

# Review of science-based assessments of species vulnerability: Contributions to decision-making for assisted migration

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## ABSTRACT

Assessing climate change impacts on forest species can significantly assist forest management planning. Recently, many tools have been developed for assessing species-specific vulnerability to climate change. These tools are question-based assessments that consider multiple criteria for individual species; the criteria are related to exposure and sensitivity to climate change. The following tools are discussed in relation to their use in Canada: (1) the NatureServe Climate Change Vulnerability Index; (2) the System for Assessing Vulnerability of Species to Climate Change (SAVS); (3) the Forest Tree Genetic Risk Assessment; (4) the Index for Predicting Tree Species Vulnerability; (5) ecological standards developed for the assisted migration of *Torreya taxifolia*; and (6) the Seeds of Success Program. These tools can all be applied to different forest species and they vary in such areas as their species-specific evaluation criteria, means for addressing uncertainty, and the integration of climate change models.

**Key words:** climate change, forest species, vulnerability assessments

## RÉSUMÉ

Évaluer les effets des changements climatiques sur les essences forestières peut contribuer significativement à la planification de l'aménagement forestier. Récemment, plusieurs outils ont été élaborés pour évaluer la vulnérabilité des espèces aux changements climatiques. Ces outils d'évaluation reposent sur des questions et considèrent de nombreux critères associés à l'exposition et la sensibilité aux changements climatiques pour chacune des espèces. Les auteurs présentent les outils suivants : (1) l'indice de vulnérabilité aux changements climatiques NatureServe; (2) le système d'évaluation de la vulnérabilité des espèces aux changements climatiques (SAVS); (3) l'évaluation du risque génétique des arbres forestiers; (4) l'indice de prévision de la vulnérabilité des essences d'arbres; (5) les normes écologiques élaborées pour assister la migration de l'espèce *Torreya taxifolia* et (6) le programme Seeds of Success. Ces outils sont applicables à différentes espèces forestières. Ils varient sur le plan des critères d'évaluation spécifiques aux espèces, du traitement de l'incertitude et de l'intégration des modèles de changements climatiques. L'utilisation de ces outils pour évaluer la vulnérabilité des espèces forestières au Canada est explorée.

**Mots clés :** changements climatiques, espèces forestières, évaluation de la vulnérabilité

## Introduction

Canadian forests are diverse, containing approximately 126 native tree species (Farrar 1995). These forests, which cover approximately half of Canada, face a variety of threats, including changes in land use, invasive pests, and climate change. Climate change is a significant risk to Canadian forests and adds an element of uncertainty to forest management (Johnston and Williamson 2007). Climate model projections predict that by 2011 areas such as eastern Canada will warm by 3°C to 5°C with increased precipitation (Dukes *et al.* 2009), whereas by 2050 in western Canada (primarily the Prairie Provinces) the mean temperature will increase by 2°C to 4°C with reduced precipitation (Schneider *et al.* 2009). Furthermore, with the projected climate changes over the next 100 years, it is likely that many tree species and populations will be unable to adapt to the projected new conditions (Aitken *et al.* 2008, O'Neill *et al.* 2008, McKenney *et al.* 2009). The potential impacts of climate change on Canadian forests are diverse,

including an increase in the length and duration of droughts in certain regions (Dale *et al.* 2001), an increase in disturbances (e.g., higher frequency of forest fires with greater intensity [Flannigan and van Wagner 1991, Stocks *et al.* 1998]), and an increase in the severity and number of native and non-native pests and pathogens (e.g., mountain pine beetle [*Dendroctonus ponderosae*]; Kurtz *et al.* 2008). These disturbances have the potential to interact, increasing the complexity associated with predicting the impacts of climate change on forests. Given the scope and complexity of the potential changes, it is challenging to assess the impacts and the vulnerability that may be present at varying biological scales.

Vulnerability has numerous meanings and can be applied to the socioeconomic, financial, or biological status of an organism or an ecological system. In a biological context, vulnerability can be assessed over various scales, from species to the ecosystem and landscape levels. When used in the context of natural systems, stresses, exposure, and capac-

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ity to adapt become key elements that define vulnerability (Chambers 1989). The Intergovernmental Panel on Climate Change (IPCC) incorporated these considerations in their definition of vulnerability, where vulnerability is a function of the character, magnitude, and rate of climate change; the variation to which a system is exposed; and its sensitivity and adaptive capacity (IPCC 2001). Similarly, Glick *et al.* (2011) state that vulnerability to climate change has three main components: sensitivity, adaptive capacity, and exposure. Sensitivity refers to innate characteristics of a species or system, and these characteristics may include tolerance to changes in temperature, precipitation patterns, or fires. At a species level, these innate characteristics are often related to a species' genetic capacity to adapt to a changing habitat. Adaptive capacity concerns the ability of a species or system to adapt to the climate change impacts, whereas exposure addresses extrinsic factors and is related to the magnitude and rate of change that a species or system may experience. In a forestry context, systems can range from the species level through to the ecozone and biome.

Vulnerability assessments are a systematic analysis of species, habitats, or ecosystems at risk and use information pertaining to sensitivity, adaptive capacity, and exposure to climate change. The assessment can also provide a level of knowledge concerning the threats to these resources or areas. Species vulnerability assessments consider vulnerability to climate change as the extent to which a species (within a defined geographical area), habitat, or ecosystem is susceptible to harm from climate impacts (Schneider *et al.* 2007). These assessments can be used to identify which species or systems are likely to be significantly impacted by the projected climate changes, and to assist in understanding why they may be vulnerable. A number of vulnerability assessment tools have recently been developed to assist land managers in their efforts to evaluate and prioritize actions taken in response to climate change, including mitigation strategies such as assisted migration (Potter and Crane 2010, Young *et al.* 2010, Bagne *et al.* 2011). This paper will review a selection of tools that have been developed for species-specific assessment of vulnerability to climate change. Additionally, we will provide examples of approaches that have integrated vulnerability assessments into management strategies for forest-associated species through assisted migration approaches.

## Assessing Vulnerability

### NatureServe Climate Change Vulnerability Index

NatureServe is a non-profit organization representing an international network of biological inventories known as "natural heritage programs" or "conservation data centers" in the USA, Canada, Latin America, and the Caribbean (NatureServe 2011). NatureServe has developed a "Climate Change Vulnerability Index" (Young *et al.* 2010) that can be used as a straightforward tool for assessing relative species vulnerability to climate change. This index is applicable to diverse taxa; it includes tree species within the USA, Canada, and Mexico, although the availability of Canadian and Mexican data is limited. This index considers two main factors in a defined geographical area: exposure and sensitivity to climate change. Depending on the species, the area may be established across the entire range of the species, or within specific geographical areas that reflect regionally defined populations. Information concerning relative species-specific vulnerability and the

importance of factors that contribute to the vulnerability of species is evaluated and converted to a numerical index, which is summed to produce a final vulnerability index (Table 1). The index can be applied to multiple species in areas on the scale of parks or refuges (NatureServe 2010).

Exposure to climate change is evaluated primarily by assessing the magnitude of predicted temperature and precipitation changes across the geographical area being considered. Information about predicted climate can be derived from many sources; however, NatureServe provides access to the Climate Wizard (Girvetz *et al.* 2009) as a source of climate predictions for use with the online vulnerability program. Climate Wizard provides both historical (1951 to 2006) and predicted future (2041 to 2060) climate data for the United States at an 8-km resolution, and at a 50-km resolution for other countries, including Canada and Mexico. The index considers vulnerability to climate change over a 50-year time frame, but the user can modify this target date.

Overall species vulnerability is based on a score against 21 criteria divided into two categories: (1) response to climate change and (2) species-specific sensitivity. First, species response to climate change is assessed by using a numerical score that represents a documented change in (1) distribution or abundance attributed to climate change; (2) modeled future change in range size; (3) overlap of predicted ideal future range with current range; and (4) occurrence of protected areas in the modeled distribution (NatureServe 2010). The latter point is considered as the species could be shielded from habitat loss if current and predicted future distributions overlap, and this overlap contains one or more protected areas.

The species sensitivity score considers multiple species-specific biological criteria, including (1) seed and pollen dispersal criteria that consider the frequency with which the species produces seed and the distance pollen can travel, and (2) genetic information that could provide an indication of any decline in genetic variation, which could in turn reduce the species adaptive capacity. This information includes, for example, genetic variation data and an indication of genetic "bottlenecks" (severe restrictions to diversity) in the evolutionary history of the species (NatureServe 2011). Other criteria include habitat specificity, reliance on interspecific interactions, and phenological responses to temperature and precipitation changes (Table 1). The selection of criteria is based on a documented response, correlated with climate change that can be identified in the scientific literature.

Once the scores for the species' exposure to climate change sensitivity are determined, they are summed to produce a final numerical score, which is converted into a categorical score referred to as the "final index score". This final index allows species ranking into one of six categories: extremely vulnerable, highly vulnerable, moderately vulnerable, not vulnerable/presumed stable, not vulnerable, decreased vulnerability, and insufficient evidence (NatureServe 2010). A ranking of decreased vulnerability could provide an indication of resilience, where resilience is the amount of change or disturbance that a system—in this case a species—can withstand without a significant loss of structure and function (Glick *et al.* 2011). There are limitations to this index: it does not consider demographic factors (e.g., population size and range size) and other non-climatic stressors.

Table 1. Summary of the species-specific vulnerability assessments

Tool	NatureServe Climate Change Vulnerability Index <sup>a</sup> Version 2.1	System for Assessing Vulnerability of Species to Climate Change (SAVS) <sup>b</sup> Version 2.0	Forest Tree Genetic Risk Assessment System <sup>c</sup> Version 1.2	Index for Predicting Tree Species Vulnerability <sup>d</sup>	Torreya Guardians <sup>e</sup>	Seeds of Success Program <sup>f</sup>
<b>Species analyzed</b>	Multiple taxa including vertebrates and plants	Multiple terrestrial vertebrates	Tree species	Tree species	Single species: <i>Torreya taxifolia</i>	Multiple plant species
<b>Integration of climate projections into the tool/framework</b>	Projected climate change analysis is required for the geographical area of interest and access to Climate Wizard is provided.	Recommends that the user obtain information on projected climate changes for the geographical area of interest.	Independent projected climate change analysis is required for the geographical area of interest.	no	no	Independent projected climate change analysis is required for the geographical area of interest.
<b>Total number of factors considered in the assessment</b>	<b>21 factors:</b> 1. Indirect climate change exposure: 3 2. Climate change sensitivity: 5 3. Geological features: 1 4. Reliance on inter-specific interactions: 5 5. Genetic parameters: 2 6. Phenology: 1 7. Documented or modeled response to climate change: 4	<b>22 factors:</b> 1. Habitat: 7 2. Physiology: 6 3. Phenology: 4 4. Biotic Interactions: 5	<b>10 factors<sup>g,h</sup>:</b> 1. Extrinsic risk factors: 6 2. Intrinsic risk factors: 2 3. Conservation modifiers: 2 4. Low risk to recipient ecosystem if AM used 5. Barriers to unassisted migration 6. Considerations of historical range	<b>11 factors:</b> 1. Ability of species to adapt in place: 6 2. Ability to move: 3 3. Plasticity: 2 4. Population level considerations: 3 5. Implementation of assisted migration: 2	<b>6 factors:</b> 1. Species threat level 2. Irreversible problems in the current range 3. Assisted migration an option	<b>18 factors:</b> 1. Development of species list: 4 2. Restoration potential: 3 3. Assisted migration potential: 6
<b>Uncertainty measurement</b>	Monte Carlo simulation.	Yes, based on the presence of adequate information or conflicting information.	no	no	no	no
<b>Species assessment output</b>	Relative vulnerability ratings with a measure of confidence.	Relative vulnerability ratings for habitat, physiology, phenology and biotic interactions, and an overall vulnerability score for each with measure of uncertainty.	Relative vulnerability ratings for extrinsic and intrinsic factors and conservation modifier, and final vulnerability score.	Numerical score that is converted to a vulnerability rating.	Recommendation to use assisted migration.	Relative vulnerability ratings with a specific recommendation for assisted migration.

<sup>a</sup>From Young *et al.* 2010

<sup>b</sup>From Bagne *et al.* 2011

<sup>c</sup>From Potter and Crane 2010

<sup>d</sup>Johnston *et al.* 2010

<sup>e</sup>Torreya Guardians 2004

<sup>f</sup>Vitt *et al.* 2010

<sup>g</sup>For each assessment a general title of the type of criteria considered and the number of factors considered for each criteria are listed.

<sup>h</sup>The user can add or remove factors.

A measure of confidence is attached to each final index based on Monte Carlo simulations. This final index provides a relative indication of whether a species has multiple known risk factors and projects its relative abundance within a defined geographical area by 2050, through the integration of data from documented or modeled responses to climate change. NatureServe recommends that this index be considered in association with the NatureServe species conservation status (Faber-Langendoen *et al.* 2009). For example, if a number of species had a vulnerability index of “highly vulnerable”, where species abundance and range extent within the defined geographical area will likely decrease significantly by 2050, they could be ranked further into higher or lower vulnerability categories by additionally considering the conservation status (endangered, threatened, etc.).

This vulnerability tool has been applied to numerous species by a variety of organizations. For example, West Virginia Division of Natural Resources conducted an assessment of the climate change vulnerability of 185 animal and plant species in the state to guide management recommendations for the revision of the Western Virginia Wildlife Conservation Action Plan (Byers and Norris 2011). Over half of the taxa assessed were scored as vulnerable. Considering plant species, results indicated that species were vulnerable for a variety of reasons, including limited dispersal ability, extant natural and anthropogenic barriers to dispersal, evidence of genetic bottlenecks, and species-specific dependence on natural disturbance regimes that may be altered by climate change. Of the 33 plant species assessed, 12 were trees, and seven of these trees were assessed as “presumed stable”, with one species likely to increase (black gum [*Nyssa sylvatica* Marsh.]). Four tree species were assessed as either highly vulnerable (red spruce [*Picea rubens* Sarg.]) or moderately vulnerable (black cherry [*Prunus serotina* Ehrh.]; pin oak [*Quercus palustris* Muenchh.]; sugar maple [*Acer saccharum* Marsh.] [Byers and Norris 2011]), where their abundance and/or range in West Virginia are predicted to decrease. For red spruce, factors identified as contributing to this species index were narrow tolerance of temperature and precipitation, poor seed dispersal, and an inability of this species to shift its range in response to climate change. Overall, mammals and plant species that are dependent on the red spruce forest, northern hardwood forest, or pin oak swamp were identified as being exposed to multiple stressors, with regeneration in these forest ecosystems shifting to species with greater tolerance to the projected climate conditions (Byers and Norris 2011). Ten management recommendations were made based on these assessments, ranging from increasing habitat connectivity and protecting water quality and stream flow to considering innovative and unconventional strategies. It is under this latter option that it was noted that the unprecedented scale and speed of environmental change may make it necessary to adopt strategies such as assisted migration (Byers and Norris 2011).

The index has also been used in the USA to assess the vulnerability of: grassland-dependent wildlife by the Great Plains Landscape Conservation Cooperative in Wyoming, Nebraska, Oklahoma, New Mexico, and Colorado (Zack *et al.* 2010); terrestrial vertebrate species in Middle Rio Grande, New Mexico (USFS 2010a); and marsh bird species in Massachusetts (Glick *et al.* 2008, Wilson and Watts 2009). To date,

this index has not been applied to species in Canada, most likely because of the lower resolution of the climatic data that NatureServe uses outside the USA and a lack of species-specific biological information.

#### System for Assessing Vulnerability of Species to climate change (SAVS)

The USDA Forest Service developed SAVS to assess the relative vulnerability of terrestrial vertebrate species to climate change (Bagne *et al.* 2011). This tool was developed to assist in identifying species requiring conservation and aid in prioritizing conservation efforts to increase the efficiency of management actions. This system assesses species vulnerability within a predefined geographical area. SAVS integrates information concerning species vulnerability, exposure, sensitivity and adaptive capacity; the information is primarily related to climate change but also considers the impact of biotic stresses (e.g., disease, competitors) and provides a measure of uncertainty (Table 1).

SAVS is presented in the form of a questionnaire, organized into four categories: physiology, phenology, habitat, and biotic interactions. Under each category are multiple criteria that focus on species' attributes that can be scored across wide taxonomic groups, including amphibians, birds, mammals, and plants. The physiology-related category considers criteria related to physiological thresholds (e.g., amphibians, where their activities can be temperature dependent), sex traits (e.g., sex determination temperature dependency), exposure to weather-related disturbances and their impact on survival and reproduction, and how temperature or precipitation regimes may alter the species' activities and metabolic rates. The criteria were selected using the scientific literature and natural history databases (Bagne *et al.* 2011). It is recommended that the user obtain information on projected climate changes in the area of interest and also that other climatic-related impacts on the species—including snowpack, frost days, drought, flooding, fires, and extreme weather events such as storms—be considered (Bagne *et al.* 2011).

In total, 22 criteria are evaluated for all four categories. Depending on the ranking of the criteria, a numerical score is calculated that allows the user to classify the species' risk as vulnerable, resilient, or neutral for the four categories and for the final score. Similar to NatureServe, SAVS identifies potential management actions associated with the various scores for each of the four categories. For example, considering the “habitat” category, possible management actions range from managing fire and thinning forests to translocation of individual populations. Uncertainty is addressed by considering whether there is adequate or inadequate information, and conflicting predictions for all of the questions. Uncertainty is determined for each of the four categories and a final numerical uncertainty score is calculated (Bagne *et al.* 2011).

The USDA Forest Service has used this tool to assess the vulnerability of vertebrates in the riparian forest of the Middle Rio Grande, New Mexico (Glick *et al.* 2011), management units in Arizona (Bagne and Finch 2010) and in the Coronado National Forest, Arizona (Coe *et al.* 2010). In the Middle Rio Grande forest region, this area of the Southwest United States is predicted to experience significant climatic changes, including large temperature increases, reduced stream and river flows, and multiple disturbances that include increased

fires and insect outbreaks (Easterling *et al.* 2004, Garfin and Lenart 2007). Initially, information on vertebrate species for that region was collated and projected for climate change effects over a period of 20 to 50 years into the future. For the 36 mammals assessed, 16% were scored as vulnerable and 44% as slightly vulnerable, whereas 5% were found to actually benefit from the projected changes, for example as opportunistic breeders with diverse habitat associations (USFS 2010b). All of the species assessments were subject to a degree of uncertainty because of the variation and availability of biological data. These vulnerability results will be used to develop management strategies and actions for this area.

The SAVS assessments are being conducted in other areas of the U.S. Southwest, including the Coronado National Forest, and results are being integrated with spatially explicit species maps to identify geographical vulnerability hotspots. This type of information will be very useful for increasing the geographical precision of their management plans and actions. This tool is not directly transferable to tree species, as the criteria are vertebrate-specific; however, it is applicable for the assessment of vertebrate forest species, and the general approach may be useful for developing tools to assess non-vertebrate species.

#### Forest Tree Genetic Risk Assessment System

The Forest Tree Genetic Risk Assessment System, developed through a partnership between North Carolina State University and the USDA Forest Service National Forest (Southern Region), focuses on the relative risk of genetic degradation of forest tree species (Potter and Crane 2010). There are four steps to this assessment: (1) identifying the geographical area for the assessment and associated species of interest within the area; (2) selecting relevant risk factors and conservation modifiers to include in the assessment; (3) collecting the necessary data pertaining to each species and calculating the indices for each risk factor and conservation modifier; and (4) weighting the indices and determining a final risk index for each species (Table 1).

The assessment considers three categories of information: intrinsic risk factors, external risk factors, and conservation modifiers. There are multiple variables that refine the assessment for each category. Indices are calculated for each variable and category. Intrinsic risk variables include population structure, rarity or density, regeneration capacity, dispersal abilities, habitat affinities, and genetic variation, whereas extrinsic risk variables consider pest and pathogen threats as well as climate change pressures. For example, for an intrinsic risk variable, population structure, an index would be calculated for the area of interest by determining: (1) area of species range; (2) number of populations; (3) mean area of the populations; and (4) number of disjunct populations. The final population index is determined by summing the values obtained for (1) to (4) and dividing by 4. Calculation of this index requires adequate species distribution maps with the necessary population-level information.

Concerning the extrinsic risk variables incorporated into pest-specific and pathogen-specific indices, the relative degree of insect and/or disease threat to populations is determined and given a relative numerical value, considering such information as severity and immediacy of the threat (Potter and Crane 2010). The second extrinsic variable, climate

change pressure, is a measure of the relative risk of climate change on a tree species and considers the expected impact of climate change on the future area, location of a suitable habitat, and the extent to which the species' current distribution is fragmented.

The conservation modifiers consider: (1) endemism, or the percentage of a given species range encompassing the area of interest; and (2) the conservation status of the species as determined by considering the official state or federal risk designation or by the NatureServe conservation status. An index is generated for these two conservation modifiers. The indices for the intrinsic, extrinsic, and conservation modifiers are then summed to provide an overall numerical vulnerability index of 0 to 100, where higher values reflect greater species' vulnerability. This system provides recommended data sources for obtaining the species-specific information, including *North America Trees* (Preston and Braham 2002), *The Woody Seed Plant Manual* (Bonner and Karrfalt 2008), the USDA's *Plant Database* (USDA 2011), and also scientific literature pertaining to population genetics. However, the focus of much of the data is on information specific to the USA.

This system allows the user to add or remove risk factors. For example, if forest fragmentation is considered to be a risk, this could be included as a variable and an index specific to this could be determined with the appropriate data (e.g., average forest patch size or forest continuity). One of the advantages of this system is that it allows the user to modify risk factors and select the relevant input data for determining the individual risk indices. Furthermore, extrinsic and intrinsic risk factors or modifiers and their variables relative to each other can be numerically weighted. For example, considering the external risk variable "pest and pathogen threats," if there is an immediate pest threat with the potential for high mortality and with no known method of eradication, this risk could be weighted higher than a similar threat that results in lower mortality. This ability is unique to this system and this weighting; although subjective, it does give the user the ability to assess the relative importance of the information. This system does not assess uncertainty or missing data. However, it appears that nothing would preclude including this element if the approach were further developed.

The framework was used to assess the vulnerability of 25 tree species in the Southern Appalachian region. The final index for these 25 species ranged from 63 for Carolina hemlock (*Tsuga caroliniana* Engelm.) to 47 for yellow buckeye (*Aesculus flava* Aiton) (Potter and Crane 2010), with the higher number corresponding to a higher vulnerability ranking. However, there is limited published information concerning how these results were used. It will be interesting to see how this system continues to develop (USFS 2010b).

#### Index for predicting tree species vulnerability

There have been Canadian efforts to develop an index to assist in ranking species vulnerability (Judy Loo, Ecological Geneticist, Natural Resources Canada, personal communication; Johnston *et al.* 2010). This index uses biological information in published reports and considers the ability of a species to move, its ability to adapt in place, and its plasticity, vulnerability, and associated sub-factors (Table 1). For example, the ability to move would consider seed dispersal, seed

size, dispersal distance, and age of reproduction, as well as habitat specificity and availability. The latter two parameters would be influenced by fragmentation and isolation. The ability to adapt in place would be a function of genetic variation, population size, fecundity, and gene flow between populations. Plasticity is an assessment of the species' resilience and environmental buffering capacity, including indicators such as heterozygosity and evidence of climatic tolerance in traits that are likely to influence adaptation.

This index was tested on nine Canadian tree species. Two species received a low vulnerability ranking: trembling aspen (*Populus tremuloides* Michx.) and sugar maple. White pine (*Pinus strobus* L.) was identified as having a low to medium level of vulnerability, whereas four species had a medium level of vulnerability: western larch (*Larix occidentalis* Nutt.), red oak (*Quercus rubra* L.), beech (*Fagus grandifolia* Ehrh.), and red spruce. Two species received medium to high vulnerability scores: butternut (*Juglans cinerea* L.) and red pine (*Pinus resinosa* Ait.) (Johnston *et al.* 2010). Among the species with medium to high vulnerability scores, red pine's low genetic diversity and short seed dispersal distance were principal determinants for the score. For butternut, low genetic diversity, short seed dispersal distance, and a large threat from an exotic disease were the principal factors that contributed to its score. This approach may benefit from the inclusion of climate-related impacts (e.g., drought, snow cover) as recent climate change predictions indicate that there will be a requirement for more drought-tolerant trembling aspen genotypes in western Canada (Gray *et al.* 2011), and this information if incorporated might increase the ranking for this species.

An index such as this would help identify species at risk. However, information is lacking concerning our understanding of phenotypic plasticity of traits associated with adaptation to climate change, plasticity within and among populations, and methods for measuring this plasticity. These constraints are applicable to the Forest Tree Risk Assessment, NatureServe Climate Change Vulnerability Index, and SAVS, all of which integrate similar adaptation-related information to varying degrees. Johnston *et al.* (2010) provide more detail pertaining to the use and calculation of this vulnerability assessment.

### Ecological standards for assisted migration developed for *Torreya taxifolia*

The Torreya Guardians are a volunteer conservation group consisting of botanists, naturalists, and citizens with an interest in conserving Florida Torreya (*Torreya taxifolia* Arn.). This group has four primary goals: (1) to save this species from extinction; (2) to test the utility of assisted migration for this and other threatened plant species; (3) to provide a model for possible activities to help mitigate the impacts of climate change; and (4) to foster collaborations with the public and appropriate professions (Torreya Guardians 2004). Florida Torreya is a small tree in the yew family (Taxaceae) with a very limited range in the southeastern United States; it is native to Georgia and Florida. Florida Torreya is federally listed as critically endangered under the U.S. Endangered Species Act (U.S. Fish and Wildlife Service 1986). Within its native range, this species has been decimated by a fungal disease (Godfrey and Kurz 1962) reported to be a novel species of *Fusarium* (Smith *et al.* 2011), which remains the largest threat to this species' survival.

The Torreya Guardians developed "Ecological Standards" as a tool for assessing vulnerability, identifying whether this species was at risk, and determining if assisted migration was an appropriate mitigation strategy (Tables 1 and 2). To assess vulnerability, two factors are used: "neediness" and "irreversible problems." The assessment identifies whether the species is endangered, and whether ecological or climate change is a major threat. Four factors then consider whether assisted migration is appropriate (Table 2), including considerations pertaining to historical information, evaluation of whether assisted migration will decrease the risk of extirpation or introduce new threats to the recipient areas, and determination of whether unassisted migration is still feasible.

The Torreya Guardians identified Florida Torreya as being highly vulnerable and incorporated this information into their management plans, where they have developed and implemented assisted migration as a conservation strategy using their own resources (Torreya Guardians 2004). They have established plantings of trees across a 600-km range, predominantly in the southern Appalachians, using readily avail-

**Table 2. Ecological standards for assisted migration developed for *Torreya taxifolia*<sup>a</sup>**

Factor	Standard
1. Neediness	Is the plant considered to be highly threatened or endangered within its current native range?
2. Irreversible problems in the current range	Is ecological change and/or climate change a major cause of the species' threatened status in its current native range? Also, would restoration efforts for the species in the current range be unsatisfactory for recovery?
3. Suitability for target range	Is there evidence that the risk of ecological or climate change would be lessened or overcome by the use of assisted migration?
4. Low risk for recipient ecosystems	Are any of the plant characteristics (e.g., dispersal mode, pathogens it may carry) a possible threat to other species in the target range, especially rare or threatened organisms? (Noting that oversight and precautions will be established in the implementation plans.)
5. Barriers to unassisted migration	Corridors either do not exist or are inadequate for unassisted and timely movement.
6. Reconstructing past range	The historical range of the plant encompasses the target range and or the types of life communities now present in the target range.

<sup>a</sup>Adapted from Torreya Guardians 2004.

able seed stock (Camacho 2010). This material is being planted on private lands, with full support of the landowners. Thus, there is no involvement of government oversight, nor has it been legally mandated.

There have been concerns that limited biological information has been used in this assessment and that assisted migration may result in unintended negative ecological consequences (McMahan 1989). These concerns include the introduction of non-native species and their potential to become invasive. However, no negative ecological consequences have been identified. This group has created an extensive online information resource for their activities (Torreya Guardians 2011), which was most likely used to assist in this decision-making process. This work has raised important questions concerning the level of information needed to determine the level of a species' vulnerability to climate change. Furthermore, how does one address the absence of information in the presence of uncertainty? Please see the papers by Aubin *et al.*, Ste-Marie *et al.* and Winder *et al.* in this issue that further discuss these issues.

This example of assisted migration has raised the issue of authorization and oversight as the official federal recovery plan does not identify assisted migration as a conservation strategy for Florida Torreya. The momentum that this group has created resulted in the U.S. Fish and Wildlife Service considering whether assisted migration is an appropriate strategy for this species (U.S. Fish and Wildlife Service 2010). It is yet to be seen if official plans will include a more thorough assessment of the ecological impacts of assisted migration, or more extensive monitoring programs. Nonetheless, this is a very interesting example of how a grassroots organization can propel assisted migration into the forefront, causing a governmental agency to consider the use of this strategy.

### Seeds of Success Program

The Seeds of Success program is a multi-partner program that collects the seed to support conservation, research, and restoration, including assisted migration (Byrne and Olwell 2008). This program was established in 2001 and is coordinated by the U.S. Department of the Interior Bureau of Land Management on behalf of the Plant Conservation Alliance, a consortium of U.S. federal government agencies and non-federal conservation-related co-operators, including botanical gardens and zoos. The Seeds of Success program is an example of a framework that assesses species vulnerability, with the final outcome a list of potential target species for which assisted migration could be applied.

The framework comprises five stages. The first consists in developing a comprehensive baseline species list for the geographical area of interest (Vitt *et al.* 2010). This list is then reduced by excluding non-native species and species producing seed that cannot be stored for long durations. The second stage refines this list based on the risk of the species becoming invasive, prioritizing pioneer species as well as non-aggressive species at the edge of their range. The third stage further refines this list, focusing on species that have a high probability of benefiting from assisted migration by assessing potential biological risk factors. The criteria used for this stage include parameters that identify taxa with (1) geographic risk, (2) life-history constraints, (3) dispersal limitations, (4) patchy or disjunctive distributions, (5) only local

abundance, and (6) characteristics considered to be highly conservative (e.g., low tolerance to disturbance and high habitat specificity). The fourth stage assesses population-level collection priorities by conducting species distribution modeling, with a focus on species at the edge of their ranges, those whose ranges are outside future climate envelopes, and those species that are currently unprotected (e.g., not well represented within *in situ* conservation areas based on future climate envelopes). Stage five is the implementation of assisted migration, which involves conducting GIS-based habitat-matching protocols and the development of species-specific assisted migration strategies.

An important step identified in the implementation stage is ensuring that the appropriate seed collections have been made so that the material for assisted migration is secure (Vitt *et al.* 2010). These protocols were adapted from those developed by the Millennium Seed Bank (2010). This very detailed protocol addresses factors such as the number of collections, knowledge concerning the proportion of genetic diversity requiring conservation, the number of plants from which to collect, and collection protocols (e.g., collection of the whole inflorescence). The Seeds of Success program recognizes that *ex situ* collections are critical to implementation of assisted migration.

The Seeds of Success program considers assisted migration to be an extension of restoration, and an integral component to their framework. One of the primary goals of this program is to establish high-quality, well-documented collections of seed from native species at the population level, with the overall goal to collect and store seed for the entire United States flora (15 000 species) (Seeds of Success 2010). The initial focus is on 1000 species, with emphasis on tallgrass prairies species, for which restoration protocols and the necessary seed collections will be made. Recent work from participating agencies (e.g., Chicago Botanical Gardens and the Dixon National Tallgrass Prairie Seed Bank) focused on determining how this program can optimize seed collections in the face of a rapidly changing climate, and how to identify which species were most vulnerable and may require assisted migration (Vitt *et al.* 2010). Within this context, a framework was developed to assess vulnerability and make recommendations as to whether assisted migration is the appropriate mitigation strategy. What is unique about this framework is that it has been applied and implemented by the Dixon National Tallgrass Prairie Seed Bank for identifying species, and collecting and storing seed from targeted ecoregions in the U.S. Midwestern states for future assisted migration activities. This is an ambitious project, with a goal of collecting and storing, on a per species basis, 10 000 to 20 000 viable seeds from single populations (with a minimum of 50 individuals per population) to capture the genetic diversity of the population (Chicago Botanical Gardens 2008). The Seeds of Success framework is a very practical strategy for storing seed for future conservation purposes.

### Conclusion

The vulnerability assessment tools presented herein all include a set of criteria related to the climatic response of a species and integrate this information using a systematic process available in the form of a spreadsheet or list. The NatureServe Climate Change Vulnerability Index is a species-

specific tool that is applicable to broad taxonomical groups including plants and vertebrates, and as such, considers diverse information related to such areas as climate change sensitivity, species reliance on interspecific interactions, phenology, and genetic information. The proposed Index for Predicting Tree Species Vulnerability considers genetic data in addition to general biological information, whereas the Forest Tree Genetic Risk Assessment is a similar genetic-based information tool but also considers criteria related to habitat, pests, and pathogens and species conservation status. The SAVS assessment considers habitat, physiological, phenological, and biotic interaction-related criteria unique to vertebrates. These assessment tools provide a final measure of the species' relative vulnerability to climate change. These tools can help set priorities and guide management actions. The approach of the Torrey Guardians, in their ecological standards, was to assess vulnerability as well as the utility of assisted migration as a specific management response. The Seeds of Success Program has developed a framework that goes further, by evaluating vulnerability, identifying the management response as assisted migration, and then proceeding to scenario planning, where the logistical steps for implementation are identified. All of these vulnerability assessment tools have developed relatively quickly, reflecting an increasing need to assess the impacts of climate change on a multiple per-species basis to enhance management decisions.

The Seeds of Success program and the Torrey Guardians specifically identify assisted migration as the outcome, whereas NatureServe and SAVS consider assisted migration as one of the potential options depending on the vulnerability rating. The only tools that do not include assisted migration as a potential management action are the two specific to trees. This may reflect these tools being in the relatively early stages of development, where developers have not yet considered potential management options. Identification of assisted migration as a management option indicates that this is becoming an accepted climate change mitigation strategy. Furthermore, all but the Index for Predicting Tree Species Vulnerability and Forest Tree Genetic Risk Assessment have been used by various agencies where the assessment results have been integrated into management strategies for forest species.

In assessing vulnerability, it is important to consider the level of confidence or uncertainty that is associated with the assessments and the impact that this may have on management decisions. This uncertainty arises from multiple sources, at various steps in the assessments, including model-generated future climate and ecological projections (Botkin *et al.* 2007, Conroy *et al.* 2011), biological information based on diverse research, including studies using qualitative and quantitative results from field and experimental studies, as well as modeling (Thuiller 2004, Keller *et al.* 2008, Hodgson *et al.* 2009). Uncertainty can arise from a variety of sources, including limited data, unknown or unanticipated interactions, and different interpretations of the data. The IPCC (2007) describes uncertainty, recommends language to be used, and levels of confidence to express uncertainty. The NatureServe approach uses a statistical technique (Monte Carlo simulations) to provide a measure of the uncertainty in the inputs to the assessments, whereby probability distributions are created for any factor that may have inherent uncertainty. Results are then calculated over multiple independent simulations, using different sets of random values from the

probability functions. This statistical approach produces distributions of possible outcomes and is commonly used in climate change research (Lorenzo *et al.* 2007). SAVS addresses uncertainty by assessing the quality of data (e.g., available, conflicting, or inadequate data) and calculates a numerical uncertainty score. The Forest Tree Genetic Risk Assessment System does not directly address uncertainty; however, this tool has the ability to weight factors and could possibly be applied to weight input factors where there are missing data or uncertainties (Potter and Crane 2010). The Seed of Success framework, the Index for Predicting Tree Species Vulnerability, and the Torrey Guardians do not address uncertainty.

These vulnerability assessments have yet to be applied to Canadian forest species based on the scientific literature, but could be applicable. Although the NatureServe assessment is tailored for the USA, with higher resolution of American vs. Canadian climatic data, the option is present to use other climatic models and sources of data for the analysis of forest species. Similarly, the Torrey Guardians guidelines and the Forest Tree Genetic Risk assessment could be applicable in Canada for tree species with the appropriate data, and the Index for Predicting Tree Species Vulnerability was developed specifically for Canadian tree species. The Seeds of Success framework provides a roadmap that could be applied to a Canadian context, but is tailored to plants (including trees) that produce seeds that can be conserved *ex situ*. This would exclude 14% of native Canadian tree species that produce seed that cannot be stored *ex situ* over the long term (e.g., oaks, butternut) (Beardmore and Simpson 2010). The relevant data for these assessment could come from multiple sources, including federal and jurisdictional official risk assessments, such as the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) species status reports; these contain diverse information, including population-level, regeneration capacity, and genetic variation data (COSEWIC 2010). For species without official assessments or designations, sources of information include scientific literature (e.g., Bower and Aitken 2008, Godbout *et al.* 2010), the National Forest Information System (CCFM 2010), and NatureServe Canada (2011). Climatic data are available through such sources as the Canadian Institute for Climatic Studies (2007) and the Canadian Centre for Climate Modeling and Analysis (Environment Canada 2010). Most likely, these assessments will be conducted in the future to contribute to the evaluation of the climate change impacts on multiple forest species.

When selecting a tool, it is important to consider the geographical and biological scope of the assessment. Is the focus to be on assessing all species with official risk designation within a geographical area or all forest species within a jurisdiction? Clearly these decisions are related to the management objectives. The ability to address uncertainty is also a very important consideration. Another consideration is the need to integrate climate change projections into the assessment; for example, NatureServe and the Forest Tree Genetic Risk Assessment incorporate modeled projections as part of the evaluation, whereas SAVS includes a set of population change predictors that represent a positive or negative response to climate change.

Vulnerability assessments can help identify species that are likely to be impacted by climate change, which will assist land managers in prioritizing efforts, thus contributing to the deci-



sion-making process for mitigating the impacts of climate change and other stressors. Further research in species-specific scientific knowledge will contribute to the future enhancement of these vulnerability assessments and should assist in decreasing uncertainty.

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## References

- Aitken, S.N., S. Yeaman, J.A. Holliday, T. Wang and S. Curtis-McLane. 2008. Adaptation, migration or extirpation: climate change outcomes for tree populations. *Canadian Journal of Forest Research* 27: 1773–1780.
- Aubin, I. *et al.* 2011. Why we disagree about assisted migration: Ethical implications of a key debate regarding the future of Canada's forests. *The Forestry Chronicle* 87(6): 755–765.
- Bagne, K.E. and D.M. Finch. 2010. An assessment of vulnerability of threatened, endangered, and at risk species to climate change at the Barry M. Goldwater Range, Arizona. U.S. Department of Defence Legacy Program Final Report. 185 p.
- Bagne, K.E., M.M. Friggens, and D.M. Finch. 2011. A system for assessing vulnerability of species (SAVS) to climate change. General Technical Report. RMRS-GTR-257. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO.
- Beardmore, T. and D. Simpson. 2010. *Ex situ* conservation of tree seeds: a Canadian perspective. In C.T. Chein and F. Chen (eds.). Symposium Proceedings IUFRO Tree Seed Symposium: Recent Advances in Seed Research and *ex situ* conservation. Taipei, Taiwan, 16–18 June 2010, No. 53. pp. 27–36. Taiwan Forestry Research Institute Press, Taipei, Taiwan.
- Botkin, D.B. *et al.* 2007. Forecasting the effects of global warming on biodiversity. *BioScience* 57: 227–238.
- Bonner, F.T. and R.P. Karrfalt. 2008. *The Woody Seed Plant Manual*. U.S. Department of Agriculture, Forest Service, Washington, DC.
- Bower, A.D. and S.N. Aitken. 2008. Genetic diversity and geographic differentiation in quantitative traits, and seed transfer guidelines for *Pinus albicaulis* (Pinaceae). *American Journal of Botany* 95: 66–76.
- Byers, E. and S. Norris. 2011. Climate change vulnerability assessment of species of concern in West Virginia. West Virginia Division of Natural Resources. Available at <http://www.wvdnr.gov/publications/PDFFiles/ClimateChangeVulnerability.pdf>.
- Byrne, M.K. and P. Olwell. 2008. Seeds of success: the national native seed collection program in the United States. *Public Gardens* 23: 3–4.
- Camacho, A.E. 2010. Assisted migration: redefining nature and natural resource law under climate change. *Yale Journal on Regulation* 27: 171–189.
- [CCFM] Canadian Council of Forest Ministers. 2010. National Forest Information System. Available at [https://ca.nfis.org/index\\_eng.html](https://ca.nfis.org/index_eng.html).
- Canadian Institute for Climatic Studies. 2007. University of Victoria, Victoria, British Columbia. Available at <http://www.cics.uvic.ca/scenarios/>.
- Chambers, R. 1989. Vulnerability, coping and policy. *Institute of Developmental Studies Bulletin* 20: 1–7.
- Chicago Botanical Gardens. 2008. Seeds of Success: preserving America's native plants for future generations. Available at <http://cbgseedbank.org/oldsite/about.php>.
- Coe, S., D. Finch and M. Friggens. 2010. Applying a decision-support tool for assessing vulnerability to wildlife to climate change: a case study on the Coronado National Forest, Arizona. USDA Forest Service, Rocky Mountain Research Station, Albuquerque, NM. Available at <http://www.fs.fed.us/rm/grassland-shrubland-desert/docs/species-vulnerability/assessing-vulnerability.pdf> [Accessed July 2011].
- [COSEWIC] Committee on the Status of Endangered Wildlife in Canada. 2010. Status Reports. COSEWIC Secretariat, Ottawa, ON, Canada. Available at [http://www.cosewic.gc.ca/eng/sct2/index\\_e.cfm](http://www.cosewic.gc.ca/eng/sct2/index_e.cfm).
- Conroy, M.J., M.C. Runge, J.D. Nicols, K.W. Stodola and R.J. Cooper. 2011. Conservation in the face of climate change: the roles of alternative models, monitoring, and adaptation in confronting and reducing uncertainty. *Biological Conservation* 144: 1204–1213.
- Dale, V.H. *et al.* 2001. Climate change and forest disturbance. *BioScience* 51: 723–634.
- Dukes, J.S. *et al.* 2009. Responses of insect pests, pathogens, and invasive plant species to climate change in the forests of northeastern North America: What can we predict? *Canadian Journal of Forest Research* 39: 231–248.
- Easterling, W.E., B.H. Hurd and J.B. Smith. 2004. Coping with Global Climate Change: the Role of Adaptation in the United States. Pew Centre on Global Climate Change, Arlington, VA. Available at [http://www.pewtrusts.org/our\\_work\\_report\\_detail.aspx?id=22878](http://www.pewtrusts.org/our_work_report_detail.aspx?id=22878).
- Environment Canada. 2010. Models, Canadian Centre for Climate Modeling and Analysis. Available at <http://www.ec.gc.ca/ccmac-ccma/default.asp?lang=En&n=4A642EDE-1>.
- Faber-Langendoen, D., L. Master, J. Nichols, K. Snow, A. Tomaino, G. Bittman, B. Hammerson, B. Heidel, L. Ramsay and B. Young. 2009. NatureServe Conservation Status Assessments: Methodology for Assigning Ranks. NatureServe, Arlington, VA. Available at [www.natureserve.org/publications/library.jsp#nspubs](http://www.natureserve.org/publications/library.jsp#nspubs).
- Farrar, J.L. 1995. *Trees of the northern United States and Canada*. Iowa State University Press, Ames, IA.
- Flannigan, M.D. and C.E. van Wagner. 1991. Climate change and wildfire in Canada. *Canadian Journal of Forest Research* 21: 66–72.
- Garfin, G. and M. Lenart. 2007. Climate change effects on Southwest water resources. *Southwest Hydrology* 6: 16–17.
- Girvetz, E.H., G.T. Zganjar, E.P. Raber, E.P. Maurer, P. Kareiva and J.J. Lawler. 2009. Applied climate-change analysis: the climate wizard tool. *PLoS ONE* 4:e8320. doi:10.1371/journal.pone.0008320.
- Glick, P., J. Clough and B. Nunley. 2008. Sea-level rise and coastal habitats in the Chesapeake Bay Region: Technical Report. National Wildlife Federation, Reston, VA.
- Glick, P., B.A. Stein and N.A. Edelson. 2011. Scanning the Conservation Horizon: a Guide to Climate Change Vulnerability Assessment. National Wildlife Federation, Washington, DC.
- Godfrey, R.L. and H. Kurz. 1962. The Florida *Torreya* destined for extinction. *Science* 136: 900–902.
- Godbout, J., J. Beaulieu and J. Bousquet. 2010. Phylogeographic structure of jack pine (*Pinus banksiana*; Pinaceae) supports the existence of a coastal glacial refugium in northeastern North America. *American Journal of Botany* 97: 1903–1912.
- Gray, L.K., T. Gylander, M.S. Mbogga, P. Chen and A. Hamann. 2011. Assisted migration to address climate change: recommendations for aspen reforestation in western Canada. *Ecological Applications* 21: 1591–1603.
- Hodgson, J.A., C.D. Thomas, B.A. Wintle and A. Moilanen. 2009. Climate change, connectivity and conservation decision-making: back to basics. *Journal of Applied Ecology* 49: 964–969.
- [IPCC] Intergovernmental Panel on Climate Change. 2001. Climate change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.
- \_\_\_\_\_. 2007. *Impacts, adaptation and vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. M.L. Parry, O.F. Canziani,

- J.P. Palutikof, P.J. van der Linden and C.E. Hanson (eds.). Cambridge University Press, Cambridge, UK.
- Johnston, M., D. Price, S. L'Hirondelle, R. Fleming and A. Ogden. 2010.** Limited report: Tree species vulnerability and adaptation to climate change: final technical report. Saskatchewan Research Council Publication No. 12416-1E10. Available at [http://bcwildfire.ca/ftp/HFP/external/publish/ClimateChange/Partner\\_Publications/Vulnerability\\_of\\_Canadas\\_Tree\\_Species\\_to\\_ClimateChange\\_Technical\\_Report\\_SRC.pdf](http://bcwildfire.ca/ftp/HFP/external/publish/ClimateChange/Partner_Publications/Vulnerability_of_Canadas_Tree_Species_to_ClimateChange_Technical_Report_SRC.pdf).
- Johnston, M. and T. Williamson. 2007.** A framework for assessing climate change vulnerability of the Canadian forest sector. *The Forestry Chronicle* 83: 358–361.
- Keller, K., G. Kohe and M. Schlesinger. 2008.** Managing the risks of climate thresholds: uncertainties and information needs. *Climatic Change* 91: 5–10.
- Kurtz, W.A., C.C. Dymond, G. Stinson, G.J. Rampley, E.T. Neilson, A.L. Carroll, T. Ebata and L. Safranyik. 2008.** Mountain pine beetle and forest carbon feedback to climate change. *Nature* 45: 987–990.
- Lorenzo, L., P. Reichert, R. Knutti, T.F. Stocker and M.E. Borsuk. 2007.** Robust Bayesian Uncertainty Analysis of Climate System Properties Using Markov Chain Monte Carlo Methods. *Journal of Climate* 20: 1239–1254.
- McKenney, D.W., J.H. Pedlar and G.A. O'Neill. 2009.** Climate change and forest seed zones: past trends, future prospects and challenges to ponder. *The Forestry Chronicle* 85: 258–266.
- McMahan, L. R. 1989.** Conservationists join forces to save Florida *Torreya*. *The Center for Plant Conservation* 4: 1–8.
- Millennium Seed Bank. 2010.** World Checklist of Selected Plant families. Available at [http://apps.kew.org/wcsp/prepareChecklist.do?checklist=selected\\_families%40%40216040820101118026](http://apps.kew.org/wcsp/prepareChecklist.do?checklist=selected_families%40%40216040820101118026).
- NatureServe. 2010.** National Heritage Program Files. Available at <http://natureserve.org/explorer>.
- NatureServe. 2011.** NatureServe Mission. Available at <http://www.natureserve.org/aboutUs/index.jsp>.
- NatureServe Canada. 2011.** NatureServe Canada Projects. Available at <http://www.natureserve.org/projects/canada.jsp>.
- O'Neill, G. A., N. Ukrainetz, M. Carlson, C. Cartwright, B. Jacquish, J. King, J. Krakowski, J.H. Russell, M. Stoehr, C.Y. Xie and A. Yanchuk. 2008.** Assisted migration to address climate change in British Columbia—recommendations for interim seed transfer standards. Tech. Report 048. B.C. Ministry of Forest and Range, Research Branch, Victoria, BC.
- Potter, M.K. and B.S. Crane. 2010.** Forest tree genetic risk assessment system: a tool for conservation decision-making in changing times. User Guide Version 1.2. Available at <http://www.forestthreats.org/current-projects/project-summaries/genetic-risk-assessment-system-description-120610.pdf>.
- Preston, R.J., Jr. and R.R. Braham. 2002.** *North American Trees*. Fifth edition. Iowa State University Press, Ames, IA.
- Seeds of Success. 2010.** Technical Protocol for the Collection, Study, and Conservation of Seeds from Native Plant Species for Seeds of Success. Bureau of Land Management. Available at <http://www.nps.gov/plants/sos/protocol/index.htm> [Accessed 20 September 2010].
- Schneider, R.R., A. Hamann, D. Farr, X. Wang and S. Boutin. 2009.** Potential effects on climate change on ecosystem distribution in Alberta. *Canadian Journal of Forest Research* 39: 1001–1010.
- Schneider, S. H., S. Semenov and A. Patwardan. 2007.** Assessing key vulnerabilities and the risk from climate change. *Climate Change 2007: Impacts, Adaptation and Vulnerability*. Contributions of Working Group II to the Fourth Assessment report of the Intergovernmental Panel on Climate Change. M.L. Parry *et al.* (eds.). pp. 779–810. Cambridge University Press, Cambridge, UK.
- Smith, J.A., K. O'Donnell, L.L. Mont, K. Shin, A. Trulock, T. Specator, J. Cruse-Sanders and R. Determann. 2011.** A novel *Fusarium* species causes a canker disease of the critically endangered conifer, *Torreya taxifolia*. *Plant Disease* 95: 633–639.
- Ste-Marie, C., E.A. Nelson, A. Dabros and M.E. Bonneau. 2011.** Assisted migration: Introduction to a multifaceted concept. *The Forestry Chronicle* 87(6): 724–730.
- Stocks, B.J. et al. 1998.** Climate change and forest fire potential in Russian and Canadian boreal forests. *Climate Change* 38: 1–13.
- Thuiller, W. 2004.** Patterns and uncertainties of species' range shifts under climate change. *Global Change Biology* 10: 2027–2027.
- Torreya Guardians. 2004.** Ecological Standards for Assisted Migration of Plants. Available at <http://www.torreyaguardians.org/standards.html>.
- Torreya Guardians. 2011.** Assisted Migration (Assisted Colonization, Managed Relocation) and Rewilding of Plants and Animals in an Era of Global Warming. Available at <http://www.torreyaguardians.org/assisted-migration.html>.
- U.S. Department of Agriculture (USDA). 2011.** Plant Database. Available at <http://plants.usda.gov/java/>.
- [USFS] U.S. Department of Agriculture Forest Service. 2010a.** Eastern Forest Environmental Threat Centre. Available at <http://www.forestthreats.org/current-projects/project-summaries/genetic-risk-assessment-system>.
- \_\_\_\_\_. 2010b.** Vulnerability of individual species to climate change: vertebrate species of the Middle Rio Grande Bosque, New Mexico. Final Report. Agreement No. 211819H705, for the U.S. Fish and Wildlife Service, Region 2, Albuquerque, New Mexico. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO.
- U.S. Fish and Wildlife Service. 1986.** Final Rule to Determine *Torreya taxifolia* (Florida *Torreya*) to be an endangered species in Florida and Georgia. *Federal Registry (Rules and Regulations)* 49: 2783–2786.
- \_\_\_\_\_. 2010.** *Torreya taxifolia* (Florida *Torreya*) 5-year Review: Summary and Evaluation. U.S. Fish and Wildlife Service, Southeast region, Panama City Field Office, Panama City, Florida. 25 p. Available at <http://ecos.fws.gov/speciesProfile/profile/speciesProfile.action?spcode=R006>.
- Vitt, P., K. Havens, A.T. Kramer, D. Sollenberger and E. Yates. 2010.** Assisted migration of plants: changes in latitudes, changes in attitudes. *Biological Conservation* 143: 8–27.
- Winder, R., E.A. Nelson and T. Beardmore. 2011.** Ecological implications for assisted migration in Canadian forests. *The Forestry Chronicle* 87(6): 731–744.
- Wilson, M. and B. Watts. 2009.** Projected impacts of sea-level rise on the population size of salt-march breeding birds within the Chesapeake Bay Region. Centre for Conservation Biology, College of William and Mary and Virginia Commonwealth University, Williamsburg, VA.
- Young, B., E. Byers, K. Gravier, G. Hammerson and A. Redder. 2010.** Guidelines for using the NatureServe climate change vulnerability index. NatureServe. Available at <http://www.natureserve.org/prodServices/climatechange/ccvi.jsp>.
- Zack, S., K. Ellison, M. Cross and E. Rowland. 2010.** Climate change planning for the Great Plains: Wildlife vulnerability assessment and recommendations for land and grazing management. Wildlife Conservation Society, North America Program, Bozeman, MT. Available at [http://www.greatplainslcc.org/PDFs/2010reports/Zack\\_GPLCC\\_final\\_report\\_100930.pdf](http://www.greatplainslcc.org/PDFs/2010reports/Zack_GPLCC_final_report_100930.pdf).