climate effects on the model into specific management activities for forest stands. With DISTRIB at a cell size of 20 × 20 km, we believe that multiples of at least 20 cells should be used for interpretation of regional trends, such as developing lists of species that are likely to increase or decrease their distribution. At a local management scale, managers must consider potential species shifts as only one of several inputs when they plan and implement management actions (Swanston et al. 2011). SHIFT, despite its finer 1 × 1 km cell size, presents a probability map in which general patterns (not specific single-cell probabilities) emerge within the larger landscape. The local factors of soils, topography, past silvicultural treatments, and the current species composition and forest structure remain the primary factors to consider in management, but overlaid on that picture is the potential for the distribution of certain species to decrease and that of certain other species to increase over time. Therefore, management can potentially provide refugia for declining species and new habitat for expanding species or even new migrant species through assisted migration in the forestry context (Pedlar et al. 2012).

Modeling the responses of a comprehensive suite of biological and disturbance characteristics that interact in myriad ways is extremely difficult—irrespective of whether statistical or process-based mechanistic models are used. We therefore developed a way to use modification factors to improve predictions. The ModFacs system (Fig. 2.3), a nonspatial scoring system, uses life-history traits obtained from a literature review (12 disturbance factors and 9 biological factors) and three post-modeling assessments as a method to increase the usefulness and practicality of the model for managers and researchers (Matthews et al. 2011). The biological characteristics attempt to assess the capacity of a species to adapt to predicted future conditions, such as a higher capacity to regenerate after a fire, to regenerate vegetatively, or to disperse; these are all positively associated with the adaptability of a species in response to expected climate change. Similarly, the disturbance characteristics assess the resilience of a species in terms of its capacity to withstand disturbances (e.g., drought, fire, floods), many of which are likely to increase in frequency or severity. To score each characteristic for each species, we reviewed the key literature to arrive at a modification factor score ranging from −3 to +3 (respectively, very negative to very positive influences in the context of expected climate change and the associated disturbance impacts). We also scored each of the characteristics in terms of their relevance in the context of the future climate (i.e., whether the changing climate will potentially increase the risk of this disturbance), with scores ranging from 1 to 4 in order of increasing relevance, and in terms of their uncertainty (e.g., our confidence in the data supporting our scoring), with scores ranging from 0.5 to 1.0 in order of increasing certainty. ModFacs also provides a means to assess each species in terms of its adaptability to the impacts of climate change. We have summarized, synthesized, and validated these modification factors as best we can based on the available information, and the overall information is then passed through management filters that adjust the results for local conditions, if necessary.

The goal is to finally arrive at appropriate information and potential tactics to support the management of a species (Fig. 2.3). Our intention is to provide the best information possible, under the uncertainty limitations imposed by the state of our knowledge, for decisionmakers to consider in their efforts to account for climate change.

2.6 Research needs

There is still plenty of research needed to better understand the relationship between climate and forests, and especially how the changing climate will affect forests.

Modeling studies have progressed a great deal in the last decade. The advent of advanced nonparametric statistical methods has greatly benefited the modeling of species distributions (Elith et al. 2006, Franklin 2009). Mechanistic modeling has also come a long way (Ravenscroft et al. 2010, Tague and Band 2004). Each approach brings its own advantages and drawbacks, and when both approaches arrive at similar answers, confidence in the predictions increases; where the approaches predict different outcomes, focused research may uncover the reasons for the discrepancy and allow improvement of the models (Morin and Thuiller 2009, Swanston et al. 2011). In addition, models that incorporate both approaches are now attempting to achieve the best of both worlds (Iverson et al. 2011). Nonetheless, there will always be trade-offs between using complex mechanistic models versus simpler empirical models to assess possible changes in species habitats (Thuiller et al. 2008). Myriad tough questions still remain to be answered (Iverson and McKenzie 2013, McMahon et al. 2011).

To improve our understanding of climate–forest relationships, much basic research must be done to understand the biological, ecological, and physiological attributes of individual species and to predict how multiple species will interact under various environmental situations.

Historically, provenance studies have assessed seed sources and genotypes. These data are being mined even now, decades later, to provide clues about the adaptability of a species under future climate change (Carter 1996). However, there is a need for competition experiments to see how seedlings will fare, for example, if their propagules travel northwards into an established forest community.

Tests of assisted migration will also be necessary to begin the process of understanding how we can help forests adapt to the new conditions created by climate change.

2.7 Conclusions

Climate change may be a more insidious agent of change than fire or anthropogenic land-use change, but it affects all forests in certain ways. Climate change will also interact with various factors and modify outcomes in unique ways, such as by increasing the frequency and severity of extreme climatic events or disturbance events, whether directly or indirectly.

Humans are largely responsible for modern climate change and must therefore decide whether and how to reduce carbon emissions to mitigate the coming changes. Humans must also decide to improve our understanding of forests and other ecosystems, including human-dominated ecosystems, and, where practical and scientifically prudent, help them adapt to the changing conditions. Part of this effort can be to simply promote healthy ecosystems via sound management. Artificially moving species also may become more and more part of the equation.

Climate is an important agent of change for forests. As the climate changes, so do the forests. In light of the increased stressors that are currently being observed, it is up to us to manage our forests in ways that will best suit the needs of a rising human population and the needs of our forests.

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