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ECOSYSTEM SERVICES RESOURCE CENTER **REPORT**

Forestry Adaptation and Mitigation in a Changing Climate

A Forest Resource Manager's Guide for the Northeastern United States

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EXECUTIVE SUMMARY

A coordinated response to reduce greenhouse gas emissions will not be adequate to prevent unprecedented climate change resulting from the elevated levels of carbon dioxide (CO_2) already in the atmosphere. Climate adaptation management strategies are essential if landowners and managers are going to have plans that help them achieve their objectives in the face of uncertainty (e.g., revenue, silviculture, retain third-party forest certification). Strategies are also needed if northeastern US forests will continue to play a mitigating role in addressing greenhouse gas emissions. In this report, we lay out a framework for understanding potential impacts of climate change on forestry. This framework draws on a review of recommended actions from forest managers and scientists throughout Canada, the US, and Europe. We then present a toolbox of practices that forest managers in the northeastern US might apply to reduce exposure to the immediate and long-term risk from climate change. The toolbox approach incorporates three broad strategies of *Resistance, Resilience,* and *Response*. A *Resistance* strategy is a set of short-term approaches to address immediate threats and focuses on minimizing the impacts of disturbance regimes that are exacerbated by climate change. *Resilience* can be seen both as a short-term and a long-term strategy. *Resilience* strategies address the capacity of a stand or community to recover from a disturbance and return to a reference or desired state. The primary purpose of a *Response* strategy is to facilitate the movement of species over time. This strategy encompasses the most costly practices and requires acceptance of a level of uncertainty that many landowners and managers will likely not choose.

What Do We Need to Adapt To?

The forestry adaptation framework we present is based on the assumption of change that is likely to occur within a suite of four stressors. We outline how these stressors might change and how these changes might affect the region's forests.

- **Seasonal Temperature and Precipitation Changes**
    - Inoperable seasons become longer
    - Changes in peak flow impact transportation infrastructure
    - Precipitation changes create industry-wide operational constraints
- **Disturbance Regimes**
    - Climate change leads to increased frequency, intensity, and magnitude of disturbances
    - Forest communities are exposed to new disturbance agents
    - Operational infrastructure is placed at risk
- **Invasive Species**
    - Invasive native and exotic plant species colonize new regions
    - Invasive plants prevent regeneration and establishment of desirable native species
- **Species and Community Latitudinal Shifts**
    - New species become important to the region
    - Previously important species become less suited to the region
    - Novel plant communities develop

What Can Be Done to Adapt?

We present specific strategies that forest managers can implement to address climate change impacts and facilitate adaptation of the forest resource. Management activities are defined by the scale, or realm, at which they are to be implemented and where decisions typically occur. Below we outline specific forest management activities for each of the five management realms.

- **Forest Stand Scale**
  - Maintain species and structural diversity
  - Maintain stand vigor
- **Ownership/Landscape Scale**
  - Maintain tree species and community diversity
  - Maintain forest connectivity
  - Monitor, control, and prevent invasive and pest species encroachment
  - Maintain watershed below Equivalent Clearcut Area (ECA) threshold
- **Silvicultural Systems**
  - Modify regeneration harvest prescriptions to favor adapted commercial species
  - Reduce rotation length
  - Plant adapted commercial species
- **Harvest Operations**
  - Minimize road networks
  - Adjust culvert size requirements for changes in Peak Flow
  - Plan for seasonal operational limitations
- **Forest Planning**
  - Modify growth and yield models

There is a strong relationship between the relative cost of adaptation practices and the degree of uncertainty around climate change impacts. Cost implications and uncertainty present challenges for forest managers interested in making the business changes necessary to adapt to a changing climate. The report describes conceptually the relative costs of implementing adaptation practices.

Mitigation

It is widely recognized that forests in the Northeast can play a significant role in mitigating the atmospheric accumulation of greenhouse gases through carbon sequestration. The report presents some brief recommendations based on a precautionary approach that is generally consistent with the adaptation strategies we describe.

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INTRODUCTION

Overwhelming evidence now exists that we are experiencing global climate change that will continue into the coming centuries (IPCC 2007) and that change is likely irreversible (Solomon et al. 2009). The northeastern US is experiencing measurably longer growing seasons, shorter periods with frozen soils and lakes, more frequent extreme precipitation events and associated peak stream flows (Union of Concerned Scientists 2006, Jacobson et al. 2009, Stine et al. 2009), and upward elevation shifts in northern tree species (Solomon and Leak 1994). There are predictions that in 50 to 100 years, parts of the Northern Forest of Maine will have a climate more like that of New Jersey today (Union of Concerned Scientists 2006). Increasingly, local and global businesses are concluding that their ability to mitigate and adapt to climate change is essential to long-term economic viability (e.g., Carey 2004). Failure to take action is predicted to result in a 5–20% reduction in global Gross Domestic Product (Stern 2006). Hence, the private business sector (rather than government) is providing most of the innovation on how to deal with climate change. Companies that are most aggressive in addressing climate change are discovering an immediate competitive financial advantage (Walsh 2007).

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A considerable volume of information has been generated about climate change and the potential impacts to forests and the forest products industry (e.g., Kirilenko and Sedjo 2007). At present, this information is unconsolidated and difficult to access.[1] More importantly, it is difficult for forest managers to interpret and translate this information into practical management actions, or even to assess the merits of any action given the level of uncertainty about potential forest impacts (Perez-Garcia et al. 2002). Based on available information, we can expect climate change impacts to be manifested in comparatively rapid changes in species distribution and/or diebacks (Aber et al. 2001, Dale et al. 2001, Kurz et al. 2008), increased disturbance from extreme weather events (e.g., ice storms, wind, drought, rain events [Irland 2000, Peterson 2000, Flemming et al. 2002, Nechodom et al. 2008]). Impacts can be positive, in terms of increased forest growth and yield for the more resilient species (Cao and Woodward 1998, IPCC 2007), or negative through the creation of water deficits (van Mantgem et al. 2009).

Climate adaptation management strategies are essential if landowners and managers are going to have plans that help them achieve their objectives in the face of uncertainty (e.g., revenue, silviculture, retain third-party forest certification). Strategies are also crucial if forests will continue to play a mitigating role in addressing greenhouse gas (GHG) emissions.

In this report, we lay out a framework for understanding potential impacts of climate change on forestry. This framework draws on a review of recommended actions from forest managers and scientists throughout Canada, the US, and Europe.[2] We present a toolbox of practices that forest managers in the northeastern US might apply to reduce exposure to the immediate and long-term risks from climate change. The toolbox approach incorporates three broad strategies of Resistance, Resilience, and Response after Noss (2001), Millar et al. (2007), Spittlehouse and Stewart (2003), and Spittlehouse (2005). We also discuss a key fourth element to the framework, which is the integration of mitigation strategies that promote carbon sequestration through practice changes and long-lived wood product storage. Our toolbox will help forest managers develop their own practical climate change adaptation management practices based on specific examples and recommendations.

WHAT DO WE NEED TO ADAPT TO?

We know from basic ecological principles that climate shapes the distribution of tree species and the assemblage of forest communities. Natural disturbance regimes such as fire, wind, and insect outbreaks are also largely determined by climate. In the northeastern US, we are now learning firsthand about how a changing climate shifts the distribution of many invasive plant and both exotic and native pest species. Through research and experience, forest managers have developed forestry practices that are appropriate to a static range of current conditions and disturbance regimes. Under most climate change scenarios, the severity and frequency of these stressors are expected to behave in unfamiliar and decidedly non-static ways. The forests of the northeastern US have inherent adaptability and resilience to change. The changing composition and structure of the forest since the retreat of the glaciers provides evidence of this fact. However, to adapt to a greater rate of climatic change while maintaining healthy and resilient forests and a viable forest products industry, we must be prepared to utilize a forest management toolbox that includes dynamic strategies.

The forestry adaptation framework we present is based on the assumption of change that is likely to occur within a suite of stressors. We describe below how these four stressors might change and how these changes might affect the region's forests (see also Fig. 1).[3]

[1] For an example of some consolidated information, see Oregon Forest Resources Institute 2006

[2] Although initially we had sought to catalogue existing management practices that forest managers are taking specifically to adapt to climate change, we could not find documented examples of practices relevant to the northeastern US.

[3] It is worth noting that we are unable to predict how these stressors might synergistically interact with each other and the possibility the interactions could pose even greater challenges than described below.

Figure 1. Primary Climate Change Stressors Relevant to Forestry

Seasonal Temperature and Precipitation Changes	• Inoperable seasons become longer • Changes in peak flow impact transportation infrastructure • Precipitation changes create industry-wide operational constraints
Disturbance Regimes	• Climate change leads to increased frequency, intensity, and magnitude of disturbances • Forest communities are exposed to new disturbance agents • Operational infrastructure is placed at risk
Invasive Species	• Invasive native and exotic plant species colonize new regions • Invasive plants prevent regeneration and establishment of desirable native species
Species and Community Latitudinal Shifts	• New species become important to the region • Previously important species become less suited to the region • Novel plant communities develop

Seasonal Temperature and Precipitation Changes

Inherent in a changing climate are changes in the physical environment, specifically precipitation and temperature. While both these factors influence species distribution as discussed above, there is the potential that climate change could have potentially large effects on forest hydrology (NRC 2008). The magnitude of these effects will be further complicated by changes in disturbance regimes, many of which modify forest structure in ways that will further influence hydrology.

The largest impact on forestry is likely to be on the operational infrastructure. Through warmer temperatures, a shift from snow to rain and a reduction of seasonal snow pack is likely to occur. The result is that the "peak flow" of water within a given watershed would likely occur earlier in the spring and increase in total and peak volume (NRC 2008). Average annual precipitation has already increased in the Northeast during the last century with the same trend anticipated to continue (Easterling 2002). The volume of peak flow in a watershed will be compounded by forest and road coverage within the watershed (NRC 2008). An increase in peak flow will impact the sizing and number of culverts and water diversions required to safely maintain a transportation network that does not negatively affect water quality. Additionally, the total area able to be covered by roads and other non-forest types while maintaining water quality standards will likely need to be reduced or closely managed to avoid increased negative impacts. Climate-induced changes in peak flow will also be accentuated in watersheds with more severe topography and a high proportion of recent harvests (NRC 2008).

The frost-free season in the Northeast now begins significantly earlier than in recent history (Easterling 2002). An increase in the number of frost-free days, combined with extended periods of rain instead of snow, impacts the ability of forest landowners to access the forest resource. If the trend continues as predicted in many models, the inoperable season both in the spring and fall will likely be extended. The implication is that a forest products industry depending upon an annual volume of wood will need to procure this volume of winter wood during a shorter time window (Shaler et al. 2009).

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Indeed there may be some areas previously accessible under frozen conditions that could be considered inoperable ground in the near future. Forest managers and wood-consuming mills will need to plan procurement systems for these new operability constraints by developing large wood yards and other storage contingencies.

Disturbance Regimes

The most immediate impact of climate change is likely to be change in both the near term and longer time disturbance regimes (Aber et al. 2001, Dale et al. 2001). Indeed, changes in disturbance regimes have the potential to overshadow direct effects of climate change on species distribution and migration (Flannigan et al. 2000). Disturbances are characterized by their frequency, intensity, and magnitude (Oliver and Larson 1996). There are two primary mechanisms by which changes in disturbance regimes will influence commercial forestry. First, increased frequency, intensity, and magnitude of disturbances will define which species are able to become established, grow to maturity, and regenerate to existing and new sites. Second, disturbances by definition make growing space available. Response to this available growing space will determine the composition of the future stand and whether that stand will contain desirable species. Invasive species in particular will likely be poised to become established following disturbances (see *Invasive Species* below). Exposure to new disturbance agents will present challenges for forest managers and will drive changes in forest community composition. For example, fire severity is predicted to increase over much of North America, including the northeastern US (Flannigan et al. 2000, Nechodom et al. 2008). Alterations to current disturbance regimes in the Northeast are also likely. Examples include a predicted increase in duration and intensity of spruce budworm (*Choristoneura fumiferana*) outbreaks in eastern Canada (Gray 2008) and a northerly shift in ice storm events (Irland 2000).

Forest managers will need to understand these altered disturbance regimes and the impacts they have on perpetuating desirable commercial species.

There is a great deal of uncertainty around exactly how disturbance regimes will change, but the consensus based on climate models that incorporate temperature and moisture patterns is that there will likely be changes in the Northeast. This should be no surprise since the major disturbance agents, such as wind, hurricanes, ice storms, insects, and fire, are all clearly influenced by climate. The 1938 Hurricane, for example, has dramatically shaped the structure and species composition throughout much of southern New England (Foster and Aber 2004). There is also evidence that hurricanes have been drivers of community change for hundreds of years in New England (Boose et al. 2001; see Box 1). Though the frequency of high intensity hurricane events decreases with distance from the coast (Box 1), climate change is likely to bring an increase in frequency throughout the region and could produce devastating impacts on the forest resource (Union of Concerned Scientists 2006).

Forest managers will need to understand these altered disturbance regimes and the impacts they have on perpetuating desirable commercial species. These changes will also likely alter the way forest managers plan and design the operational infrastructure, such as transportation networks. As we discuss in more detail below, road networks in particular can influence how disturbances affect forest communities. Besides the ecological impacts, increases in the frequency and intensity of disturbance events and the resulting impacts on the landscape will have economic impacts on management and may influence the social license and public support for forestry practices in a watershed or region.

BOX 1. New England Disturbance Agent: Hurricanes

Hurricanes have been a driving force for change in New England's forests for centuries. The frequency and intensity of these disturbances varies with geographic location and proximity to the coast (Boose et al. 2001). Boose et al. (2001) also found that at least eight F3 rating (sustained winds between 48 and 62 m/s) hurricanes have made significant inland impacts in the last 400 years—on average, one every 50 years. The best example of the dramatic impacts of hurricanes in New England can be seen in the infamous 1938 hurricane. Today, the forests in its path still show evidence of how the strong winds have shaped both structure and species composition (Fig. A). It is likely that climate change will increase the likelihood of high intensity hurricane occurrences during a typical commercial forest rotation.

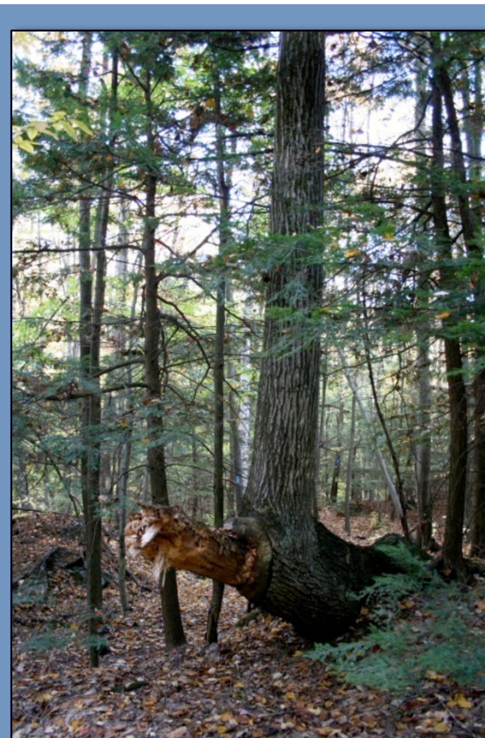


Figure A. Red oak blown partially over by the 1938 Hurricane, then sprouted vertically (photo by Daniel Zeh, Horatio Colony Preserve, NH 2006)

Invasive Species

Common characteristics of invasive plant species include high growth rates and long-distance dispersal mechanisms. Such characteristics will benefit many of these species in a rapidly changing climate and thus may preferentially enhance the success of invaders (Dukes and Mooney 1999). The presence of invasive species, both exotic and native, present challenges to regenerating desirable commercial species (Burke and Grime 1996). In general, forest communities are more vulnerable to invasion following a disturbance, particularly on rich sites (Burke and Grime 1996, Huebner and Tobin 2006, Huebner et al. 2009). As discussed above, climate change scenarios predict a greater frequency of disturbances, which would ultimately create opportunities for some invasive species to gain footholds within native forest communities. These climatic shifts may exacerbate opportunities for native species to build to epidemic levels within native forest communities—acting in similar fashion to invasive species and attacking larger landscapes. We are already seeing an increase of invasive and native species as new stressors to forest communities appearing in Maine and throughout New England. Invasive exotic plant species such as Japanese barberry (*Berberis thunbergii*), Asiatic bittersweet (*Celastrus orbiculata*), and species of honeysuckle (*Lonicera* spp.) are becoming established in woodlots throughout southern Maine. Invasive native species such as poison ivy (*Toxicodendron radicans*) are predicted to thrive in environments with elevated CO_2 levels (Mohan et al. 2006).

Harvest prescriptions that do not account for the presence or proximity of invasive species have the potential to further accelerate the movement of undesirable species deeper into the working forest's core. Road networks facilitate the movement of many invasive species and therefore become vectors for invasion (Parendes and Jones 2000, Trombulak and Frissell 2000). Forest managers who have not yet made the investment in understanding the workings of invasive species will need to become more skilled in the identification of these species and understand the silvical characteristics of these new competitors for growing space.

Invasive exotic pest species, such as the hemlock woolly adelgid (*Adelges tsugae*) and balsam woolly adelgid (*Adelges piceae*) also present climate-related challenges for forest managers. The spread of both species is limited by cold temperature extremes during the dormant season (Dale et al. 2001, Skinner et al. 2003). When extreme temperatures are less frequent, the risk to forests from these and other new disturbance agents increases.

Species Shifts

Other stressors are more speculative at this time, and addressing them requires significant forethought and strategies that anticipate change. We know that changes in climate will produce changes in weather, especially temperature, wind patterns, and precipitation. These are key factors in determining plant species distribution especially during germination and establishment phases of stand dynamics when species differentiation occurs. These weather shifts may also affect pollination and seed dispersal.

It is difficult to predict how fast and which species will shift their ranges in response to changes in climate. While there is uncertainty, several credible models do predict that significant change is in store for many of today's primary commercial species in the Northeast (Iverson et al. 2008). Iverson et al. (2008) found that many of the currently important species in the Northeast will see decreasing areas of habitat. These species include: balsam fir (*Abies balsamea*), paper birch (*Betula papyrifera*), red spruce (*Picea rubens*), bigtooth and quaking aspen (*Populus grandidentata* and *P. tremuloides*), black cherry (*Prunus serotina*), sugar maple (*Acer saccharum*), red maple (*Acer rubrum*), yellow birch (*Betula alleghaniensis*), eastern white pine (*Pinus strobus*), eastern hemlock (*Tsuga canadensis*), American beech (*Fagus grandifolia*), and white ash (*Fraxinus americana*). This list includes the top eight most harvested species in Maine for the period of 1996–2003 (McWilliams et al. 2005). Others have predicted an expansion of currently important commercial species, such as the white pine (Jacobson and Dieffenbacher-Krall 1995). In some climate models, species such as northern red oak (*Quercus rubra*), white oak (*Quercus alba*), and, red maple will significantly increase in area (Iverson et al. 2008). Though the Iverson et al. (2008) models predict otherwise, species that are at the southern or "rear" edge of their ranges in the Northeast may have characteristics that will allow them to persist in the face of climate change (e.g., genetic diversity, local adaptation, older population age), whereas those in the middle of the range may lack the regional genetic diversity to adapt to significant change (Hampe and Petit 2005).

All tree species will react to climate change as a component of the forest system where they exist and also as individual species with specific genetic traits.

All tree species will react to climate change as a component of the forest system where they exist and also as individual species with specific genetic traits. These more individualized species reactions will likely lead to the development of novel forest community types. Mature trees may survive for long periods on sites where their regeneration niche may not be supported by emerging climatic conditions. The current communities on the landscape are largely the climatic legacy of decades or centuries past (e.g., black gum [*Nyssa sylvatica*] swamps in southern Maine and New England and red oak on ridge tops in northern Maine). The climatic conditions at the time of establishment combined with available seed or clonal stock limit seedling establishment. When disturbances occur, species might be replaced by species better suited

Figure 2. Adaptation Toolbox

to current climatic conditions but will not necessarily be the most commercially desirable. If changing disturbance patterns alter the season of disturbance by several weeks or months, it is possible that fast-growing pioneer tree species producing seeds, fruit or nuts at specific times may not have the same competitive advantages in the face of these climatic shifts. Since the stand types of today may not exist in the future, forest managers must pay close attention to silvical characteristics of desirable commercial species and have a strong understanding of forest stand dynamics.

FORESTRY ADAPTATION FRAMEWORK—RESISTANCE, RESILIENCE, AND RESPONSE

We present an approach to climate change adaptation that incorporates three broad strategies of *Resistance, Resilience,* and *Response* after Noss (2001), Millar et al. (2007), Spittlehouse and Stewart (2003), and Spittlehouse (2005). Figure 2 summarizes these concepts and fundamental management actions. Later we will discuss a key fourth element to the framework, which is the integration of mitigation strategies that promote carbon sequestration through practice changes and long-lived wood product storage.

Resistance can be seen as a short-term strategy for primarily high-value resources and investments such as plantations or stands near financial maturity. Specific actions include maintaining adjacent mature stands for protection against wind events and taking early defensive actions against pest species such as the hemlock wooly adelgid (*Adelges tsugae*). In this case, defensive actions might require removing isolated infested hemlocks from a stand (USDA 2005). Resistance strategies address immediate threats and focus on minimizing the impacts of disturbance regimes that are exacerbated by climate change.

Resilience can be seen both as a short-term and a long-term strategy. Resilience refers to the capacity of a stand or community to recover from a disturbance and return to a reference state (Noss 2001). Since forest communities are most vulnerable to invasion and significant species shift following a disturbance, a strategy that promotes resilience at the stand establishment phase will be important to deliberately maintain desired commercial species (e.g., encouraging or allowing for the retention of diverse native species), particularly if climate change results in more frequent stand-replacing disturbance types in New England. Resilience strategies must pay particular attention to invasive plant species and maintaining vigorous and diverse communities at the landscape scale.

Enabling forest managers in the northeastern US to respond to climate change requires an acceptance of a great deal of uncertainty around how quickly change will occur. The primary concept of *Response* is to facilitate the movement of species over time. Many of the strategies proposed to maintain diversity and landscape connectivity will be appropriate in this case as well. The long-term approach to facilitate response may also include the planting of adapted species and shortening rotation lengths to allow for more frequent modification of genotypes. Response will also require that growth and yield models are adjusted to reflect changing conditions and the tree species characteristics that become more prevalent. This strategy is clearly the most costly and requires acceptance of a level of uncertainty that many landowners and managers will likely not choose (Figure 3). For each of the strategies to be considered, there is an accompanying debate about which landowners and managers should be held accountable for implementation and how. Alternatively, there is a policy debate about how private landowner assistance and cost-share programs should be used to subsidize or incentivize the use of specific strategies depending on the perceived public benefit. For strategies to be widely adopted, especially on private non-industrial lands, there is a need for public policy action.

FOREST MANAGEMENT STRATEGIES AND ACTIONS

There is little indication that forest managers within the temperate and boreal forest regions of the world are significantly adjusting management activities explicitly in the name of climate change adaptation. However, managers are adjusting practices to many of the conditions that are a result of a changing climate. Recommended strategies to address climate change directly are emerging as well. Table 1 lists these specific strategies and the broader "management realm" that defines the scale and part of the management process where decisions typically occur. Below we outline specific forest management activities for each of the management realms. We also identify where each of these strategies fits in terms of the Forestry Adaptation Framework described above and in Figure 2.

Forest Stand Scale

Maintaining species and structural diversity at the stand scale serves to maintain genotypic and phenotypic options in a changing climate. The intent is to promote both the *resistance* and *resilience* of stands to climate change impacts. This strategy is consistent with an "ecological forestry" approach that: (1) retains biological legacies at the time of harvest, (2) uses intermediate treatments that enhance stand health and diversity, and (3) allows for appropriate recovery periods between regeneration harvests (Franklin et al. 2007). The biological legacies such as inclusions of softwood patches within hardwood stands (or vice versa) and the maintenance of coarse woody structure serve both to provide a diverse seed source for desirable species and maintain hospitable regeneration sites for those species.

Of paramount importance is the implementation of intermediate treatments with objectives that include

Table 1. Management Realm, Action and Adaptation Framework

Management Realm	Management Action	Adaptation Framework		
		Resistance	Resilience	Response
Forest Stand Scale	Maintain species and structural diversity	✓	✓	
	Maintain stand vigor	✓	✓	
Ownership/ Landscape Scale	Maintain tree species and community diversity	✓	✓	✓
	Maintain forest connectivity		✓	✓
	Monitor, control, and prevent invasive and pest species encroachment	✓	✓	
	Maintain watershed below Equivalent Clearcut Area (ECA) threshold	✓	✓	
Silvicultural Systems	Modify regeneration harvest prescriptions to favor adapted commercial species	✓	✓	✓
	Reduce rotation length		✓	✓
	Plant adapted commercial species			✓
Harvest Operations	Minimize road networks	✓		✓
	Adjust culvert size requirements for changes in Peak Flow	✓		✓
	Plan for seasonal operational limitations	✓		
Forest Planning	Modify growth and yield models			✓

maintaining *stand vigor and health*. Such treatments are critical for maintaining a stand's *resistance* to invasive and pest species and other stresses that are likely to become greater threats. This strategy is consistent not only with an ecological forestry approach, but also for landowners with economic objectives. Further, allowing for significant recovery and establishment of regeneration between harvest entries minimizes the physiological stress to trees and the potential for physical damage to the residual stand.

Several published resources appropriate to the Northern Forest describe explicit management actions that support these adaptation strategies at the stand level (e.g., Elliot 1999, Lindenmayer and Franklin 2002, Lindenmayer and Fischer 2006, Franklin et al. 2007). This ecological forestry approach is consistent with the standards established by the Forest Stewardship Council (FSC) and the Sustainable Forestry Initiative (SFI).

Of paramount importance is the implementation of intermediate treatments with objectives that include maintaining stand vigor and health.

Ownership/Landscape Scale

Stand-scale practices of maintaining species and structural diversity should be extended to the landscape or ownership scale to facilitate *resistance, resilience,* and *response* of the forest resource to climate change. At the landscape scale, the landowner should also maintain the *diversity of communities* appropriate to the ecoregion. Maintaining this diversity is, again, essential to preserving the genetic bank and tree species options necessary to adapt to an uncertain future climate. Significant resources exist to guide managers in this landscape ecological approach to forest management (e.g., Elliot 1999, Lindenmayer and Franklin 2002, Lindenmayer and Fischer 2006, Franklin et al. 2007).

Maintenance of forest connectivity will be essential for facilitating the *resilience* and *response* of native trees to a changing climate. Connectivity, as used here, refers to the maintenance of a forest cover sufficient to allow potential dispersal by tree species on pace with a changing climate. While generally we know that increasing isolation of habitats hinders dispersal of many forest plant and animal species, we cannot say with any certainty how much forest cover in a given landscape is required (Lindenmayer and Fischer 2006). Indeed, connectivity per se is a species-specific concept. From a forest management perspective, it is easiest to think about this in terms of overall landscape connectivity, which is based on human perception of forest cover. Significant research has gone into understanding the connectivity needs of birds and mammals, but not of trees. Limited model-based research found that dispersal was significantly limited when suitable habitat (i.e., forest cover) dipped below a 25% threshold in the landscape (Collingham and Huntley 2000). Forest managers that practice the type of ecological forestry described above would likely be maintaining a forest landscape well above any dispersal barrier threshold. However, if intensive management increases significantly, barriers to natural dispersal may be created (e.g., fragmentation through conversion of forests to agricultural uses or residential development). Large-scale biogeographical dispersal is outside the scope of most forest managers, but will certainly be facilitated by the ecological practices we describe above.

Invasive species prevention, control, and monitoring are largely a landscape issue. In many parts of the US, native forest pests are behaving in similar fashion to invasive species—another indicator that climatic shifts may exacerbate existing disturbances and stressors. Specific actions will take place at the stand level, but *resistance* and *resilience* will require a landscape focus. The US Forest Service has developed a useful approach to addressing the threat of invasive species to native plants. This approach is summarized below.[4]

1. Prevention

a. Based on risk assessments, develop and implement prevention programs for identified priority invasive species and areas

2. Early detection and rapid response

a. Develop maps of priority ecosystems and habitats placed at risk by invasive species

b. Working with partners, develop rapid response incident teams that cross jurisdictional lines and respond quickly to any invasive species outbreak

3. Control and management

a. Complete comprehensive (all invasive species) inventory and mapping for ownership, including neighboring land where appropriate

b. Conduct a comprehensive (all invasive species) risk assessment based on existing information for the specific purpose of identifying priority species and areas for program focus

c. Focus resources on priority species control in priority areas as identified through risk assessments

4. Monitoring

a. Monitor effectiveness of control and management actions

b. Update invasive species inventory and mapping periodically

c. Monitor long-term invasive species population trends and the effectiveness of treatments (in cooperation with state natural heritage program)

[4] Modified from http://www.fs.fed.us/invasivespecies/documents/Final_National_Strategy_100804.pdf

The invasive species strategy described above has relevance in the absence of a climate change threat. The strategy will also require significant training for appropriate field foresters and logging contractors to identify and report invasive species that pose a potential threat. Public policy with respect to the use of chemical control methods would likely need to be modified to allow more timely treatments at both the stand and landscape levels. Research into effectiveness is also needed to support the responsible application of chemicals while minimizing the potential for other negative environmental effects.

Adaptation to changes in forest hydrology as a result of climate change will need to be addressed at the landscape scale. Since the proportion of harvested area significantly influences peak flow in a forested landscape, it will likely become more important for northeastern forest managers to pay attention to watershed vegetation patterns. This is common practice in the western US and western Canada and solid science has developed around this issue. Increases in peak flow have been detected in northern Lake States watersheds (where the topography is similar to the Northeast) following as little as 25% removal of forest cover in a small watershed. These thresholds are likely to change as peak flow timing and volume is modified. A precautionary *resistance* and *resilience* strategy would be to *maintain minimum watershed vegetation cover standards* above a threshold. This threshold is referred to as "equivalent clearcut area" (ECA) and is used widely in forest management outside the Northeast US. ECA is defined as:

> "an index of potential watershed level hydrologic impacts (e.g., increased peak runoff) due to forest cover removal, normally expressed as a percentage of the naturally forested area of a watershed; areas where forest cover has been completely removed by harvesting, fire or other disturbances are assessed as full percentages (e.g. clearcuts, intensive burns), areas with partial stand removal are pro-rated according to the percentage of the crown cover removed (i.e. equivalent to clearcut) (FSC 2005)."

In mountainous regions, the ECA threshold is often set at 25%. Verry et al. (1999, p. 326) suggest that this threshold is at 20% for the continental eastern United States. Northeastern watersheds will need to be further evaluated in the context of changes in peak flow, regional soils, and topography. While the individual landowner will need to address ECA concepts, the development of standards will need to be science-based and occur in a larger context involving federal and state agencies.

Silvicultural Systems

Significant adjustments in the current silvicultural systems employed in the Northeast may need to be made under rapid climate change scenarios. *Natural regeneration harvest prescriptions* can be modified to favor adapted commercial species (e.g., oak species and white pine) to promote *resistance*, *resilience*, and ultimately *response*. This strategy is facilitated by the ecological forestry approach described above where species and community diversity are intentionally maintained to create the options needed for natural regeneration silvicultural systems. Natural regeneration methods will be appropriate in assisting the migration of desirable species only if the climatic conditions change within the range of tolerance of existing species. Therefore, it will be necessary to accurately assess the tolerance of different forest types and seral stages to both the current and future conditions of the Northeast US. Designing silvicultural prescriptions in even and uneven-aged systems to reduce vulnerability to future disturbances by managing tree density, species composition, and forest structure is also important. Density, composition and structure can be managed such that they will be resilient under a variety of potential future climates. For example, maintaining lower densities of some species and communities could create conditions that are more likely to survive future drought stress, fire, and insect and disease problems.

Increases in peak flow have been detected in northern Lake States watersheds (where the topography is similar to the northeast) following as little as 25% removal of forest cover in a small watershed.

One potential risk management strategy in even-aged systems to promote *resilience* and *response* during a period of rapid climate change would be to *reduce rotation lengths*. The intent of a rotation length reduction would be to decrease the period of vulnerability to catastrophic disturbances and to allow for quicker adjustments in species or genotypes. This strategy would be more feasible where artificial regeneration is used, but would also be appropriate in natural stands that have maintained diverse and resilient stand structures (as described in natural regeneration harvests). The degree of rotation reduction will depend upon a combination of economic maturity and disturbance risk factors for each forest type.

A comprehensive long-term climate change *response* strategy will require significant modification of business-as-usual practices in the Northeast. Most northeastern states do not currently have a nursery and seed stock infrastructure of sufficient size to begin a process where adapted genotypes are moved into the landscape. Significant costs would be incurred to develop the infrastructure needed to assist migration through the *planting of adapted species*. As an example, the recent trend of silviculture investment in Maine is clearly shown in the Maine Forest Service's Silvicultural Activities Reports. These annual reports show only a minor investment in planting as a method of regeneration; only 0.9% of acreage relative to the total harvested land is currently being replanted (MFS 2008). Given a lack of industrial ownerships, other northeastern states likely have lower planting rates than Maine. This is compared to the neighboring province of New Brunswick, which plants 33% of harvested land every year (New Brunswick Forest Products Association 2009). Industrial landowners in the

Northern Forest will have a difficult time keeping pace with their Canadian competitors who will have a greater capacity to adapt quickly. Northeastern states can learn from experiences in the neighboring provinces, but significant investment in seed provenance trials will still be needed to determine where and which species are best adapted for planting. A coordinated effort beyond the scope of a single ownership will need to be undertaken to provide the knowledge base for adaptation by forest landowners. Assisting the migration of commercial tree species will require seed provenances that have been developed under the following framework (adapted from Johnston et al. 2006; Spittlehouse and Stewart 2003):

- define climate-based seed zones to ensure seedling survival to future climate changes;
- develop breeding programs for pest resistance and wider tolerance of climate change stresses; and
- maintain biodiversity by planting mixed provenances and species that have been tested for resilience to future climate change for a particular forest site.

Seed transfer guidelines will need to be developed for the Northeast that describe the maximum movement from the point of collection in distance east, west, north and south as well as in elevation. These seed transfer zones would by necessity be dynamic and will need to be adjusted according to the rate of climate change. Planting adapted species is a strategy that will require the greatest financial investment by landowners, industry, and governments. This strategy also requires an acceptance of the greatest amount of uncertainty, yet investment would need to begin soon if forest landowners wish to influence the direction of commercial forestry in the Northeast under a rapidly changing climate. Besides being responsive to the potential impacts of climate change, a commitment to tree improvement and development of adapted species could provide other benefits, such as improved productivity or increased disease resistance. Traditional tree breeding programs can be time consuming due to the delay in reproductive maturity of many tree species. It will be necessary for forest managers and researchers to consider the prudent use of tree improvement techniques, such as genetic modification, in order to provide a sufficiently rapid response to climate change stressors.

Harvest Operations

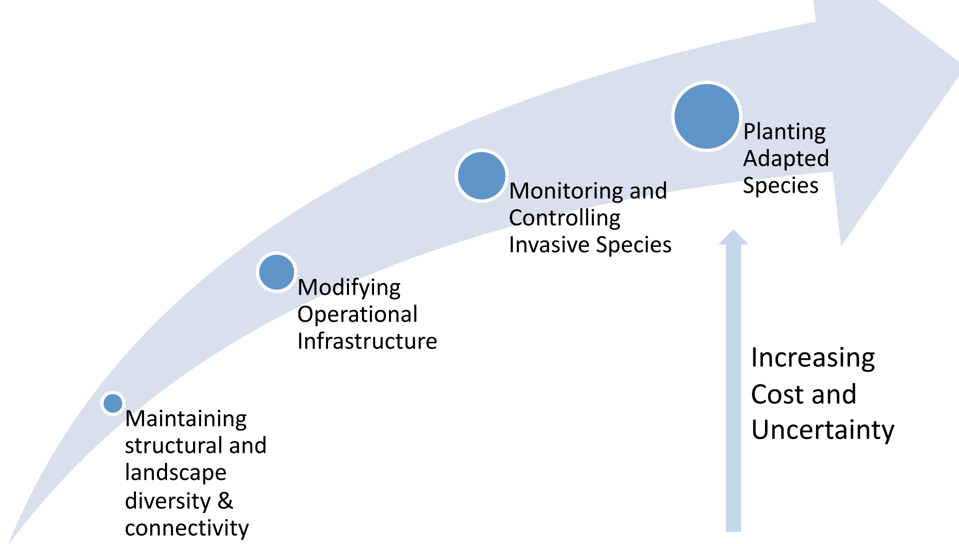
The largest impact on forestry is likely to be on the operational infrastructure of large landowners. Changes in precipitation and temperature patterns will likely modify conditions in ways that require change from current business-as-usual practice. Road networks in particular become important focal points for adapting to climate change. Roads destabilize landforms, increase sediment production, permanently alter hydrological regimes, and accentuate flood flows (Lindenmayer and Franklin 2002). However, permanent road networks will likely be necessary to implement increased intensity of management associated with adaptation activities. Roads may also generate new patterns of disturbance in landscapes by acting as vectors for invasive plants, pests, and fire and increasing the potential for windthrow (Miller et al. 1996). *Minimizing road networks*, including decommissioning of unnecessary roads, will be an important *resistance* strategy. Reconsideration of *culvert sizing requirements* based on changes in peak flow regimes will be needed to maintain investments in the transportation infrastructure. Cross-slope road construction techniques will also need to be modified if surface flow increases significantly. Maintaining the road network also becomes a *response* strategy, as intensive management will require reliable and functioning road networks.

Seasonal operational limitations for both forests and mills are already becoming apparent in the Northeast. Warmer winters with fewer days of frozen ground require planning for an operability calendar much reduced from the current situation (Spittlehouse and Stewart 2003). To facilitate further *resistance* to climate change impacts, significant investment in low-impact harvesting technologies will need to be made in the Northeast to extend operable seasons where possible (Spittlehouse and Stewart 2003). The adoption of harvesting equipment more adapted to sensitive sites is already taking place in parts of New Hampshire and Maine and is being facilitated through the use of creative financing mechanisms (Coastal Enterprises, Inc., pers. comm.). Increased logging capacity during operable periods will likely have to be supplemented by off-season employment opportunities in other forest management activities such as in tree nurseries or invasive species management. Wood-consuming mills will need to consider storage requirements necessary to sustain production through inoperable periods.

Forest Planning

Climate change will bring changes in the physical environment that will influence the growth and yield of commercial species in natural and artificial stands. As a long-term *response* strategy, managers will need to adopt new approaches to models used to determine annual allowable harvest levels. Changing growth and mortality rates (i.e., through increased disturbance by fire, insects, and disease [Spittlehouse and Stewart 2003]) for all species will need to be incorporated into models based on real data. US Forest Service Forest Inventory and Analysis (FIA) data and private landowner continuous forest inventories will be needed to develop empirical growth models. FIA data and tree growth projections will need to be sensitive to changes in climate and the differences in forest management activities by types of ownership. Succession rules within growth models also will need to be modified to address the different community interactions likely to occur as species vary in their adaptability to the new physical environment. Changes to forest planning models will require significant investment and coordination among federal and state agencies and forest landowners.

Figure 3. Relative Costs of Adaptation Practices



RELATIVE COSTS

There is a strong relationship between the relative cost of adaptation practices and the degree of uncertainty around climate change impacts. Figure 3 shows this trend among the primary adaptation strategies. Cost implications and uncertainty present challenges for forest managers interested in making the business changes necessary to adapt to a changing climate.

Making adjustments in practices that maintain species and community diversity within stands and on the landscape does not present a financial challenge to landowners. These practices are becoming more commonly employed as additional lands enroll in forest certification programs and the benefits of such practices are recognized. Maintaining diverse stands is seen as a short-term strategy but one that could be engaged in now without requiring comprehensive evaluation of climate change vulnerability.

More expensive practices are associated with modifying the operational infrastructure. Replacing culverts and decommissioning and rehabilitating roads are obviously quite costly endeavors. However, the intent of these activities is to maintain the integrity of a transportation infrastructure that will be subject to greater stress. The decision to implement these activities will be based upon predictions that are fraught with uncertainty. Investment in vulnerability assessments would be prudent prior to implementing these costly measures across an entire land base.

The costs associated with monitoring and controlling invasive species (and native species acting as an epidemic pest) are largely unknown at this time. Few, if any, large landowners in the Northeast are engaged in such activities. Investment would be required in training personnel, hiring labor for monitoring and control, and the purchase of new equipment and chemicals for eradication and control. It is expected that the upfront costs associated with monitoring and prevention could achieve payback by avoiding the need for more expensive eradication and control practices. Silvicultural practices that include maintaining a higher degree of canopy cover adjacent to roads could minimize the risk of invasive plants species moving into interior forests (Parendes and Jones 2000). However, if mechanical and chemical control practices are consistently required, it is conceivable that costs could exceed those required to modify an operational infrastructure.

> Arguably, the most expensive adaptation practices will be the planting of adapted species.

Arguably, the most expensive adaptation practice will be the planting of adapted species. Planting and pre-commercial silviculture activities are not currently widely employed throughout the Northeast. As discussed above, the investment needed to establish a viable tree nursery infrastructure would be quite high. Further complicating this issue is scientific uncertainty around the need for assisted migration of commercial tree species. The development of this adaptive practice will largely depend upon federal and state agencies' support from both a technical and financial perspective. The individual landowner will need to advocate strongly for this support.

MITIGATION

It is widely recognized that forests in the Northeast can play a significant role in mitigating the atmospheric accumulation of greenhouse gases through carbon sequestration (Stoddard and Murrow 2006). Managing forests for carbon has generated a great deal of debate and speculation around the relative value of long-term storage of carbon in wood products versus leaving forests unmanaged. This is further complicated by emerging carbon credit markets with widely variable requirements for generating forest carbon sequestration credits. There is currently insufficient data available on the life-cycle of wood products to justify universally advocating intensive management over a "let it grow" strategy. Comprehensive life-cycle models would allow policy makers to evaluate the effectiveness of alternative carbon management policies to meet public goals, stakeholder needs, and the variable regulations/requirements for generating credits. We present here some brief recommendations based on a precautionary approach that is generally consistent with the adaptation strategies we describe above.

Practices that increase the amount of biomass retained on a given acre can be seen as having a carbon benefit. This is particularly true when the removal of the retained biomass (e.g., for pulp wood) would have generated carbon emissions in a relatively short time. Increased stand-level retention practices consistent with an ecological forestry approach are considered an appropriate mitigation strategy as well. Also appropriate are reduced impact logging practices that minimize soil disturbance and residual damage to stands thereby reducing mortality and maintaining stand vigor. Under such approaches, late-successional forest structures are seen as beneficial to forest health and resiliency, as well as achieving the biomass levels needed to yield carbon benefits (NCSSF 2008). The relative value of extending rotations is being debated, but there is evidence accumulating that older forests continue to sequester carbon well beyond stand ages we are likely to see in the Northern Forest any time soon (Luyssaert et al. 2008). Extending rotation lengths, though potentially inconsistent with an adaptation approach, serves to enhance structural complexity, thereby accumulating more biomass. This strategy could also serve to sequester more carbon off-site in long-lived wood products through the production of larger diameter trees suitable for use in these products. Carbon market protocols will ultimately determine what an acceptable carbon sequestration practice is. Forest managers ultimately will need to balance the needs of climate change adaptation practices with the demands of all forest product markets, including carbon.

FOREST MANAGEMENT CLIMATE ADAPTATION NEEDS

There are many elements of a climate change adaptation strategy that will need development beyond the scope of an individual landowner. The first critical step is to conduct vulnerability assessments of commercial tree species and forest communities (Spittlehouse 2005). These assessments should be based on realistic climate change models and site-specific conditions. Forest resource managers will need this information to determine if, when, and how to apply the climate change adaptation practices described above.

The second critical step is to develop and deploy a coordinated regional monitoring program to track climate change impacts on tree species productivity, peak flow regimes, and movements of invasive species and pests. This real-time monitoring can inform forest managers on the directions of change and appropriate response at local scales. It would also allow forest managers to mimic natural adaptive responses rather than rely on models (Millar et al. 2007). A monitoring program would also include the modification of FIA and continuous forest inventory programs to incorporate these indicators.

The third critical step is to develop and promote the use of decision support systems (DSS) designed for land managers to assess if, when, and how much to strategically invest in various adaptation practices to reduce risk exposure to climate change. This could include making modifications to existing growth and yield models and using watershed analysis tools to guide harvests and reduce vulnerability of logging road networks and water bodies to extreme rainfall events. The DSS should also include native and exotic pest vulnerability assessment tools that can easily be incorporated into Geographic Information Systems typically used by land managers.

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