Creating and Maintaining Resilient Forests in Vermont:

Adapting Forests to Climate Change

Vermont Department of Forests,
Parks and Recreation

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Forests in Vermont:
Adapting Forests to Climate Change

Commissioner Michael Snyder's
Adaptive Silviculture Work Group Report

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Executive Summary

Climate change presents a major challenge to the ecological and economic viability of forests. While there is uncertainty about the timing and magnitude of forest impacts, it is certain that forest changes are and will be occurring. Understanding climate trends, impacts to forest ecosystems, and the capacity of forest species to adapt to change will be the responsibility of forest practitioners as new outcomes to previous practices unfold.

As caretakers of Vermont's natural resources, the authors accepted the challenge of coupling literature and professional experience to develop this first Vermont guide to forest adaptation. In the midst of a storm of new information we created a pathway to travel in preparing our forests to be as ecologically and economically resilient as possible, hopefully staving off additional costs of taking no action.

While the main focus of this document is to provide land managers with a menu of forest adaptation strategies, many policy-level strategies have been included in recognition of the connections between statewide policy and forest management. Existing forest management challenges such as invasive plants, non-native insect invaders, and protection of connected forest tracts need local and regional solutions. Climate change considerations need to be incorporated into these broader management topics to achieve successful outcomes.

The complexity of our Vermont forests makes it difficult to generalize when offering guidance on silviculture. This is very important to keep in mind when reviewing the adaptation strategies in this document. Not every strategy is applicable for every acre of forest land. Consider those strategies relevant to your situation.

SUMMARY OF GENERAL ADAPTATION GOALS

- ✓ Maintain a continuous forest resource.
- ✓ Focus on regeneration requirements.
- ✓ Manage for high forest carbon storage.
- ✓ Identify areas suitable as climate change refugia.
- ✓ Understand tree silvics and climate adaptability.
- ✓ Prevent extinction of rare, threatened, and endangered (RTE) species.
- ✓ Support low-impact harvest operations.
- ✓ Manage to limit impacts of increased waterflow.
- ✓ Monitor during and after management operations.
- ✓ Monitor silvicultural outcomes and plan for adaptive management.
- ✓ Carefully manage invasive plants.
- ✓ Implement integrated pest management.

I. Introduction

The intent of this document is to supplement current forest management planning and practices with forest-adaptation strategies appropriate to current climate change trends and modeled projections. The content is mostly intended as guidance for forest practitioners, but includes some policy-relevant recommendations.

PURPOSE

- ✓ Supplement current forest management planning and practices with forest-adaptation strategies.
- ✓ Outline concepts of resistance, resilience, and assisted transitions within stands and across landscapes.
- ✓ Summarize projections of future climatic conditions and effects on trees and forested natural communities.
- ✓ Provide a framework for addressing climate change impacts on forests and forestry in Vermont at large and small scales.
- ✓ Provide guidelines for mitigating effects of climate change and other stresses through forest management.

Many will wonder which strategies are climate-change specific, and which are simply good forest management practices. Strategies that build forest resilience can be considered part of any forest management system (see boxes throughout text). These practices become more important as climate change impacts alter the forest environment. More climate-specific strategies, such as resisting change (e.g., refugia) or developing transitional forest systems (e.g., assisted migration) are based on interpretation of scientific literature as viewed by these authors.

Climate change science is evolving and growing in depth. This document relied on published information relevant to the region, filtered by the authors' knowledge of Vermont forests and how they function today. The species-specific vulnerabilities, adaptive capacities, and silvicultural strategies were especially tailored to Vermont and based on years of the authors' forest expertise.

Prior to our work, several important climate change adaptation works were published in Vermont. The Nature Conservancy published *Climate Change in the Champlain Basin: What Natural Resource Managers Can Expect and Do* (Stager and Thill 2010). Betts compiled research results on climate trends and indicators in Vermont in several publications (Betts 2011). The Nature Conservancy released *Resilient Sites for Terrestrial Conservation in the Northeast and Mid-Atlantic Region* (Anderson, Clark and Olivero Sheldon 2012). Concurrent with work on this document, the Vermont Agency of Natural Resources (ANR), including these authors, held several workshops on vulnerability and adaptation of natural resources and solicited input from local experts. The outcome was a document produced by Tetra Tech, Inc. for ANR "VT Agency of Natural Resources Adaptation Framework" (Tetra Tech, Inc 2013). Links to these are available on the Vermont Department of Forests, Parks and Recreation website (see http://fpr.vermont.gov/forest/ecosystem/climate_change).

Finally, the authors feel strongly that addressing climate change effects on forests is only part of the larger issue of global change. So while these adaptation strategies can be effective in addressing climate-related changes, mitigating the root causes requires substantial and prompt attention.

II. Forest Resilience and Adaptation

Changes to Vermont's climate are creating different growing conditions for forests. How we manage forests for the variety of landowner and societal values will likewise need to change to remain viable in shaping future forests. Some examples of post-glacial climate-driven vegetation change have been documented (Jacobson 2009) (Webb, Shuman and Williams 2004), but given the uncertainties of how and when climate changes will be evident, and the greater uncertainties about forest responses to climate changes, an important strategy is to tend forests in ways that render them adaptable and resilient. Most adaptation recommendations should promote a favorable forest health outcome regardless of climate impacts; a no-regret approach. While building resilience is a major focus for forest adaptation, actions to resist change (e.g., establish refugia) and transition systems (e.g., assist migration) are also part of the climate-smart forester's toolbox.

BUILDING RESILIENT FORESTS MAY INCLUDE STRATEGIES TO MITIGATE WIND DAMAGE IMPACTS.

Uncertainty about forest responses over the next few decades have led some to refer to our future forest as the "novel forest". Silvicultural responses to anticipated changes will further contribute to uncertain forest results.

Adapting forests to climate change is much like other forest stewardship actions, but there is no roadmap. Forest adaptation may include actions that improve forest resiliency and therefore reduce the severity of negative consequences from climate change. Adaptive management is about learning by doing. But in some cases forests may be resilient in their current state, and for the time-being the choice of no human intervention (i.e., self-adaptation) may be the best strategy.

Asking questions that include climate predictions can be constructive in identifying adaptation actions: Can forests be manipulated to create stands more resistant to wind damage? Can tree species selections change to better tolerate high summer temperatures? Are there measures that would better protect against soil moisture loss following harvesting? Climate predictions and forest response science will help us ask the right questions; forest adaptation will help us influence outcomes towards resilient, adaptable forests.

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Resilience is the capacity of a forest to withstand (absorb) external pressures and return, over time, to its pre-disturbance state (Thompson, et al. 2009). When viewed over an appropriate time span, a resilient forest ecosystem is able to maintain its “identity” in terms of composition, structure, and ecological functions. Given that our forests are dynamic to begin with, part of successful adaptive silviculture includes active monitoring of forest conditions and forest changes to better understand forest response, and to incorporate monitoring results to improve future forest manipulations. Ideally, forest monitoring should take place in all forest types and should include working forests and forests in ecological reserves that serve as benchmarks.

A final general consideration is that of scale. There are strategies useful at the stand and parcel scales, and different strategies that should be addressed at a statewide, watershed, or other landscape scale. Building resilience at large and small spatial scales are both important to forest adaptability to climate change. Creating resilient stands and reducing stress factors are important to adaptive silviculture for stand and parcel scales, while creating resilient landscapes includes creating and maintaining representation and replication of forest types, successional stages, and age classes; identifying sites to serve as refugia for vulnerable species; and planning for connectivity of large forest blocks.

III. Forest Landscape of Today

A discussion of Vermont’s forested landscape should begin with an understanding of changes that have taken place since early settlers arrived (Albers 2002). Pre-settlement forests had larger trees and a more complex forest structure than our forests of today. Forest soils were deeper, with more incorporated organic matter, and higher nutrient levels. The forest floor had more abundant woody material than today’s forests. Beech and red spruce were much more abundant in the pre-settlement forest canopy (Cogbill, Burk and Motzkin 2002).

Dramatic changes took place once land was cleared for agriculture. Most trees were harvested or girdled. Erosion was widespread as hillsides were cleared of vegetation and tilled or left fallow. Exposed soils experienced erosion and increased rates of organic matter decomposition. After clearing was complete, the land was used for subsistence agriculture for some period of time. In some areas farming lasted only 50-80 years before the land was abandoned and allowed to revert to forest. In other areas, the land was farmed for nearly two centuries prior to abandonment. During this extended period, various crops were produced and removed from these sites, but little in the way of nutrients or organic material was returned to the soil. As soils were eroded, compacted, and depleted, productivity declined.

Just as Vermonters today tend to favor sugar maple, so did early Vermont settlers. Sugar maple provided sugar, sap, and firewood. Wherever possible, sugar maples lined borders between pastures or crop fields, were large shade trees in pastures or near houses, and because most Vermonters were reluctant to cut healthy sugar maples, constituted a significant portion of farm woodlots. It therefore stands to reason that when Vermont farms were abandoned, the trees left to repopulate the new forest had a higher proportion of sugar maple than the original forests. The combination of degraded soils and higher proportions of a tree species that requires fertile soils may have resulted in less healthy sugar maple populations than would otherwise have been the case. In addition, since the remaining trees consisted of only a small subset of the original population of forest trees, it is likely that genetic diversity was reduced, resulting in less ability of individual trees or the forest as a whole to adapt to change.

FEW OLD GROWTH FORESTS EXIST IN VERMONT, BUT WE HAVE AN OPPORTUNITY TO MANAGE FORESTS TO CREATE MANY STRUCTURAL AND FUNCTIONAL SIMILARITIES.

In more recent times, as a result of global travel and commerce, new species have been introduced to our native ecosystems. New diseases or insects have largely removed certain species, such as American chestnut, elm, and butternut from our forests. Ash species are threatened by the emerald ash borer (EAB). Hemlock is threatened by the hemlock woolly adelgid (HWA). Maple and many others are threatened by the Asian long-horned beetle. Concurrently, new species of plants have been introduced that outcompete native plants for growing space and alter conditions for the reproduction of native tree species. To this setting of extended soil recovery, altered forest tree gene pools, losses of native species, and gains of aggressive new plant competitors, we have added new stress and disturbance from climate change. It is in this environment that we practice forestry today.

AMERICAN CHESTNUT IS ONE EXAMPLE OF A NATIVE SPECIES REMOVED FROM OUR LANDSCAPES DUE TO NON-NATIVE PESTS.

We can never return to the pre-settlement forest of Vermont. It no longer exists. The deep, rich soils that were present under old growth forests have been diminished and are less productive today. We only have the present and the future to work with, and our charge as landowners, foresters, and land managers must be to leave the forests of Vermont more resilient than we find them. There is much we do not know, but there is reason to believe that pre-settlement forests were stable, healthy, functioning ecosystems. While we cannot replicate all conditions of the pre-settlement forest, we can use what we know about the structure of those forests, and the soils that produced and sustained them, to inform our management decisions today. Through thoughtful management, we can move our forests toward more natural conditions that will hopefully result in gradual improvements in site productivity at the stand level and enhanced resilience to climate change at the landscape level.

IV. Climate Change and Forest Response

A. Observed Climate Trends

Historic and current climate trends form the foundation for information on climate predictions. These include trends for Vermont and New England pertaining to air temperature, precipitation, extreme events, snow, flow/runoff, evaporation, soil moisture, ice dynamics, onset of spring, and length of growing season.

Climate trends show changes have already been set into motion. Forty- and 50-year temperature and precipitation trends have been analyzed for this region and are documented in several recent publications (Betts 2011) (Global Change Research Information Office 2008) (Tetra Tech, Inc 2013) and are summarized (see boxes later in the text).

There have also been notable weather disturbances, but these are more difficult to point to as part of climate trends. They could be viewed as events that would have happened without changes in climate. However, another perspective is that all weather events are affected by climate change because the environment in which they occur is warmer and moister than it used to be (Trenberth 2012).

Historic and Current Climate Trends for Vermont

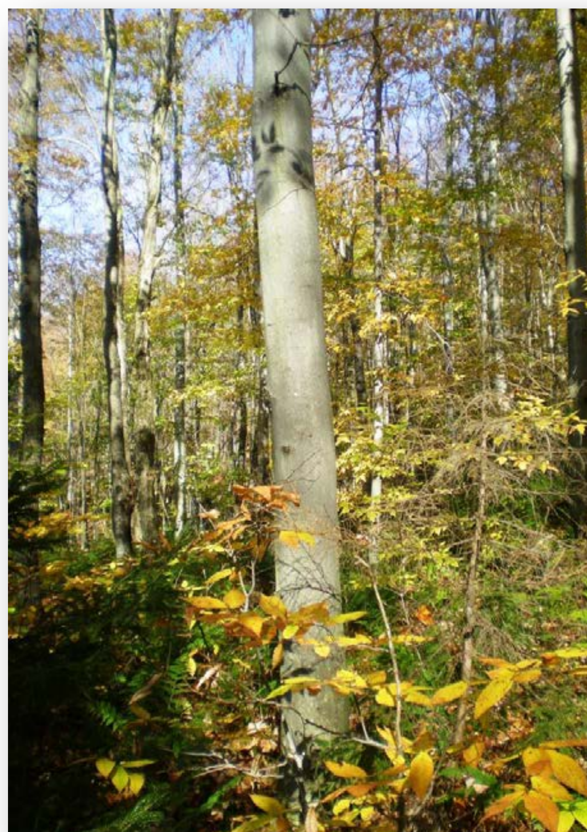
50-year trend (1960-2010)
- Summer temperature rose 0.4° F per decade
- Winter temperature rose 0.9° F per decade
- Annual average temperature has increased by 2° F since 1960

Growing season changes
- Last freeze day in spring is earlier by 2.3 days per decade
- First freeze day in fall is later by 1.5 days per decade
- Freeze period is shorter by 3.9 days per decade
- Growing season is longer by 3.7 days per decade
- Growing season has increased by 2 weeks over the past 40 years

50-year trend in Vermont precipitation
- There was a 15-20% increase in precipitation, with 67% from "heavy precipitation" events

B. Future Climate Projections

Temperature and precipitation data projections derived from various global and regional models were part of the recent work by Tetra Tech, Inc. on behalf of the ANR, and are reported here (Tetra Tech, Inc 2013). Future climate projection models use current trends, greenhouse gas emission scenarios, and global predictions downscaled to the regional or state level. There are many respected climate models that provide a range of climate predictions. The A1 scenarios assume very high economic growth, a peak in global population at mid-century, and energy needs being met by a balance of fossil fuels and alternative technologies; therefore, these scenarios project higher levels of greenhouse gas emissions and greater subsequent climate warming. The B1 scenarios are at the lower limit of projected changes in greenhouse gas emissions and assume a global population reduction by mid-century, a rapid economic shift toward service and information economies, and use of less polluting technology. These scenarios are used in global climate models to forecast changes to the future climate, and these broad-scale results are then downscaled to a regional scale (12 × 12-mile grid). Unfortunately, climate data cannot be reliably produced at a finer resolution, and this limitation needs to be considered when using climate data to inform management at smaller



Retention of disease-free American beech trees helps build resilient forests by maintaining a desirable gene pool.

geographic scales. The climate projections are then used with tree species information on optimum growing conditions to assess the sensitivity of each species to climate change.

C. Ecosystem Responses

Assessing the adaptive capacity of forest species begins with understanding the factors that affect where species grow such as the stress factors associated with site conditions and likely response to these stress factors. Other indicators of adaptability include current species distribution, genetic plasticity, and historical level of forest resiliency.

Tree species will respond differently to disturbances depending on their physical environment. Across regions, individual species' ranges reflect their optimum growing conditions (physiological niche) and/or where they have a competitive advantage (ecological niche) (Hutchinson 1957). Species with broad physiological niches may be highly resilient to even significant climate change. Species with a narrow ecological niche may be more resilient than they appear, especially if new environmental conditions provide them with an advantage at the expense of other species.

Predictive models of future tree species distributions under climate change are usually based on suitable future habitat, an analysis using edge-of-range and physiological tolerances to determine climate change vulnerability (Prasad, et al. 2007).

Species with large gene pools and the ability to migrate are likely to be the most successful. Where population sizes are small and genetic diversity is reduced, or where natural species dispersal is lacking, the likelihood of successful adaptation to climate change is diminished (Thompson, et al. 2009).

One of the drivers of change is human effects on forest ecosystems. People change land use, alter species composition and forest structure through harvesting, suppress natural fire cycles, change water flow, reduce forest health through exposure to air pollution, and transport destructive non-native species that disrupt forest dynamics. These in turn affect ecological processes and responses. These additional changes need to be considered in predicting forest response to climate change and formulating land management goals. Forest managers can play a valuable role in influencing future forests through silvicultural practices.

A general assessment of expected impacts to forests from climate change was conducted during the development of a climate change adaptation framework process by the ANR, and the results are presented in **Table 1**. The impacts (expected effects) are presented in **Table 2**. Vermont forest ecosystems have been categorized into natural communities, which are interacting assemblages of plants and animals, their physical environment, and the natural processes that affect them. As these assemblages of plants and animals repeat across the landscape wherever similar environmental conditions exist, they can be described based on these repeating assemblages and grouped as natural community types (Thompson and Sorenson 2000). Using these pre-existing groupings of species allows us to make informed predictions about how communities of species are likely to respond to changes in climate factors, and therefore, what forest management options may be needed for forest adaptation.

For this guide the authors provide forest adaptation considerations for each of the three major natural community formation groups, followed by timber management considerations. **Appendix A** includes species-specific information on stress agents, climate responses, and silviculture considerations for 30 tree species native to Vermont. These species were chosen based on three criteria: (1) abundance in Vermont, (2) value as a commercial timber species, and/or (3) value ecologically.

TABLE 1. SUMMARY OF PROJECTIONS

Parameter	Trend	Projections*
Temperature		
Annual temperature	Increase	By 2050, projected increase in average annual temperature by 3.7-5.8° F; by 2100, increase by 5.0-9.5° F
Seasonal temperature	Increase	By 2050, projected increase in average winter temperature (December, January, February) by 4.3-6.1° F; average summer temperature (June, July, August) by 3.8-6.4° F
Hot days >90° F	Increase	More frequent and more intense; by end of century, northern cities can expect 30-60+ days with maximum daily temperatures >90° F
Cold days <0° F	Decrease	Reduction in days with minimum daily temperatures <0° F
Variability	Increase	Greater variability (more ups and downs)
Hydrology		
Annual precipitation	Increase	By end of century, projected total increase of 10% (about 4 inches per year)
Seasonal precipitation	Variable	More winter rain, less snow; by 2050, winter precipitation could increase by 11-16% on average; little change expected in summer, but projections are highly variable
Heavy rainfall events	Increase	More frequent and intense
Soil moisture	Decrease	Reduction in soil moisture and increase in evaporation rates in the summer
Snow	Decrease	Fewer days with snow cover (by end of century, could lose one-fourth to more than one-half of snow-covered days); increased snow density
Spring flows	Earlier, reduced volume	Earlier snowmelt, earlier high spring flows with reduced volume; could occur 10 days to >2 weeks earlier
Summer low flows	Increase	Extended summer low-flow periods; could increase by nearly a month under high emissions scenario
Ice dynamics	Changing	Less ice cover, reduced ice thickness
Extreme Events		
Flood events	Increase	More likely, particularly in winter and particularly under the high emissions scenario
Number of short-term droughts	Increase	By end of century, under high emissions scenario, short-term droughts could occur as much as once per year in some places
Storms	Increase	More frequent and intense (ice, wind, etc.)
Fire	Increase	More likely
Phenology		
Growing season	Increase	By end of century, projected to be 4-6 weeks longer
Onset of spring	Earlier	By end of century, could be 1 to almost 3 weeks earlier
Onset of fall	Later	By end of century, could arrive 2-3 weeks later
Biological interactions	Changing	Could potentially be disrupted

Based on data from (Union of Concerned Scientists 2006) and (Hayhoe, et al. 2007). Table prepared by Tetra Tech, Inc., 2014.
*Range = low-to-high-emission scenario.

TABLE 2. EXPECTED EFFECTS OF MAJOR CLIMATE FACTORS ON UPLAND FOREST HABITATS

Key Climate Change Factors	Expected Effects	Timeframe
Increased temperatures	Increased evapotranspiration, resulting in a decrease in soil moisture; moisture limitation/stress negatively impacts productivity and survival in many species	Immediate
	Increased physiological stress, resulting in increased susceptibility to pests and disease, decreased productivity, and increased tree mortality	Immediate
	Increase in overwinter survival of pests, such as balsam and HWA	Immediate
	Decrease in winter snow pack, leading to change in deer- and moose-browsing patterns, which affect regeneration	Immediate
	Lengthening of growing season resulting in changes in species competitiveness, especially favoring non-native invasive plants	Immediate
Increase in extreme storm events (i.e., wind and ice)	Increased physical damage and disturbance, leading to gap formation, which could facilitate the spread of invasive plants	Immediate
Phenology (timing)	Longer growing season	Immediate
	Compositional changes associated with changes in thermally suitable habitat (loss of cold-adapted and increase in warm-adapted species)	Long-term, but localized effects could occur on a shorter timescale
	Increased decomposition rate of organic material may enrich soils and make them more suitable for competitors	Long-term, but localized effects could occur on a shorter timescale
	Early spring thaws/late frosts can damage buds, blossoms, and roots, which affect regeneration	Immediate
	Change in freeze cycles could disrupt regular cone production (Messoud 2007)	Immediate
	Asynchronous changes in phenology may negatively impact some migratory species and pollinators	Immediate
Increase in fire risk	Earlier, warmer springs and smaller snow packs and hotter, drier summers conducive to increased fire risk	Immediate
	Loss of fire-intolerant and increase in fire-tolerant species, such as red and pitch pines	Long-term, but localized effects could occur on a shorter timescale
Increase in short-term droughts	Declines in forest productivity and tree survival associated with water limitation	Long-term

D. Climate Change Mitigation Through Forest Carbon Sequestration

Nationally, forests recover and store 15% of all carbon dioxide emissions from US sources (Environmental Protection Agency 2014), and the Environmental Protection Agency (EPA) estimates that improved forest carbon management could double this to approximately 25% of US emissions. Maintaining New England's forests and managing them to maximize storage of carbon will be important to combating the build-up of greenhouse gases in the atmosphere. Prompt emission reductions are needed to reduce the magnitude of climatic changes and predicted impacts. Model predictions for ecological impacts under low-emission scenarios are much more favorable than those under high-emission scenarios. The pace of change and the rate of forest adaptation are much more feasible if we can reduce continued emissions and maximize opportunities for forest carbon sequestration.

Vermont forests play an extremely important role in removing carbon dioxide from the atmosphere—currently estimated at about 70% of Vermont's greenhouse gas emissions—and stockpiling substantial quantities of carbon for the long term. However, large changes in land use or forest heath can release stored forest carbon back to the atmosphere. Conserving forest land and protecting forest health are two steps to take in providing greater carbon sequestration.

As stated by the New England Governors and Eastern Canadian Premieres, "The challenges posed by upcoming climate change underscore the great urgency of maintaining healthy forests in New England and adjacent Canadian provinces. As in the past, the composition of these forests will be altered by changing climate, but the productivity of the forest ecosystems may well increase (biomass per area per year). These extensive landscapes can and should serve as one of the primary mechanisms for carbon sequestration at a time when slowing the rate of increase in greenhouse gases must be given highest international priority" (Jacobson 2009). Trees sequester carbon dioxide better than any other land cover, and incentivizing this ecosystem service is in our best interest.

We see a need to develop public and private programs that provide payments to private forest landowners for management practices that increase carbon sequestration and provide other ecological services such as clean water and biodiversity. In regions where small parcels predominate, landowner cooperatives could facilitate participation in carbon markets. Practices that increase carbon sequestration may include increasing above- and below-ground biomass retained on site for carbon storage by working to increase stand level retention minimizing site disturbance where scarification is not an objective extending rotations and cutting cycles to develop late successional stands comprised of a diversity of species. Additional carbon management guidance is offered in **Appendix B**.

MANAGING FORESTS FOR VALUES IN ADDITION TO TIMBER PRODUCTION CAN MEAN MANAGING FOR A HOST OF ECOSYSTEM SERVICES BENEFICIAL TO SOCIETY.

V. Fundamental Adaptation Strategies

Over time the breadth of forest values has expanded beyond timber production. Managing forests is different from managing agricultural crops, where the main focus is on a single product. Silviculture needs to focus on broader issues such as sustaining the full functions and dynamics of forested ecosystems, maintaining biodiversity and ecological resilience, and providing for a variety of ecosystem services of value to society. Recent publications recognize the potential for silviculture to "manage forests as complex adaptive systems" (Puettmann, Coates and Messier 2009), creating resilient forests that will adapt as our Vermont climate changes.

Complex adaptive systems are those in which the individual components are constantly reacting to each other, continually modifying the system and allowing it to adapt to altered conditions (Durrett and Levin 1998). The functioning of the system as a whole cannot be understood by only observing an individual part. Interactions among and between species, and their relationships with environmental and stress factors creates new, adapted systems.

This concept is similar to silvicultural practices that attempt to mimic historical patterns of forest disturbance across the landscape. Forests were dominated by relatively frequent, partial disturbances that produced finely patterned, diverse mosaics of species and structures. Seymour developed a natural disturbance comparability index to aid foresters in planning harvests that would create resilient forests within stands and across landscapes based on the size and frequency of gaps (harvests) (Seymour, White and deMaynadier 2002).

Advances in adaptation tactics, such as strengthening resiliency and building resistance to stressors, help forest managers incorporate climate change considerations into management (Swanston and Janowiak 2012). These general adaptation strategies and approaches are useful when seeking ways to implement adaptive silviculture at specific sites, as well as across landscapes.

Other adaptation strategies include slowing climate change impacts by identifying and managing refugia, providing mechanisms for species migrations, and incorporating frequent observations of changes so that management plans can be revised to reflect unexpected results. Each strategy plays a role in the adaptation toolbox available for use.

How these are to be incorporated into forest management planning will be covered in subsequent chapters.

VI. Natural Community Adaptation Strategies

A. General Overview

Climate change is expected to alter species abundance and distribution, affecting the composition of the Northern Forest and the forests of Vermont. Because there is no historical equivalent to the current rate of global climate change, the future forest is unknown and is now increasingly being referred to as novel forest.

In addition, components of global change do not act in isolation. Because of the complexity surrounding these changes there can be no simple general silvicultural recommendation or widely applicable silvicultural response to climate change (Puettmann 2011). The silvicultural goal for mitigating climate change is to promote ecosystem resilience through practices that allow for complex systems to respond and adapt to global change, and by doing so, ensuring the continuation of a functional ecosystem through the novel forest. Ecosystem resilience is the response to change in a way that sustains fundamental functions, structure, identity, and feedback (Peterson, Allen and Holling 1998).

This chapter identifies strategies unique to certain natural communities of Vermont, at times drawing from information from subsequent chapters to provide a more complete set of recommendations by natural community type. Not all species are similarly affected by changes in temperature and moisture regime. However, current forest management is focused more on natural community sites and associations than on individual species. So although recognizing that future associations may be different, using natural community formations as a starting point allows us to consider strategies that may be applied to the current forest to provide resiliency and natural adaptation to the future novel forest.

An alternate way to view stand-level adaptation is by identifying sites that may be particularly strong in conserving biodiversity and tailoring management strategies to match these "resilient sites" (Anderson and Ferree 2010) (Anderson, Clark and Olivero Sheldon 2012).

The goal of this chapter is to outline a number of climate change adaptation strategies that are becoming commonplace in the literature and which can be applied to the forest ecosystems in Vermont. It is important to recognize that not all strategies are appropriate for every stand. In addition, this document will address specific strategies that may be applied in distinct natural communities as described in *Wetland, Woodland, Wildland* (Thompson and Sorenson 2000). This book is referenced extensively in this chapter to describe the habitats and ecology of Vermont's natural communities, and at times the language is verbatim.

BOX 1. RECOMMENDATIONS: *MINIMIZING CLIMATE CHANGE IMPACTS AND CREATING RESILIENT FORESTS*

Forest Adaptation Strategies for All Forests

- Ensure that advance regeneration is abundant before removing the overstory when implementing even-aged or large-gap forest management.
- Retain or improve the amount and distribution of coarse and fine woody material for maintaining adequate nutrient cycling and soil protection.
- Monitor for early detection and removal of invasive plant species. Where invasive plant populations are already established, include aggressive management as a component of any silvicultural treatment.
- Manage for tree age diversity and forest structural complexity across the landscape with particular attention to landscape-level management when using even-aged silvicultural techniques.
- Increase forest cover in riparian areas and upland forests adjacent to riparian areas and wetlands to moderate stream temperatures, maintain wildlife corridors, and mitigate flooding impacts.
- Maintain forest species diversity including trees, shrubs, herbaceous plants, and bryophytes to aid in maintaining forest processes.
- Monitor harvests and temporarily halt operations as needed to protect soil, water, and access infrastructure.
- Match equipment to terrain and harvest objective to reduce soil and stand impacts. Use low-impact equipment when harvesting in steep terrain and wet ground conditions. Encourage the use of cut-to-length (CTL) systems, forwarders, tracked machines, and smaller skidders for steep terrain and wet ground conditions
- Manage deer and moose populations and hunter access to limit over-browsing. In high-value forest sites consider strategic placement of exclosures to protect regeneration.
- Protect uncommon and rare natural communities in reserves or in Use Value Appraisal Ecologically Significant Treatment Area categories where appropriate to meeting landowner goals.
- Work with the agricultural community to enhance forest connectivity through forest restoration efforts.
- Work with communities to conserve uncommon forest communities and maintain connectivity.

A1. Sustain fundamental ecological functions: Protect soil quality, nutrient cycling, and hydrology.

Nutrient cycling and soil protection can be enhanced by augmenting coarse and fine woody material on the forest floor. Logging debris (material) contains significant amounts of carbon and nitrogen—elements critical for soil productivity. Its physical presence in the regenerating forest creates microclimates that influence a broad range of soil and plant processes. Keeping logging debris (material) in place improves soil fertility, especially in areas with coarse-textured, nutrient-poor soils. Soil nitrogen and other nutrients important to tree growth increase. Soil water availability increases due to the woody material mulching effect. The material cools the soil, which slows the breakdown and release of soil carbon into the atmosphere (Kirkland, 2012). Consideration for leaving tops in the woods and recruiting a few large stems per acre for coarse woody material can accomplish these goals. Other strategies include matching equipment to the site for soil protection and building roads prior to operations; considering the natural hydrology of the site by preventing excessive ditching, and building roads to sheet water through slopes and broad based dips; minimizing the number of skid roads; and pre-bunching harvested trees in a manner that minimizes skidder trails.

Box 2. Recommendations: *Strategies on How to Sustain Fundamental Ecological Functions*

- Leave tops in the woods and recruit a few large stems per acre for coarse woody material to keep debris in place to improve soil fertility and water availability.
- Match equipment to the site for soil protection and build roads prior to operations.
- Consider the natural hydrology of the site by preventing excessive ditching, and build roads to sheet water through slopes and broad based dips
- Minimize the number of skid roads.
- Pre-bunch harvested trees in a manner that minimizes skidder trails.

Single-tree and small-group selection harvesting or tending treatments using machinery on sensitive sites should take place in winter conditions with snow cover to protect the roots of the residual trees. Other systems where gaps, patches, or clearcuts are part of the treatment may require scarification which could happen in summer or snow-off conditions. If harvesting in conditions where frozen ground is not present, additional care should be taken to minimize ground disturbance of the mineral soil and alteration of the natural hydrology. In all cases, roads should be kept to a minimum and all acceptable management practices (AMPs) followed. Main haul or skid roads should be at least 300 feet apart when using feller-bunchers. When overall ground conditions are soft or muddy the job should be temporarily halted.

A2. Reduce impacts of existing biological stressors on trees and regeneration: Manage invasive species and limit herbivory of native species.

Healthy trees are better at resisting insects and diseases. Tending forests in ways that minimize negative impacts will help encourage vigorous tree growth and minimize pest damage.

Vigorous native regeneration is a first step towards a healthy future forest. Invasive plant species prevention, eradication, and/or management should be a top priority in Vermont. Where the level of invasive plant species occurrence is low, the plants should be targeted for removal with a goal to eradicate the plants on that property. Plants can be removed mechanically by pulling or burning, or with chemicals using foliar, chemical girdle, or stump application of herbicide depending on landowner objectives. Investigating plant-specific best management practices and appropriate chemical use are recommended [see www.vtinvasives.org, (Vermont Chapter of The Nature Conservancy 2011)]. When the level of plant species occurrence is moderate or high, control measures should be implemented using integrated pest management strategies and manual and/or chemical control as well as mowing, chipping, and targeted rotational animal grazing. Stands impacted by a large disturbance event should be monitored for invasive species. Invasive species should also be a priority for managers of roadside and median vegetation, and education on identification and removal should be implemented regularly.

Limiting herbivory of native plants through management of vegetation is a subject for which experience in Vermont is limited. Common recommendations at the local and regional level include strategies to limit access to seedlings with residual slash and or fencing, timing harvests to match low points in local deer populations, syncing up harvests with nearby parcels to "overwhelm" local populations with browse (thereby allowing seedlings to outgrow browse pressure), conducting overstory removals only when the next generation of trees is well established, and matching harvest timing to abundant seed crops of desired species.

A3. Moderate the impacts of severe disturbances, such as natural stand-replacing fire and wind events.

More severe storms, as well as drought conditions, are expected to increase as part of climate change. These occurrences of extreme events cannot be changed but our responses to them can. It will be important to identify high-risk areas and have a plan for response to disturbance. Such high-risk areas might include ridgelines, or other exposed sites, or lowlands with a high water table. Managing for a multi-age forest will allow the forest to be resilient in the face of disturbance. If a large windthrow event takes place, established regeneration can be ready to respond to release. Where invasive species are a significant problem, a plan to control invasives and to plant appropriate species may be necessary.

A4. Create and maintain refugia and increase ecosystem replication across the landscape.

Refugia are areas that have resisted ecological changes occurring elsewhere, often providing suitable habitat for relict populations of species that were previously more widespread (Miller 2011). Not all locations currently supporting a species will be suitable in the future. By identifying sites that may be better buffered against climate change and short-term disturbances, species can be better the greater landscape. Uncommon and rare natural communities along with small-patch natural communities are areas with disproportional biological and physical diversity relative to their acreage on the landscape. Thus protecting these small areas and managing them for ecological quality will go a long way toward saving all parts of a landscape.

Species as well as natural communities are strongly associated with geological conditions, more so than temperature and moisture. Anderson and Ferree found that four geophysical factors—number of geological classes, latitude, elevation range, and amount of calcareous bedrock—predict species diversity with certainty (Anderson and Ferree 2010). Identifying and conserving locations that have a greater chance of resiliency (i.e., "protecting the stage") is another way to mitigate climate change effects (Anderson, Clark and Olivero Sheldon 2012).

Refugia should be identified and replicated throughout the range of species or natural communities as a means to increase successful conservation of genetic material. A reserve system

ENRICHED SITES WITH INDICATOR PLANTS SUCH AS BLUE COHOSH MAY BE GOOD CANDIDATES FOR REFUGIA.

could be established by setting targets based on natural community type within a regional context.

Management is not precluded in refugia as some sites may require management to maintain them as climate change refugia. For example, retaining trees to a very old age should be a priority for all climate change refugia and include biological legacies that live out their biological life span to vertically and horizontally enhance the complexity of forest structure, which can be done through enhancing coarse woody material, snags, and den trees. Passive management in refugia is an appropriate strategy. Active management may be possible as long as the refugia goals take precedence over timber management.

A5. Maintain and improve species diversity and structural complexity and facilitate community adjustments through species transition.

Species are at risk from climate changes at different stages of their life cycle. Diversity in species and ages provides resiliency to forest systems. Although forest management has long advocated for species and structural diversity, climate change further supports this strategy as critical to long-term forest health. Climate change impacts may result in regeneration failure due to drier site conditions at certain times of the year or fluctuating spring temperatures resulting in frost damage to flowers. Regeneration recruitment should receive greater attention in many Vermont forests.

Actively managed landscapes can assist forest transitions by favoring those species predicted to be more compatible with projected climatic conditions. However, one should retain individual trees of a variety of species as biological legacies, even when favoring species that are expected to be better adapted to future conditions. Rare, threatened, and endangered species, particularly edge-of-range species, may need their full genetic variation to adapt and move in response to climate change.

A6. Promote landscape connectivity.

Protection of the stage was mentioned earlier, but protection alone is insufficient. Connecting intact areas of forest across an increasingly developed landscape is essential. Landscape-level planning; identification of critical connecting landscapes; and protection of these landscapes through land use, zoning, and conservation easements should be priorities.

At local scales, riparian area corridors can be restored by expanding forest cover from adjacent forests. Likewise, habitat corridors along field edges and in abandoned farmland could be enhanced through reforestation.

Increased funding would facilitate the purchase of conservation easements. A conservation community should not overlook the eligibility of aggregated small parcels to create connected landscapes.

B. Northern Hardwood Forests

Northern Hardwood Forests are the matrix forest in Vermont occupying much of the state on a variety of site conditions, with a number of compositional variants. This diversity of natural communities provides an opportunity for managers to assess the potential climate effects on that community based on site, present composition, silvics, and stand history. These characteristics inform the development of adaptation strategies to mitigate climate change impacts. This section is focused on broad management strategies for Northern Hardwood Forests.

TABLE 3. NORTHERN HARDWOOD FORESTS

Natural Community	Variants	Other Related Communities
Northern Hardwood Forest	Beech-Red Maple-Hemlock-Northern Hardwood Forest Sugar Maple-Ash-Jack-in-the-pulpit Northern Hardwood Forest Yellow Birch Northern Hardwood Forest White Pine-Northern Hardwood Forest	Mesic Maple-Ash-Hickory-Oak Forest
Rich Northern Hardwood Forest	Northern Hardwood Limestone Forest	Mesic Maple-Ash-Hickory-Oak Forest
Mesic Red Oak Northern Hardwood Forest		Dry Oak-Hickory-Hophornbeam Forest Dry Oak Forest
Hemlock-Northern Hardwood Forest	Hemlock-White Pine-Northern Hardwood Forest	Yellow Birch-Hemlock Forest
Hemlock Forest	Hemlock-Red Spruce Forest	Temperate Hemlock Forest
Northern Hardwood Talus Woodland		Transition Hardwood Talus Woodland

B1. Sustain fundamental ecological functions: Protect soil quality, nutrient cycling, and hydrology.

Northern Hardwood Forest communities are found on a variety of soil types, but are usually characterized by either moderately well-drained glacial till or excessively drained shallow-to-bedrock soils. In all cases soils are neither extremely wet nor extremely dry. Bedrock varies from schist to limestone. The matrix Northern Hardwood Forests of beech/birch/maple are often found on soils that are interspersed with bedrock outcrop, deeper pockets of enriched soil, and an abundance of seeps that may make operability difficult. Beech-Red Maple-Hemlock Northern Forests and White Pine-Northern Hardwood Forests are found on coarser, better-drained soils and these could be operated on under snow-off conditions. Rich Northern Hardwood Forests can be found on deep, colluvial soil that is compost-like in consistency or where calcium-rich bedrock is found near the surface. Shallow-to-bedrock limestone soils are also fragile and generally include high species diversity in rare and uncommon plants. These sites may also be susceptible to expected longer summer droughts. Shorter winters and more frequent rain events make harvesting on these sites more complicated as a result of disturbance and soil loss. Harvesting these sites with frozen or snow-covered conditions may become even more important.

Retaining organic matter on the forest floor is essential to maintaining soil health. Northern Hardwood Forests include species that have very high nutrient cycling capability with basswood likely the most important, but also ash and some of the early successional species such as aspen, pin cherry, and Rubus (Leak, personal communication). It is recommended that most basswood and some ash be retained in stands where these species occur. Aspen is also often found as inclusions within Northern Hardwood Forests where disturbance has occurred. Maintaining this species through coppice growth

NORTHERN HARDWOOD FORMATION FORESTS INCLUDE A WIDE SPECTRUM OF SPECIES SUCH AS SUGAR MAPLE AND WHITE ASH.

should be considered as an enhancement to biodiversity and nutrient cycling. Aspen and poplar species have a narrow regeneration requirement, so coppice resprouting can be used to successfully maintain this species in the ecosystem.

B2. Reduce impacts of existing biological stressors to trees and regeneration, increase resistance to pests and pathogens, limit herbivory on native regeneration, and manage invasive plant species.

Healthy trees are better at resisting insects and diseases. Tending forests in ways that minimize negative impacts will help encourage vigorous tree growth.

Northern Hardwood Forest communities comprise a diverse number of species. Studies have shown that the greater the diversity the greater the resistance to insect defoliators (Tobi 2005) (Gurr 2012). A primary goal in forest management should be to maintain or enhance species diversity. Advancing or expanding the northern boundaries of the more southern species that make up the Northern Forest could augment species diversity.

In some parts of the state (e.g., southern Vermont or sandy soils) Northern Hardwood Forests once included American chestnuts as part of the species mix. Disease-resistant trees are now being developed for outplanting in the seed orchards. This may be another diversification possibility for the future.

Species found in Northern Hardwood Forest communities are the preferred browse species of white-tailed deer. Northern white cedar is the only preferred browse species not typically found in a Northern Hardwood community. Further work is needed to find management solutions to prevent herbivory under high deer population numbers, and to develop methods for ecosystem recovery from decades of overbrowsing. Deer-exclusion fencing or other barriers may be necessary where deer populations are excessive until population numbers are reduced. Managing and improving hunter access is an important consideration.

Invasive plant species are often found in the richer limestone soils that support Rich Northern Hardwood and Mesic Red Oak Northern Hardwood Forests as well as in any location where they have been introduced. Management (not necessarily eradication) of invasive species is an important practice in Northern Hardwood silviculture. In areas where invasive species are not established, periodic monitoring and removal should be an employed strategy. Methods can include mechanical removal, chemical control, or a combination. Invasive species are less likely to be found in areas that have never been in agricultural use, such as some areas of the Northern Green Mountains and the Northeastern Highlands.

DEER BROWSE DAMAGE ON WHITE ASH REGENERATION WILL AFFECT THE FUTURE FOREST.

B3. Moderate the impacts of severe disturbances, such as natural stand-replacing fire and wind events.

Wind storms are the primary means of natural stand-replacing disturbance in our Northern Hardwood forests. Historically wind events have been small, with one-tenth to 2 acres being the most common gap size (Seymour, White and deMaynadier 2002). Wind events may become stronger and more frequent but it is probably unlikely that stand-replacing wind events will become the norm, though predictions are that they will become more frequent. High-risk areas can be identified to develop plans for response to severe disturbance. It is recommended that diverse forest ages be developed within an ownership and across the landscape. A multi-age forest will provide some resilience to disturbance but may also serve to lessen the force of the wind by absorbing wind energy among the vertical and horizontal layers of the forest. In addition, when crown development in all layers of the forest is vigorous, the corresponding root systems will be healthier and able to withstand greater wind force. Northern Hardwood Forests are generally less prone to fire disturbance.

B4. Create and maintain refugia and increase ecosystem replication across the landscape.

Northern Hardwood Forest refugia may include cove hardwoods (Rich Northern Hardwood Natural Community) where soils are high in nutrients and protected from wind and weather. These cove hardwoods are ideal locations for sugar maple, white ash, basswood, and butternut as well as a variety of specialized ferns and herbaceous plants. The variant Northern Hardwood Limestone Forest may be treated similarly where moisture conditions will remain adequate. Limestone forests tend to be shallow to bedrock and thus there may be fewer locations occurring on the landscape. Other Northern Hardwood communities that have special consideration include Northern Hardwood Talus Woodland and the related Transition Talus Woodland. These woodlands offer opportunities as reserves because of limited access and difficult terrain. The Hemlock, Northern Hardwood-Hemlock, and Spruce-Hemlock Forests would also benefit from the establishment of refugia where conditions for spruce and hemlock regeneration are optimal. In the case of hemlock and spruce, refugia may be identified by soils with adequate moisture content. Aspect is a consideration in identifying refugia. Spruce is limited by adequate moisture for regeneration success. North- or east-facing slopes receive less direct sun and often have a higher capacity to retain moisture. Scarification of the soil may be a requirement when managing these communities, as the lighter seed of hemlock and spruce benefit from direct seeding on mineral soil. Hemlock swamps should be identified and categorized as reserves with invasive species monitoring only. Any natural community that is considered S3 (uncommon) or Rare S1 and S2 should have a higher priority for protection. These include Northern Hardwood Talus Woodland, Transition Hardwood Talus Woodland, and related communities; Mesic Maple-Ash-Hickory-Oak Forest; Dry Oak-Hickory-Hophornbeam Forest; and Dry Oak Woodland.

B5. Maintain and improve stand-level species diversity and structural complexity, and facilitate community adjustments through species transition.

Age diversification is already a goal of uneven-aged silviculture and where at least three age cohorts are maintained, the structural diversity and stand complexity achieved can build more resilient forests. Resilient forests can be maintained using stand-level, even-aged silvicultural methods but it would be important to consider this approach within a larger landscape-level context to assure that age and structural complexity is accomplished. Management objectives should include species diversity that naturally occurs in these communities, up to 8-11 principal tree species, 2-6 shrub species, and 13-35 herbaceous species (Thompson and Sorenson 2000). This would include species that are predicted to be better adapted to future conditions such as red oak, white pine, and hickory. Wherever these species occur on the landscape, efforts should be made to retain and increase their proportion while also maintaining caution as the current science projections may change in the future. Group selection and irregular shelterwood methods can be applied to establish and release red oak and white pine wherever appropriate for the site. Red oak, hickory, sugar maple, and hemlock are long-lived species and a number of biological legacies of these species should be retained throughout individual ownerships and across the landscape. In some cases, assisted migration of red oak in the north and along the foothills and slopes of the Green Mountains could be considered.

Assisted migration of naturally occurring native species should be considered for those species that are appropriate to the site, have the potential for success in warmer climates, and are already occurring in the stand but in low numbers. Site assessment should drive the management objectives in all cases.

B6. Promote landscape connectivity.

Restore corridors at a local level including in and adjacent to riparian areas. Riparian forests—forests adjacent to streams and frequently inundated with water—often merge into Northern Hardwood Forests where Red Oak Northern Hardwood is common along larger rivers in both the Champlain and Connecticut River Valleys. Corridor restoration can also occur along smaller streams in more upland sites. Other areas to consider for local restoration include lower quality pastures and cropland not being used for food production. On abandoned pasture lands in northern parts of Vermont, hemlock is a common species on Cabot soils. Expanding hedgerows along fence lines would also increase potential species migration, provided invasive species can be managed. Planting trees that have better potential in warmer climate conditions such as oaks, hickories, and others may be appropriate if already present in the natural community and region. Continued statewide planning and implementation to protect large forest blocks and the areas that connect them is crucial to protecting the stage.

BOX 3. RECOMMENDATIONS: *NORTHERN HARDWOOD FOREST ADAPTATION STRATEGIES*

- Retain or establish species with high nutrient cycling capability: basswood, ash, aspen, pin cherry, and Rubus.
- Identify and manage refugia across the landscape, especially for cove hardwoods and talus woodland communities. Use of passive or active management depends on the ownership objective, but with ecological functions taking priority over timber production.
- Retain or plant hedgerows and fence lines wider and with a greater diversity of climate-adapted species to maintain connectivity through open lands, provided invasive species can be managed.
- Retain species at the northern edge of their range that may be better suited to future conditions (i.e., red oak, hickory, white pine), where they are found in the natural community and region.
- Retain long-lived species as biological legacies (e.g., sugar maple, oaks, hickory, and hemlock).

C. Spruce-Fir-Northern Hardwood Formation

These forest communities inhabit the colder regions of the Northern Forest which experience a short growing season, cold temperatures, and ice and snow load in trees. These conditions tend to favor conifer species that may be capable of photosynthesizing comparatively earlier and during warm intervals in the winter months and that can shed ice and snow more effectively. Mosses and liverworts also have a competitive edge in the harsh conditions, dense conifer shade, and infertile soils. Given their little-to-no value in agriculture, many of these forest communities remained forested at a time when Vermont land was mostly cleared. It is these forest communities that may be susceptible to the greatest level of stress from climate change as their location at the highest elevations provides little opportunity for migration. For this reason even greater consideration should be given to management practices that include site assessment, silvics, and land-use history to favor the greatest increase in resiliency of these forest communities.

How we address these strategies in the Spruce-Fir-Northern Hardwood communities is the focus of this section. Each strategy will be discussed specifically as management in Spruce-Fir-Northern Hardwood communities is addressed.

TABLE 4. SPRUCE-FIR-NORTHERN HARDWOOD COMMUNITIES

Natural Community	Variants	Other Related Communities
Subalpine Krummholz		
Montane Spruce-Fir Forest	Montane Fir Forest Montane Spruce Forest	
Lowland Spruce-Fir Forest	Well-drained phase	Black Spruce Swamp Spruce-Fir-Tamarack Swamp
Montane Yellow Birch-Spruce-Fir Forest	Montane Yellow Birch Northern Hardwood Forest Sugar Maple-Spruce-Fir Forest	
Red Spruce-Northern Hardwood Forest		
Boreal Talus Woodland		Northern Hardwood Talus Woodland
Cold-Air Talus Woodland		
Red Spruce-Heath-Rocky Ridge Forest		

C1. Sustain fundamental ecological functions, including protecting soil quality, nutrient cycling, and hydrology.

Spruce-Fir-Northern Hardwood Forests are found on shallow, acidic, and infertile soils. Heavy precipitation and organic acids from needle decomposition leaches nutrients, forming an E horizon in the soil profile, a characteristic of spodosol soils. Decomposition is slow and organic matter accumulates. Soils are generally more fragile and prone to erosion on the steeper upper-elevation slopes. Operations should be limited or discouraged on higher elevations. In the lower elevations, on the cold wet pockets where the Lowland Spruce-Fir Forest is found, harvesting should be limited to winter conditions and/or by using tracked equipment. The well-drained Lowland Spruce-Fir phase is found on benches, plateaus, shorelines, and glacial outwashes located in cold-air drainage basins, and thereby may be less likely to warm with a changing climate. Quaking aspen and balsam poplar are common associates in Lowland Spruce-Fir, Montane Yellow Birch-Red Spruce, and Red Spruce-Northern Hardwood Forests.

C2. Reduce the impact of existing biological stressors on trees and regeneration, increase pest and pathogen resistance, limit herbivory on native regeneration, and manage invasive plant species.

Spruce budworm infestations and damage may exacerbate the potential for fire as a climate warms and becomes drier. One goal of forest management should be to maintain or enhance tree species diversity in each entry. Managing stands for a decreased proportion of balsam fir to minimize spruce budworm outbreaks is recommended. Maintaining balsam fir in moist pockets is recommended to retain the species as a component of the landscape in areas where it grows well. A goal of maintaining all the boreal conifers to some extent is recommended. These include balsam fir, black spruce, tamarack, white spruce, northern white cedar, and red pine, all of which respond to climate variations over time. The silvics of these particular species should be considered when managing these forest communities.

Moose can impart severe browse pressure on balsam fir, red maple, sugar maple, and yellow birch. It is likely that moose pressure will decrease with a warming climate as moose numbers decline as a result of warmer winters and winter ticks.

Invasive plant species do not appear to be a problem at present in Spruce-Fir-Northern Hardwood natural communities. Monitoring, early detection, and eradication are the management strategy recommended at this time.

C3. Moderate the impacts of severe disturbances such as natural stand-replacing fire and wind events.

Wind disturbance, fire, and tree mortality are the primary means of natural disturbance in Red Spruce-Northern Hardwood Forests. Historically, wind events are generally small with gap sizes from one-tenth to 2 acres being the most common (Seymour, White and deMaynadier 2002). Of the three major forest types in New England (oak-pine, northern hardwood, and spruce-fir), spruce-fir forests have the highest expected percentage of the regional landscape occupied by seedling-sapling-age class as a result of natural disturbance (Lorimer 2003). Wind events may become stronger and more frequent but it is unlikely that stand-replacing wind events will become the norm. It is recommended that high-risk areas be identified with a plan to respond to disturbance. It is also recommended that a diversity of age class be developed within larger ownerships and across the landscape. Even-aged silvicutural methods could include irregular shelterwood systems (including patch or strip cuts under area regulation), expanding gap, or extended shelterwood treatments as well as uneven-aged systems using group or single-tree selection. A multi-age forest will provide resiliency to response but will also serve to impact the force of the wind by absorbing wind energy among the vertical and horizontal layers of the forest. In addition, when crown development in all layers of the forest is healthy, the corresponding root systems tend to be healthier and better able to withstand greater wind force. In all management scenarios the establishment of conifer regeneration and the retention of the boreal conifer overstory for stand structure and future seed source are critical.

C4. Create and maintain refugia and increase ecosystem replication across the landscape.

Spruce-Fir-Northern Hardwood refugia may be prioritized to include those forest communities that are found on north-facing slopes with adequate moisture availability. North-facing slopes are generally colder than their south-facing counterparts. High elevations and cold-air drainage basins represent other potential refugia. It would also be an appropriate option to leave any of these communities as reserves to allow the forest to self-adapt and increase redundancy, with invasive species monitoring only. All of the Spruce-Fir-Northern Hardwood communities are ranked as S3 (uncommon) or rarer with the exception of the Red Spruce-Northern Hardwood Forest (widespread S4). Some climate change resilience of the alpine meadow and krummholz has been suggested, but not for montane spruce-fir forests (Seidel, et al. 2009). It is recommended that refugia across the region include large, high-quality examples of the community types in a well-connected landscape.

C5. Maintain and improve native species diversity and structural complexity, and facilitate community adjustments through species transition.

Species objectives should include the diversity of species that naturally occurs in these communities and includes up to 5-13 tree species, 3-12 shrub species, up to 20 herbaceous species, and 11 bryophytes (mosses and liverworts), depending on what the site supports (Thompson and Sorenson 2000). Diversity occurs less at higher elevations, though bryophyte diversity is higher in moist montane and Lowland Spruce-Fir Forests. As the climate warms, yellow birch may be found at higher elevations; white pine may displace balsam fir on coarse, well-drained soils; and balsam fir may be stressed on sites that have decreased moisture availability. In Lowland Spruce-Fir communities white pine, red maple, Northern white cedar, white spruce, and birch could be become more common if site conditions become drier. It is highly recommended that balsam fir be retained and regenerated in areas that have good moisture availability and/or have north and east aspects.

Group selection and irregular shelterwood methods can be applied to maintain balsam fir where possible as well as to encourage the establishment of a greater diversity of species for forest resiliency enhancement. Even-aged management methods could be used at the stand level but it would be important to consider this approach within a larger landscape-level context to ensure that age and structural complexity is accomplished.

C6. Promote landscape connectivity.

Lowland Spruce-Fir communities are often associated with wetlands such as slow-moving streams with shrub swamps and spruce-fir swamps. These wetland forest associations are excellent wildlife corridors, and wetlands continue to provide connectivity across the landscape for both plants and animals.

Maintaining and restoring these corridors at a local level including in and adjacent to riparian areas is recommended. Forested landscapes often include landforms and soils where these natural Red Spruce-Northern Hardwood communities would naturally be found.

BOX 4. RECOMMENDATIONS: *SPRUCE-FIR-NORTHERN HARDWOOD FOREST ADAPTATION STRATEGIES*

- Limit harvesting to frozen, snow-cover, winter conditions on fragile soils and to protect advance regeneration of conifer species. Scarification for the establishment of regeneration is an exception.
- Identify and manage climate change refugia across the landscape, in particular north-facing slopes with adequate moisture or moist basins. Passive or active management of refugia depends on the circumstance, but always with ecological functions and species composition taking precedence over timber.
- Establish reserves to conserve mature, high-quality examples of all Spruce-Fir-Northern Hardwood Forest natural community types.
- Favor for retention species at the north edge of their range, that may be better suited to future conditions (i.e., white pine on dry coarse soils and yellow birch at higher elevations).
- Retain long-lived species as biological legacies (red spruce, northern white cedar, and yellow birch).

D. Oak-Pine-Northern Hardwood Formation

These forest communities are considered transitional between the Central and Northern Hardwoods. They are found in the warmer climates of Vermont and often found locally in small patches. These patches are common in the foothills of the Champlain and Connecticut River Valleys. In lower elevations these forest communities would have been abundant in pre-European settlement forests. Many of these communities are now rare as a result of historic and current conversion of forest land to other uses, including the rare Valley Clayplain and Pine-Oak-Heath Sandplain Forests. The patchy nature of these forest communities provides an opportunity for forest managers to consider strategies for climate adaptation through natural migration and assisted migration of native tree species. Oaks, hickories, and pines may become more abundant in the landscape under the right soil conditions, climate, and management. How we address these strategies in the Oak-Pine-Northern Hardwood communities is the focus of this section. Each strategy will be discussed specifically as management in Oak-Pine-Northern Hardwood stand is addressed.

OAK SPECIES MAY BE BETTER SUITED FOR OUR FUTURE CLIMATE CONDITIONS.

TABLE 5. OAK-PINE-NORTHERN HARDWOOD COMMUNITIES

Natural Community	Variants	Other Related Communities
Red Pine Forest		
Pitch Pine-Oak Heath Summit		
Limestone Bluff Cedar-Pine Forest		
Red Cedar Woodland		
Dry Oak Woodland		
Dry Oak Forest		
Dry Oak-Hickory-Hophornbeam Forest	Sugar Maple-Hophornbeam Forest	
Mesic Maple-Ash-Hickory-Oak Forest	Transition Hardwoods Limestone Forest	
Mesic Clayplain Forest		
Sand-over-Clay Forest		
White Pine-Red Oak-Black Oak Forest		
Pine-Oak-Heath Sandplain Forest		
Temperate Hemlock Forest		Hemlock Forest

D1. Sustain fundamental ecological functions, including protecting soil quality, nutrient cycling, and hydrology.

Oak-Pine-Northern Hardwood communities are found on a variety of substrates that conform to specific community groups. Red Pine Forest, Pine-Oak, Heath Rocky Summit, Limestone Bluff Cedar Pine Forest, Red Cedar Woodland, Dry Oak Woodland, and Dry Oak Forest are found on shallow-to-bedrock soils with deeper soils interspersed, often but not always on ridgetops and knobs. Frequently some of these forest communities are fire adapted. Dry Oak-Hickory-Hophornbeam and Mesic Maple-Ash-Hickory-Oak Forests are found on glacial-till-derived soils. Clay may be present and bedrock exposures may be occasionally found. Mesic Clayplain, Sand-over-Clay, White Pine-Red Oak-Black Oak, and Pine-Oak-Heath Sandplain Forests are found on soils that are mostly derived from lake or maritime sediments, either clay or sand, and bedrock exposure may be found throughout.

Plants found in these communities are not generally considered high-nutrient cyclers. Many of the soils are low in nutrients with the exception of when clays and limestone bedrock are present. In these cases basswood may be present, and in early successional stage, aspen may be a component of these forest communities. Aspen should be identified and regenerated using coppice cutting methods to allow persistence. Aspen has a narrow ecological range for germination. Maintaining the species in this forest will enable its future establishment in disturbed areas, minimize potential for invasives' establishment, and create conditions for the establishment of later successional species. Soil scarification is recommended during harvesting operations to enhance the potential of oak and pine seeding.

Sivilcutural practices in these forests can include a variety of methods, though it should be recognized that oaks and pines need full sunlight to become established and thrive. Group selection and irregular shelterwood systems to develop multi-age stands are encouraged. Even-aged management including regular shelterwood, seed tree, and progressive clearcuts can also be successful. Oak success requires the presence of advance regeneration prior to the removal of the overstory. Invasive species control is recommended before any harvest, and periodically thereafter.

D2. Reduce impacts of existing biological stressors on trees and regeneration, increase pest and pathogen resistance, limit herbivory on native regeneration, and manage invasive plant species.

Oak-Pine-Northern Hardwood communities are composed of a diverse number of species. Studies have shown the higher the diversity, the greater the resistance to insect defoliators (Parker, Skinner and Tobi 2013). The goal in forest management should be to maintain or enhance species diversity in each entry. Advancing or pushing the northern boundaries of the more southern species of which these forests are comprised will augment species diversity across the landscape.

Many species found in Oak-Pine-Northern Hardwood communities are heavily browsed by white-tailed deer. At present many of the forest communities in this formation are found in smaller forest blocks fragmented by agricultural land and developed areas. Deer can find more abundant and varied food in agricultural areas where farm crops provide part of their diet. This higher deer population is also more concentrated which increases browse pressure. Oak, hickory, ash, sugar maple, northern white cedar, and even white pine are often heavily browsed with a visible browse line in farm woodlots. Further work needs to take place to find management solutions that prevent herbivory under high deer population numbers. Deer-exclusion fencing or other barriers may be necessary when populations are high.

Invasive plant species are often found in the richer limestone or clay soils that support Limestone Bluff Cedar-Pine, Mesic Maple-Ash-Hickory-Oak, and Mesic Clayplain Forests and in any location where they have been introduced. Management of invasive species is an important component of Oak-Pine-Northern Hardwood silviculture. In areas where invasive species have not colonized, periodic monitoring and removal should be employed. The presence of invasive plant species and high deer browse can result in reduced biodiversity or even regeneration failure. Controlling invasive plant species and aggressive control of deer populations may be two of the most important steps toward allowing forests to perpetuate native tree populations and a functioning natural ecosystem.

D3. Moderate the impacts of severe disturbances such as natural stand-replacing fire and wind events.

Wind disturbance and on occasion fire are the most common disturbance types in Oak-Pine-Northern Hardwood Forests. In the past 200-300 years human disturbance from intentional fires, logging, and land clearing have played the most substantial role. In fact human disturbance has likely played a role for the last several thousand years in these forests as native peoples managed for game and foraged. The conversion of many of the fire-adapted communities such as the White Pine-Red Oak-Black Oak and Pine-Heath Sandplain Forests has resulted in an almost complete lack of fire disturbance in Vermont. The small areas that still exist are often located in densely urbanized areas where fire suppression would be the norm. It is recommended that controlled burns be implemented under professional supervision as a means to reinstitute a natural fire regime. Fire is still an important form of natural disturbance on many small patches and ridge- and cliff-top natural communities, such as Red Pine, Dry Oak-Hickory-Hophornbeam, and Limestone Bluff Cedar-Pine Forests and Dry Oak and Red Cedar Woodlands.

Historically wind events are generally small, with one-tenth to 2 acres being the most common gap size (Seymour, White and deMaynadier 2002). Wind events may become stronger and more frequent but it is unlikely that stand-replacing wind events will become common-place. It is recommended that high-risk areas be identified with a plan to respond to disturbance in a way that builds future resilience (e.g., seed tree retention). It is also recommended that a diversity of age classes be developed within an ownership and across the landscape. Silvicutural methods could include irregular shelterwood or group or single-tree selection. A multi-age forest will provide resiliency to response but also serve to impact the force of the wind by absorbing wind energy among the vertical and horizontal layers of the forest. In addition, when crown development in all layers of the forest is healthy, the corresponding root systems tend to be more healthy and able to withstand greater wind force. Even-aged management methods, particularly regular shelterwood methods, could be used at the stand level but it would be important to consider this approach within a larger landscape context to ensure that age and structural complexity are accomplished.

D4. Create and maintain refugia and increase ecosystem replication across the landscape.

Oak-Pine-Northern Hardwood refugia may be prioritized to include those forest communities that are rare or uncommon. Climate change may increase drought, placing added stress on those sites that are already defined by drought such as Dry Oak Woodland and Dry Oak Forest. It would be an appropriate option to leave these two dry oak communities as reserves to allow the forest to self-adapt and to increase redundancy, with management being limited to restoration efforts. All of the Oak-Pine-Northern Hardwood communities are ranked S3 or higher, mostly because of land-use history and clearing for agriculture and development. The Mesic Maple-Ash-Hickory-Oak Forests may begin to occupy more of the area that is now composed of Mesic Red Oak-Northern Hardwood and Northern Hardwood Forests. Clayplain, Pine-Oak-Heath Sandplain, and White Pine-Red Oak-Black Oak Forests have more specific soil requirements but these soils remain abundant. In some areas that are no longer supporting agriculture these forests could be restored. The remaining examples of these forest communities may also be degraded from past use and the impact of invasive plant species, and are in need of restoration as well.

D5. Maintain and improve native species diversity and structural complexity, and facilitate community adjustments through species transitions.

Species diversity in these communities can be significant, and management objectives should include the diversity of species that naturally occurs in these communities to possibly includ0e 5-14 tree species, 3-6 shrub species, and 24 or more herbaceous species—many of them rare. The species found in natural communities such as Mesic Maple-Ash-Hickory-Oak Forest may be naturally migrating northward in Vermont and upward in elevation as a response to climate change. As species naturally migrate they should be favored for retention during logging operations.

Although the importation of new species into Vermont is not recommended, facilitated or assisted migration of the southern oaks and hickories already growing in Vermont may improve the future resiliency of our natural communities. For example, chestnut oak may be planted in the Champlain Valley, Vermont Valley, Taconics, and Southern Piedmont areas. Chestnut oak does best on dry coarse-textured soil but can do well in bottomlands and coves. Using Vermont native seed sources is recommended to prevent introduction of non-native insect or disease pests.

Group selection with retention and irregular and regular shelterwood systems are recommended in this forest type. Regeneration success may depend on establishing advanced regeneration as well as early intervention to manage competition with invasive species and competing trees species before removing all or part of the overstory.

D6. Promote landscape connectivity.

Landscape connectivity is a major problem in this forest formation due to the highly fragmented landscape where the component natural communities are found. It is important to engage the agricultural community in efforts to restore forest connectivity. Where forested natural communities have been diminished, it is recommended that you promote practices that allow some agricultural lands to be converted back to forest land, such as Clayplain Forests in the Champlain Valley. Forested and naturally vegetated corridors along rivers and streams are especially important for connectivity in the Champlain Valley and other developed regions. These riparian corridors also provide river resilience from flooding. Another local-scale method to improve forest corridors would be to encourage retention and enhancement of hedgerows and islands of forest across meadows and agricultural fields that could serve as species stepping stones, provided invasive plant species can be managed. Assistance should be given to communities seeking to identify their remaining forest fragments and working to permanently conserve them.

BOX 5. RECOMMENDATIONS: *OAK-PINE-NORTHERN HARDWOOD FOREST ADAPTATION STRATEGIES*

- Retain or establish species with high nutrient cycling capability (aspen and Rubus) as one component of the Oak-Pine communities.
- Include soil scarification when harvesting to promote the establishment of oak and white pine, where site conditions are appropriate.
- Use silvicultural practices that enhance conditions for the establishment of oak and pine while maintaining the full suite of species found in any specific natural community.
- Identify and manage refugia across the landscape of Oak-Pine-Northern Hardwood communities. Use of passive or active management depends on the ownership objective, but with ecological functions taking priority over timber production.
- Establish reserves to conserve mature, high-quality example of all natural communities in the Oak-Pine Forest formation.
- Manage degraded Mesic Clayplain Forests and Sand-over-Clay Forests to restore their structure, species composition, and ecological functions.
- Maintain species diversity including trees, shrubs, and herbaceous plants that is characteristic of each natural community type, but also allow for additional native species to become established that may be the result of climate change induced species shifts.
- Favor retention species at the north edge of their range that may be better suited to future conditions (i.e., oaks, hickories, and white pine).
- Retain long-lived species as biological legacies (all species of hickory, oak, and northern white cedar, as well as native pine).
- Retain unusual tree species as biological legacies (pitch pine, chinkapin oak, scrub oak, black oak, scarlet oak, chestnut oak, and pignut hickory).

VII. Monitoring

Post-harvest monitoring should be implemented to evaluate the effectiveness of adaptation strategies. This would include monitoring the effectiveness of erosion control measures and evaluating success in meeting silvicultural goals. Clearly defining goals and thresholds for success for each adaptation strategy will help identify what measurements to include in a monitoring system.

MONITORING FOREST CHANGE IS PART OF ALL FOREST ADAPTATION STRATEGIES.

BOX 6. RECOMMENDATIONS: *MONITOR EFFECTIVENESS OF ADAPTATION STRATEGIES*

- Choose a cost-effective suite of indicators that are likely to detect change.
- Use indicators that are likely to be early signals of change (species or processes):
  - ✓ *Early regeneration success (<6 years post-harvest)*
  - ✓ *Dieback and mortality of overstory trees (not related to residual damage)*
  - ✓ *Frequency of species at the edge of their range (northern or southern)*
  - ✓ *Frequency and intensity of disturbance agents (pests, drought, fire, invasive plants*)
- Identify your definition of "effective" for each adaptation strategy, either at a landscape or stand level.
- Establish science-resource manager partnerships to better understand change or predict management outcomes.
- Include other ecosystem services as part of the monitoring (i.e., carbon storage).
- Monitor public perception of climate change impacts and adaptation strategies to determine "social effectiveness".
- If you determine that an adaptation strategy was not successful (effective), decide when and how to intervene.
- Develop a method for integrating monitoring results into the next forest management cycle.
- Broaden monitoring of landscapes. This may require landowner cooperatives or state-initiated partnerships to develop a network of monitoring for climate change impacts and adaptation.

VIII. Building Resilient Landscapes

Vermont's forested landscape is a network of hills and valleys, mountains and plateaus. Species tend to grow in micro-climates of this complex landscape according to their optimal growing conditions and in response to competition from other species. Biological features such as tree species composition and distribution are likely to shift with climate changes, but the physical characteristics of the land will remain mostly unchanged. Several maps of forest lands that use physical features that have been developed for Vermont [*The Biophysical Regions of Vermont* (Thompson and Sorenson 2000), nine regions of the state identified by their geology, soils, and climate] may depict where vegetation will change, resist, and recover from climatic events and provide an opportunity for landscape planning for climate change response. At a finer landscape scale, the Land Type Associations for Vermont uses areas according to similarities in glacial landforms, bedrock, soil parent material, hydrology, and pre-settlement vegetation and may be useful in determining suitable habitats for tree species (Vermont Agency of Natural Resources, Department of Forests, Parks & Recreation, Division of Forests 2010) (Anderson, Clark and Olivero Sheldon 2012). The new ANR BioFinder map (http://biofinder.vt.gov/) uses both of the aforementioned maps, along with other factors to identify and rank unique and important areas of biodiversity across lands and waters of the state.

In their 2010 paper "Conserving the stage: Climate change and the geophysical underpinnings of species diversity", Anderson and Feree state, "If geophysical diversity does drive regional diversity, then conserving geophysical settings may offer an approach to conservation that protects diversity under both current and future climate. Protecting geophysical settings through land conservation will conserve the stage for current and future biodiversity and may be a robust alternative to species level predictions" (Anderson and Ferree 2010).

In addition, in 2001 the Vermont Biodiversity Project proposed that to conserve Vermont's biodiversity in the face of a changing climate and landscape, conservation of "a full representation of the mountains, cliffs, clayplains, and moist hollows that give Vermont its physical beauty and diversity is needed" and that land conservation is currently not balanced by region and geophysical features. Both projects recommend conservation of a full representation of geophysical settings as a critical step in allowing natural systems to adapt and migrate in responses to climate and landscape level stresses.

Unlike geophysical maps, groupings of natural communities (Thompson and Sorenson 2000) or forest types (Morin, et al. 2011) will likely change in the future. Each tree species has unique characteristics and a range of environmental conditions that are required for growth. The adaptability of species will vary as temperature and precipitation affect growth and reproduction. Each individual species in each physical setting is likely to respond differently from other species, changing current species associations. For the near future, however, the authors believe many of these associations will continue to be a valid management framework. In this guide the authors chose to assess climate adaptation and silviculture of individual tree and the broad natural community formations.

Box 7. Recommendations: *Maintain Forest Blocks and Connectivity*

- Increase funding specifically for forest land conservation, such as through the Housing and Conservation Fund.
- Aggregate large, unfragmented blocks of forest from several ownerships and give these a high priority for conservation easements.
- Identify and conserve critical linkages between large habitat block and along riparian corridors to maintain a connected landscape.
- Assist regional and municipal planning groups with strategies to encourage the retention of forest blocks and areas that connect these blocks.
- Provide funding and/or professional assistance to towns to identify local habitat corridors.
- Facilitate assisted migration of locally occurring species by encouraging nurseries that use local provenances to grow stock for outplanting. Note: This recommendation is more aggressive than maintaining resilience.
- Plant native tree species appropriate to each planting site to enhance forest connectivity, riparian functions, and increase carbon sequestration.
- Increase multi-parcel stewardship efforts through cross parcel boundary management planning.
- Engage users of the forest (e.g., outdoor recreation groups) in promoting conservation of primary wildlife habitat or trail sites through easements and permanent protection as another means to keep forests forested.
- Develop public and private programs that provide payments to private forest landowners for passive and active management practices that keep forests forested and provide other ecological services such as clean water and biodiversity.
- Strengthen the forest-based economy of Vermont that supports quality jobs and dynamic rural economies through promotion and marketing of wood products, and supports incentives for capital investment in new value-added technologies for forest products and thermal energy applications.

A. Connectivity as a Strategy for Climate Adaptation

The Northern Forest—which ranges from the Tughill area of western New York through the Adirondacks, Vermont, New Hampshire, and Maine and north through Quebec and New Brunswick to the tip of Nova Scotia—remains one of the most intact temperate forests in the world. The integrity of this forest is evidenced by the ability of animal species to move through the landscape, keeping populations viable and thriving. Connectivity has also allowed populations of wildlife to recover when they were locally extirpated by past land-use practices. The ability for species recovery may suggest that this potential remains for the future as our forests and wildlife adapt to a changing climate. Keeping forest blocks intact and connected is a strategy for species movement and for healthy forest ecosystems.

Maintaining large forested blocks with adequate corridors for animal and plant movement is an important landscape resiliency strategy.

Land ownership in the Northeast is primarily in the hands of small non-industrial private landowners. In Vermont this proportion of ownership is around 80%. Private lands are frequently subject to economic pressures and have a high incidence of ownership turnover as well as subdivision. Strategies are needed to facilitate maintaining large blocks of forest on both public and private lands.

Large forest blocks tend to house the greatest number of wildlife species, particularly wide-ranging mammals and the more wilderness-associated species such as black bear, lynx, fisher, bobcat, and moose. Large blocks of forest are also important for species that move more slowly through the landscape and perhaps do not move more than a mile in their lifetime. An example of meta-population movement is amphibians that rely on vernal pools for reproduction. Under normal conditions, vernal pools are not successful on a yearly basis and so having a sufficient number of pools is essential for long-term viability of a population. As one pool disappears due to development or perhaps climate change, animals may migrate further to find adjacent pools facilitating genetic mixing and long-term success of the population as a whole. Alternatively, if species become too isolated from loss of habitat they may no longer be able to reach new pools. This example holds true for a variety of habitat types and species requirements. Large blocks of forest also have a lower incidence of invasive species that are usually associated with forest edges, urban landscapes, and former agricultural fields. Tree, shrub, and herbaceous species diversity can be great in large blocks of forest due to their large variation in soil, topography, microclimate, and site productivity. Diversity may allow forests to maintain resiliency as climate change brings conditions impossible to predict. Plant species movement is slower and perhaps less predictable than wildlife populations but seed source availability is certainly a prerequisite. Some wind-dispersed seed may be carried great distances but large-seeded plants rely on gravity, water, or wildlife movement to move across the landscape. Seed dispersal can also depend on maintaining intact mycorrhyzae and insect species associated with dispersal and establishment. Keeping our large forest blocks intact is a critical strategy for maintaining healthy forests. Protecting the stage (i.e., large forest blocks) may be the most important step we can take to enhancing resiliency of our forests. The ANR habitat block project identifies 4,053 forested blocks statewide, ranking each block according to multiple biological and physical landscape features and is a helpful tool for evaluating the relative importance of habitat blocks (Austin, et al. 2013).

Connecting blocks is important to successful forest migration. Throughout the Northern Forest our landscape is fragmented by roads, agriculture, and development. Some areas of the Northern Forest that include large blocks of forests are separated from other large blocks. Linkages have been identified and ranked based on ecological importance and risk of loss through development or degradation. The protection of these forest links is essential to the long-term integrity and viability of the Northern Forest. This concept is equally important at a more local level as communities work to protect natural resources in their own backyards. Protecting the resource locally is the first step in protecting the greater landscape. This important work is being done by foresters, landowners, town planners, recreation enthusiasts, and all the lovers of wild places. Recommendations for further protecting the stage include funding permanent conservation easements for large blocks of forest and connecting corridors through aggregation of private lands that allow connectivity across landscapes. The ANR's BioFinder project identifies a "network of connected lands" that includes a subset of the habitat blocks and riparian corridors (see http://biofinder.vt.gov/).

The connected forests of the Northeast also have an essential role in maintaining the region's biodiversity into the future. Although the many public and private conservation lands (parks, natural areas, ecological reserves, etc.) are central to this, the extensive working forests that connect them across the landscape are equally important if species are to successfully change distribution and abundance through time (Jacobson 2009).

IX. Timber Management Considerations

General goals for forest management can be considered at both stand and landscape scales. Managed forests are an important and common feature of Vermont landscape. Land use; herbivory; and introduced plants, insects, and pathogens have been a challenge for managers for decades. Adding climate uncertainty and impacts to this situation presents major challenges to managers attempting to create productive and resilient forests of native species.

Alterations in temperature and precipitation patterns expected under climate change can impact forests in several ways. These changes may include shifting distributions of tree species and wildlife habitats, increases in the frequency and magnitude of disturbance events, introducing new and/or intensifying the impacts of invasive and non-native species, altering the economic contributions of forests to the economy, and changing the way the public uses and values forest lands.

Responsible management of Vermont's forests is a critical component of maintaining the rich biological diversity of the state, along with special attention to conserve high-quality examples of all natural community types, special habitats, aquatic resources, and physical landscape diversity.

MANAGING FORESTS TO IMPROVE SOIL HEALTH INCLUDES LEAVING DOWN WOODY MATERIAL.

A. Soil Productivity

Forest soils provide the foundation for the productivity of any forest. Over much of Vermont our forest soils have been greatly affected by human activities such as land clearing, erosion, compaction, nutrient and organic matter depletion through practices associated with subsistence agriculture, high-grade logging, biomass harvesting, development, pollution, and climate change.

Natural forest soils are a product of the mineralogy of native soil parent material as impacted by climate, vegetation, and soil organisms over long periods of time. Soil texture, fertility, organic matter content, moisture-holding capacity, and rooting depth all impact tree growth and productivity.

The forest soils that we work with today are quite different than pre-settlement forest soils. Just as the pre-settlement forest had larger trees and more complex structure than our forests today, pre-settlement forest soils tended to be deeper, richer, and more complex, with more structure, incorporated organic matter, and higher nutrient levels. Although there has always been great variability in soils, we know that pre-settlement forest soils generally had more surface organic matter, more coarse woody debris in the forest floor, thicker A horizons (exclusive of plow layers), greater capacity to hold water and plant nutrients, and more diverse microbial populations than the forest soils of today.

The changes that took place in these soils as the land was cleared for agriculture were dramatic and rapid. Most trees were harvested or girdled, and although some were used to construct the buildings of the new agrarian society, most were ultimately burned either to generate heat or produce potash, or simply removed to eliminate overhead cover from the site quickly. Sometimes the stumps were pulled and used as fences or were burned. Erosion was widespread as hillsides were stripped bare of vegetation and tilled (sometimes across the contours) or left fallow and exposed to rain and snowmelt events. With less vegetation occupying the open land than had been the case in the forest, less moisture was taken up by vegetation and more water was available to move over or through the soil. Surface soils and leaf litter that were suddenly exposed to the sun experienced increased rates of decomposition. Without the protection of overhead cover, rain events or spring snowmelt led to soil movement. More water movement through and out of soils concurrent, with more rapid decomposition of soil organic matter, led not only to loss of mineral soil, but also loss of associated soil organic matter and nutrients. System vegetation (trees and understory plants) was dramatically diminished, followed by loss of soil organic matter, soil organisms, and soil nutrients during the conversion to agriculture. Once new vegetation (principally grass) was established, soils stabilized, but long-lasting damage had been done that persists today. Rebuilding soil biomass can be accomplished at each rotation by leaving an abundance of organic matter (leaves, tops, branches, boles, and roots) on-site. Because tree biomass increases exponentially with tree age, to increase soil organic matter old or large trees need to be carried longer. When they die they replace much more organic matter than do many small trees

BOX 1. CONSIDERATIONS: *WHY BUILD HEALTHY SOIL*

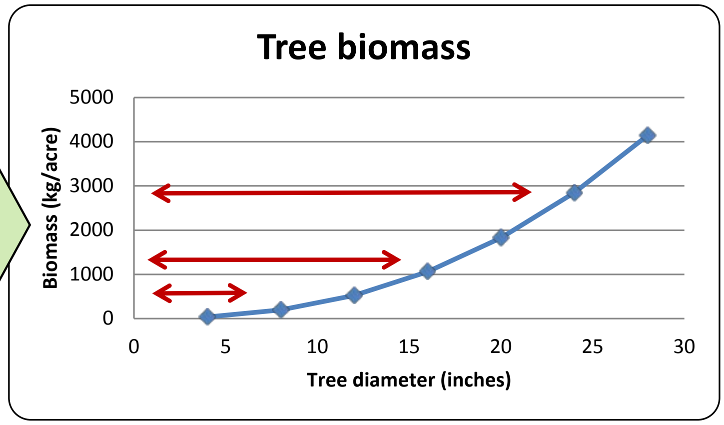
- Leaving dead trees as snags or down woody material builds soil organic matter, improves available nutrients, and increases water-holding capacity of soils to guard against drought.
- Feeding soil by leaving large diameter trees as down wood further improves the site for tree growth and forest resiliency.

BOX 8. RECOMMENDATIONS: *MAINTAIN SOIL PRODUCTIVITY*

- Implement forestry practices that tend to increase the vegetative biomass retained on site.
- Maintain higher residual basal area after treatments to moderate temperature and moisture fluctuations in forest soils. This is especially important when invasive earthworms are present.
- Encourage the establishment and maintenance of healthy, native herbaceous vegetation as a safeguard to protect soil integrity; information is lacking on how plants and forest floor organisms will be affected so maintaining diversity at this level is prudent.
- Promote more complex forest structure with the proper mix of native tree species, abundant down woody material, standing dead trees, and large trees that can ultimately be recruited into down woody material of the future as a way to build soil health and therefore soil resilience.
- Negative soil impacts include rutting, compaction, and erosion. Assess soil capabilities and conduct harvests to minimize negative impacts. Utilize available mitigation techniques such as geotextile fabric, tire sidewall mattes, and tracked machinery. Time harvests in sensitive areas carefully with flexibility to take advantage of mitigating conditions such as deep snow or frozen ground.
- Building soil health includes promoting native species regeneration, therefore attempt to control invasive plant infestations and manage populations at acceptable levels.

BOX 2. CONSIDERATIONS: *WHY GROW LARGER TREES*

Example of how the quantity of soil organic matter biomass is dependent on the size of trees left as down woody material onsite following a harvest. Trees accumulate biomass exponentially as they grow so trees left to reach large diameter sizes, then left as down woody material contribute more to building soil organic matter than many rotations of smaller diameter trees as down woody material. Arrows show differences between trees of 8-, 16-, and 24-inch diameters in biomass and therefore potential soil organic matter recruitment.



B. Property-Level Management

Major adjustments to goals, objectives, and implementation at the property level are anticipated as managers adjust to a rapidly changing environment. General adaptation strategies include site, species, and operational considerations. Changes in climate will need to be matched by changes in forest management.

Adapting to climate change consists of developing strategies and management options that will help landowners plan and prepare for the changing climate to ensure that forests continue to provide benefits for future generations.

Consider diversification as a first step in forest adaptation. The more healthy trees of diverse species that we have growing in our forests, the more options we have for management planning now or in future years. Those trees that we do not harvest will ultimately die and transition to snags or coarse woody material, then to soil organic matter. Soil organic matter is a critical source of plant nutrients and acts as a platform to hold nutrients and water in soil long enough that they may be taken up by the roots of plants. More soil organic matter generally leads to better soil aeration, greater rooting depth, and improved soil structure. In all of these ways more soil organic matter leads to better growing conditions and more potential to grow healthy trees. The more above-ground biomass we carry in our forest, especially in some very large-diameter trees, the more recruitment we have of soil organic matter and the greater likelihood that our forest soils will improve over time, resulting in still-healthier forests. Where owner objectives or site, species, or operational considerations do not support this approach, consider managing a portion of the trees in the forest for timber and the remainder for other objectives.

Sustainable management strategies that maintain species as well as structural and age class diversity are important in the face of climate change. Diversity strategies can create a mosaic of habitats for existing wildlife species and new species that may shift into the area. Stands with a diversity of species and age classes are less vulnerable to climate impacts, protect against widespread damage and financial loss due to disturbance events, and create economic opportunities by including managing for species that are well suited to changing climatic conditions (see *IV. Natural Community Adaptation Strategies* for more detail).

A shortened winter-logging period, an extended mud season, and increasingly frequent and severe storm events are likely to reduce the number of days with conditions favorable for timber harvesting, increase logging costs as machinery sits idle during marginal and unfavorable conditions, and increase pressure on forest managers to operate during marginal or unfavorable conditions, risking damage to soil and water quality. A recent survey of logging businesses in the Northern Forest concluded that weather conditions were overwhelmingly cited by logging businesses as the most important limitation to achieving maximum production across all four states (Maine, New Hampshire, New York, and Vermont) and all business sizes (Leon 2012) (see *C. Forest Operations and Water Quality* below).

Warmer winters can increase survival of forest pest. In general, keep abreast of new forest pest developments (see www.vtinvasives.org). Currently, infestations of HWA and temperature stress have profoundly negative implications for the long-term survival of hemlock (see *G. Forest Pest* below).

Climate change predictions include increased frequency and intensity of widespread disturbances from weather or fire episodes that result in injury or death of canopy trees and loss of economic value.

As winters warm and the depth and duration of snow cover decreases, population size and deer density will likely increase. Increased deer populations can damage vegetation, interfere with forest regeneration, perpetuate invasive plants, and increase the abundance of deer ticks. In areas where invasive plants have taken advantage of gaps in regeneration as a result of heavy deer browse, an increase in rodent populations and incidence of Lyme disease may be more likely (see *E. Herbivory: Deer, Moose, and Forest Regeneration* below).

BOX 9. RECOMMENDATIONS: *PROPERTY-LEVEL MANAGEMENT*

Conduct operationally sound timber harvests

- Create infrastructure that can withstand a variety of weather conditions.
- Promote low-impact harvesting techniques and equipment to minimize potential site impacts.
- Use seasonal weather forecasts to understand probable conditions and plan operations.

Be aware of and plan for threats facing hemlock stands due to HWA

- Keep abreast of HWA in Vermont and on site.
- Reduce risk of introduction and spread of HWA.

Create and maintain complex vertical and horizontal forest structure and improved soil productivity

- Improve soil productivity by maintaining substantial organic matter as coarse woody material.
- Strive for higher residual basal areas and volumes and carry some trees to very large diameters.
- Maintain species, structural, and age class diversity.

C. Forest Operations and Water Quality

Climate change predictions suggest that forestry operations in Vermont will be significantly affected by temperature increases and changes in precipitation patterns. Reduced winter logging periods and increased spring and fall mud seasons combined with increased heavy precipitation events will require adapting harvesting practices and infrastructure to maintain forest product economies while ensuring water quality protection.

Managers should develop strategies to minimize impacts to the site prior to the actual timber harvest. Sensitive areas need to be identified on the ground and roads, landings, and skid trails need to be planned in advance. Specific techniques for dealing with a particular element of a site should be described and included in a timber sale contract.

1. Operational Considerations.

Extreme precipitation events create the need for higher standards for how skid roads are created, used and maintained. Warmer winters with fewer days of frozen ground require adequate planning for a reduced operability calendar (Spittle and Stewart 2003). Short-term drought periods in summer and early fall can be taken advantage of to access marginally operable sites if operators are able to remain flexible.

Caution should be exercised though as drought periods can lull operators into complacency in installing and maintaining erosion-control devices critical for heavy precipitation events. Climate changes increase the necessity to match the appropriate harvesting system to the site.

Studies show that high rates of cutting in forested basins that result in more than two-thirds of a basin in young forest (0-15 years old), or in combination with agricultural land increase peak flows (Verry 1997). Consider maintaining older stand size-classes at or above B-level stocking within watersheds above this one-third threshold.

2. Truck Roads Considerations.

Poorly designed and/or maintained roads or excessive road networks can destabilize landforms, alter hydrology, increase sediment production, and accentuate flood flows (Lindenmeyer 2002). Road networks should be limited such that ditched roads are less than 15% of a basin (Verry 1997). Consider decommissioning unnecessary or poorly constructed or situated roads. Culverts on low-use roads should be removed when harvesting activities are completed. If they remain to accommodate recreation, they should be left in a manner that reduces erosion and subjected to periodic maintenance. When planning new road construction, pre-plan potential routes considering topography, slope, soil types, drainage, and water features to minimize impacts of location. In the field, consider layout using a soil auger. Bright-colored soils drain well and it is acceptable to make road cuts with deep ditches, whereas soils that are primarily black and gray have a tendency to slump, requiring ongoing maintenance.

Consider weather and ground conditions when scheduling road building. Avoid construction during wet seasons/periods and plan culvert and bridge installation during summer months when stream flows are lowest.

BOX 10. RECOMMENDATIONS AND CONSIDERATIONS: *TRUCK ROADS*

- Climate change increases the likelihood of heavy precipitation that could adversely affect timber road and operational infrastructure.
- Restore natural hydrology and land stability by reducing the number of ditched roads (less than 15% of a basin), decommissioning unnecessary roads, and removing culverts after harvest operations on low-use roads.
- Avoid building gravel roads with ditches below groundwater table.
- Line ditches with coarse stone for stabilization and to trap sediment.
- Avoid road construction during wet weather and avoid bridge or culvert installation when stream flow is high.
- Stream-crossing infrastructure is best installed with abutments placed outside of bank-full-width.
- Portable, temporary truck bridges are a cost-effective option for stream infrastructure.
- Use of stone-lined overflows adjacent to brook culverts can improve water flow during storm events.
- Road closeouts following a harvest should be completed immediately after harvest completion to reduce the risk of soil erosion and sedimentation.

When replacing stream culverts, evaluate whether their size is sufficient to handle increased precipitation or whether it would be more prudent to replace them with bridges whose abutments are beyond bank-full-width. This type of work generally requires a stream alteration permit. Side-by-side culverts are ineffective in enhancing capacity, become plugged more frequently, and are therefore discouraged. Logging contractors should consider purchasing/using portable temporary truck bridges as they offer the advantage of being reusable and save on maintenance costs associated with permanent bridges. As most soil erosion and sedimentation from roads occurs within the first few years after harvest operations, AMPs for road closeout should be implemented before leaving the site for an extended period of time or immediately after a harvest is completed. Additional details are available through the USDA Forest Service (see http://www.na.fs.fed.us/spfo/pubs/stewardship/accessroads/accessroads.htm).

3. Skid Road Considerations.

Existing skid trails may not have been placed in suitable locations. Stabilize or consider closing these and constructing new ones where they will afford better water quality protection.

When planning skid road locations, pre-plan potential routes considering topography, slope, soil types, drainage, and water features to minimize impacts of location. Perform skid trail layout during bare-ground conditions. Proper layout will reduce the number of AMPs needed to stabilize trails following operations, saving time and money while preventing erosion.

Maintain reinforced waterbars on steep slopes during operations. Stabilize skid trails before rutting begins using brush and/or corduroy. Corduroying skid trails with tops and woody debris laid perpendicularly to the trail is far more effective than material laid parallel to the trail. Consider including in your timber sale contract a requirement that skid trails be pre-built and stabilized and have a chance to freeze-in before skidding begins to minimize erosion and rutting.

Inspect and repair erosion-control devices on a regular basis to ensure that they remain functional. Wait an appropriate number of days after heavy rains for soils to properly drain. This allows the soils to convert from mud to a condition which will again support equipment. Consider using temporary timber mats and/or slash mats where weak soils are unavoidable.

As a first choice, use temporary skidder bridges to cross stream channels (see http://fpr.vermont.gov/forest/your_woods/harvesting_your_woodlots/skidder_bridge).

Trends toward increasing heavy precipitation events may decrease the effectiveness of poled-ford and frozen brushed-in crossings in winter. Expect increases in winter precipitation as rain will render these crossings ineffective in handling the higher flows. If using poled fords, limit their use to ephemeral or intermittent streams. It is critical that these crossings be removed at the completion of operations and prior to spring breakup.

Consider using delayed skidding in winter to allow skid roads ample time to freeze. When whole-tree harvesting, use topwood material where needed to armor wet or unstable sections of trails, provided doing so follows AMP and Wetland Protection Rules (see http://www.watershedmanagement.vt.gov/rulemaking/htm/rules.htm).

BOX 11. RECOMMENDATIONS AND CONSIDERATIONS: *SKID ROADS*

- Extreme precipitation events create the need for higher standards for how skid roads are created, used and maintained.
- Assess suitability of existing skid trails and replace where this will improve water quality protection.
- Plan skid trails using soil survey maps and perform layout in bare-ground conditions.
- Preemptively stabilize skid trails using brush and/or corduroy by using a tracked dozer to freeze skid trails and/or by using timber mats and/or slash mats where weak soils are unavoidable.
- Avoid erosion by maintaining reinforced waterbars during operations, by delaying harvests an appropriate number of days following heavy rains, and by using temporary skidder bridges to cross stream channels.
- Limit use of poled-ford and frozen brushed-in crossings in winter as these will be ineffective in projected climate conditions.
- Special considerations may be needed for whole-tree harvests to use topwood material to build trails before building the chip pile.

4. Forest Management in Wetlands.

Wetlands are important for their ability to filter sediments, help control floods, recharge groundwater, and improve water quality. Wetlands may be forested (such as white cedar swamps) or non-forested (such as scrub-shrub wetlands) and include small or ephemeral areas such as seeps. Increased precipitation heightens the importance of maintaining the functions and values of wetlands. You may refer to and can follow the Wetland Rules for Vermont (see http://www.watershedmanagement.vt.gov/rulemaking/htm/rules.htm).

Reductions in winter freezing means greater care is needed in riparian areas.

Box 12. Recommendations: *Maintain Water Quality During Forest Operations*

- Use a timber sale contract to provide written documentation of how the timber harvesting is to be performed and any specific steps that are needed to address operational modification (LeDoux 2011).
- Involve the harvesting contractor and crew in the discussions on minimizing impacts and why it is important. Explain clearly what post-harvest conditions should look like.
- Minimize negative impacts of disturbance events by identifying stands or areas within stands that are most vulnerable to disturbance events (fire, wind, drought) and manage them early (i.e., young) to improve vigor and resistance.
- Monitor regeneration and invasive species after stand-replacing events and address invasive plant management where needed to protect regeneration.

5. Forest Management in Riparian Areas.

Riparian areas consist of both the aquatic and terrestrial ecosystems of streams, rivers, lakes, ponds, and wetlands. The forested buffer zone is the transitional area between surface water and uplands and has highly variable widths or boundaries. Flood control, stream channel migration, stream flow regulation, sediment filtration, and water temperature regulation are all values and functions of healthy riparian areas that will be affected by climate change. Impacts will be more frequent heavy precipitation events, high-intensity and large-magnitude disturbance events, year-round increases in average temperatures, and more short-term drought periods.

Box 13. Recommendations: *Forest Management in Riparian Areas*

- Manage riparian zones with the primary goal of protecting water quality with management for timber and other uses secondary only where and when appropriate.
- Retain stream-side shade by maintaining a minimum of 60% crown closure.
- Designate riparian zone boundaries prior to harvesting and include specific management provisions for them in the language of the contract.

D. Operational Monitoring

Monitoring during the actual operation (a.k.a., timber sale inspections) is frequently performed by the forest manager to assess ongoing harvesting operations and to ensure that the conditions of the sale are being met. Harvests should be visited regularly and shut down during rainy periods or winter thaws when ground conditions are unstable. There is an opportunity to observe and learn if a particular technique is working or not. If heavy rains are predicted, operators should expect to take measures to avoid erosion, including installing temporary waterbars, culverts, or diversion structures.

Box 14. Recommendations and Considerations: *Operational Monitoring*

- Climate changes increase the necessity to match the appropriate harvesting system to the site. CTL systems are generally advantageous because they use tracked transport machines (which reduce site impacts), offer efficient mechanized operations, and reduce fuel use.
- Drought periods can rapidly change to flood so it is essential that erosion control precautions are in place during all harvest operations.
- Flooding can be reduced within a forested basin with harvest planning that maintains B-level stocking on at least one-third of the area.
- Because climate change increases the need for operational oversight, document operational strategies and techniques that work well for use in the future and identify those where improvements can be made. Make notes for any follow-up. Consider documenting the site with using digital photos.

E. Herbivory: Deer, Moose, and Forest Regeneration

The impacts of excessive deer browsing in lower elevations and moose browsing in upper elevations and northeastern regions of Vermont have been notable for many decades. Combined with other influences such as beech bark disease, silviculture and landscape changes have contributed to shifts in species composition in some regions of Vermont. The Vermont Fish & Wildlife Department has made significant progress in balancing moose and deer populations with resource conditions, and some land managers have increased their use of regeneration harvests to encourage the growth of desired reproduction. As changes in our climate and landscape accelerate, more significant adaptation of policy and on-the-ground management will be needed to counteract the likelihood that changing climates favor white-tailed deer population expansion and the success of vegetation that competes with more desirable forest regeneration.

The Pinchot Institute assessed population management decisions in eastern states, "Managing deer in the commonwealth: A study of other states", and concluded that very few eastern states use forest vegetation or ecologically based goals in deer management decision making (Shiddler 2009). With new climate change pressures, a greater focus on regeneration success should be incorporated into wildlife population management and silvicultural prescriptions. In addition, a number of on-the-ground practices are recommended for maintaining or creating native plant diversity in the forest understory in anticipation of climate stresses and associated negative impacts that could exacerbate existing regeneration problems in some regions of Vermont. The experience of Vermont foresters indicates that there are a number of silvicultural techniques which have been successful in regenerating native species in areas of moderate-to-heavy deer browsing. Recent studies throughout the region have lent credence to vegetation management strategies. The "White-tailed deer herbivory and timber harvesting rates: Implications for regeneration success" research project in the central Appalachians found that heavy browsing impacts dropped substantially when the 0 to 10-year-old age class reached 14% of the 4,000 hectares.

However, the potential for success is reduced dramatically where excessive browsing is a historical problem and/or exotic invasive shrubs are common or expanding. High deer densities can reduce understory vegetation such that it is unable to recover for decades (Nuttle, Ristau and Royo 2014). In these cases more aggressive and specific restoration efforts may be needed. To ensure that forests grow a native suite of tree and plant species which are thought to be inherently more adaptable, the goal should be long-term solutions that provide good habitat for deer or moose and diverse, native forests that are self-perpetuating.

BOX 15. RECOMMENDATIONS: *STRATEGIES THAT ADDRESS WILDLIFE HERBIVORY*

Statewide

- Continue efforts to balance hunter satisfaction and forest health with a focus on aggressively controlling populations where native regeneration success is hampered by overbrowsing.

- Modify forest regeneration harvests by introducing silvicultural techniques to manage competing vegetation and prescribe silviculture that matches local conditions (i.e., competition and browse pressure on regeneration).

- Support the following actions outlined in the Vermont Fish & Wildlife Department's Big Game Management Plan 2010-2020:
  - ✓ *Maintain and evaluate regional population goals, established during this planning period, that are based on deer densities that recognize a lower limit that is unsatisfactory to the public and an upper limit that is ecologically unsustainable.*
  - ✓ *Use existing data-driven methods for assessing localized deer overabundance problems that might lead to development of localized deer-management methods. Data must provide measures of forest condition, not just deer nutritional carrying capacity.*
  - ✓ *Where deer are found to be problematic for successful forest regeneration, reduce populations.*
  - ✓ *Provide outreach to landowners regarding methods that may minimize damage and encourage reduction in locally overabundant deer populations. Expand the formal program to connect hunters with landowners to address locally overabundant deer populations.*
  - ✓ *Evaluate feasible options to expand antlerless deer-only hunting opportunities prior to the regular rifle season. These options will include, but are not limited to, an early muzzleloader season, expanded archery season, and increased archery bag limits.*
  - ✓ *Encourage communication and cooperation between antlerless deer hunters and landowners that seek relief from locally overabundant deer.*

- Develop a study to assess the (ecological) carrying capacity for moose and deer on Vermont's forest land.
- Public and private foresters should encourage the incorporation of the US Forest Service Forest Inventory and Analysis program's understory results as part of deer and moose population planning by the Vermont Fish & Wildlife Department and regeneration planning by land managers.

Localized

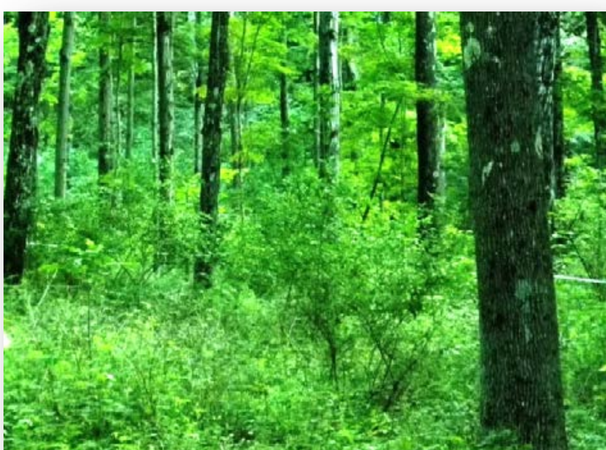
- Engage in cooperative timing of harvests between neighboring landowners to create a flush of seedling and sapling growth over a wide area that can outcompete deer and possible temporary population growth.
- In white-tailed deer browse areas, where large ownerships (or an aggregate of smaller ownerships) permit, increase the use of gap harvests (groups and patch clear cuts) from 1 to 10 acres in size to allow seedlings, saplings, and sprouts to gain height ahead of browsing. Typically a total of 20 acres (in combined gaps over several hundred acres) is needed before regeneration out competes moderate deer numbers.
- Leave tops of trees intact after harvest, particularly over desired deciduous species stumps, to discourage browsing of seedlings and encourage sprout regeneration success.
- Incorporate regeneration surveys into forest planning and pre- and post-harvest inventories on state and private lands.
- Improve hunter access and encourage the taking of antlerless deer in high deer density areas through archery, youth, and muzzleloader seasons.
- Heavily cut areas of northeastern Vermont have experienced expansive regeneration failures due to intensive moose browsing. When harvesting in areas with historically high moose densities, allow for multiple opportunities to regenerate stands.
  - ✓ *If clearcutting, use progressive treatments that leave seed sources around the edges of patches.*
  - ✓ *If shelterwood-cutting, avoid low-density shelterwoods as the first cut. Begin with the first of a three-stage shelterwood cut (light-prep cut). If regeneration fails, successive second-stage cuts, low-density cuts, and finally seed-tree cuts will all provide further opportunities to scarify and prepare the site as well as break up over-browsed saplings in an attempt to cause resprouting.*

F. Invasive Plant Species

Non-native invasive plants are a serious threat to forest regeneration in Vermont. The number of sites and abundance of these plants has been increasing rapidly over the past several years in some parts of Vermont. In some of these areas the quality of forests has been severely compromised. The problem of invasive species may be one of the most serious threats to our natural ecosystems, and climate change will continue to give these plants a competitive advantage. Higher average temperatures are predicted to enable invasive species to take advantage of weakened ecosystems and out-compete native species (Dukes, et al. 2009). Warming climate will allow invasive plant ranges to expand northward. Studies have also shown that increased carbon dioxide levels appear to stimulate the growth of invasive plants (Idso, et al. 1987). Additionally, herbicides may be less effective as carbon dioxide increases in the atmosphere (Ziska and George 2004).

Invasive species are more likely to colonize sites that have been disturbed. Climate change models predict that weather events will be more intense and more frequent, resulting in greater disturbance to our forested landscape. Silvicultural practices may also cause disturbances that benefit invasive species, and harvesting equipment can transport invasive plants from one area to another. Climate change may also disrupt the amount and seasonal distribution of precipitation, stressing our native flora and allowing invasive species another competitive opportunity. Lastly, the increased browsing by white-tailed deer exacerbates the spread of invasive plant species by limiting the success of native plants.

Non-native invasive plants can cause great harm to our ecosystems by replacing native species, interrupting natural succession, decreasing forest regeneration, disrupting the food chain, degrading habitat, hastening erosion, and changing soil chemistry. Invasive species have characteristics that make them extremely competitive with our native



NON-NATIVE INVASIVE PLANTS HAVE BEEN VERY SUCCESSFUL IN RESPONSE TO RECENT CLIMATE CHANGES.

BOX 3. CONSIDERATIONS: *INVASIVE PLANT SPECIES*

- Non-native invasive plants can cause great harm to our ecosystems by:
  - replacing native species
  - interrupting natural succession
  - decreasing forest regeneration
  - disrupting the food chain
  - degrading habitat
  - hastening erosion
  - changing soil chemistry

- Invasive species have some of the following characteristics that make them extremely competitive with our native species:
  - Produce abundant viable seed.
  - Engage in seed germination and leafing out earlier in the spring and retain leaves later in the fall, which afford a photosynthetic advantage.
  - Have few pests and disease.
  - A possible source of chemicals that inhibit growth of native plants.
  - Successfully grow in a variety of soil types, moisture regimes, and light conditions, often producing mono-cultures over large areas and limiting diversity.
  - Reproduce both sexually and vegeta-tively.

species. Some of these common characteristics include the production of abundant viable seed; seeds germinating and plants leafing out earlier in the spring and keeping their leaves later in the fall allowing for photosynthetic advantage; having few pests and diseases; potential production of chemicals that inhibit growth of other plants; success in a variety of soil types, moisture regimes, and light conditions which often produce monocultures over large areas limiting diversity; and reproducing both sexually and vegetatively.

In addition, it has been shown that non-native species, and invasive species in particular, have been very successful in response to recent climate change by adjusting their phenology, specifically their flowering time (Willis and Davis 2010). This adaptability may be an even greater advantage as climate change progresses.

It is imperative that efforts be made to control the spread of invasive plant species as we move toward the novel forest. With no intervention, the invasive species problem could become monumental.

BOX 16. RECOMMENDATIONS: *STRATEGIES THAT ADDRESS NON-NATIVE INVASIVE PLANTS*

- Continue to educate the public (landowners, forester, loggers, landscapers) in the identification and management of invasive species. Encourage annual scouting.
- Strengthen policies to prevent new introductions of non-native invasive plants.
- Dedicate ANR staff and funds for managing invasive plants in upland forests and to track existing and emerging threats of invasive species.
- Prioritize stewardship funding to landowners for invasive plant management.
- Recommend that invasive species assessments and management be incorporated into forest inventory and silvicultural prescriptions.
- Prevent the spread of invasive plants: avoid or limit activity in infested areas without treatment and clean equipment before moving from one site to another; and carry out forest management activities when conditions would limit spread, such as on frozen ground or snow cover.
- Develop an integrated pest management plan to address infestations based on level and severity of infestation, difficulty of control, potential impacts, and feasibility to eradicate or manage.
- When present in a stand, invasive species will need to be controlled at the early stages of infestation. Avoid harvesting before treating.
- Vegetated road edges and medians are often sources of heavy seed production of invasive exotic shrubs and herbs such as glossy buckthorn, Japanese honeysuckle, and wild chervil as well as seed and rhizome dispersal via mowing and construction equipment. Develop, promote, and fund methods of seed source control and develop seed-/weed-free equipment policy, practicing these state-wide for road and land managers.

G. Forest Pests

One of the major studies on forest pest behavior under climate change examined native and non-native insects and diseases (Dukes, et al. 2009). Soft-bodied insects such as the HWA and the balsam woolly adelgid are expected to expand their range and reproduce abundantly as temperatures increase. Insect defoliators, such as forest tent caterpillar that overwinter as eggs, often rely on synchrony between host-tree leaf out and young larvae development. Because spring phenology is already affected by warmer climate, it is expected that these types of insect pests will be at a disadvantage under climate change. Diseases that are widespread and dependent on host-tree vigor and associated tree chemistry, such as Armillaria root rot, will likely become more prevalent in future forests as they respond to tree stress. Many native insects experience high and low population cycles. One of the major management recommendations has been to avoid harvesting during an insect outbreak to reduce additional stress on host trees (Vermont Department of Forests, Parks and Recreation, personal communication). It may be more difficult to predict outbreaks and understand population cycles in the future. Err on the side of caution and use conservative forest management activities when high pest populations are expected.

Other non-native forest pests may be only somewhat influenced by climate but none- the-less will cause irreversible impacts on tree health (Venette and Abrahamson 2010). The emerald ash borer (EAB) must be part of any consideration of forest health. All ash species are susceptible, and when forests are invaded by EAB, forest structure, diversity and processes will be adversely affected. The Asian longhorned beetle is another significant risk to many hardwood forests, but may not impact Vermont's forests if eradication at current out-of-state locations is successful.

Box 4. Considerations: *General Forest Pest Management**

- ❖ Healthy trees are more resistant to insects and diseases, so take all necessary precautions to keep trees vigorous.
- ❖ Postponing silvicultural treatments when damaging pest population levels are expected may reduce tree stress and improve recovery.
- ❖ To avoid transporting unwanted pests living within or on wood material, do not move out-of-state firewood into Vermont.
- ❖ Long-term management goals to build resistance and resiliency should include creating forests with a diversity of species, age classes and structural features.

*For the most up-to-date information on non-native forest pests, see http:/www.vtinvasives.org/tree-pests.

Box 5. Considerations: *Hemlocks and HWA**

- ❖ Healthy hemlocks, growing on deep soils with good water availability, are more likely to survive HWA infestations. Maintain the hemlock component on these sites, release young hemlocks, and avoid significant disturbance.
- ❖ In hemlock stands where softwood cover is critical, consider diversifying species composition by releasing or planting other conifers.
- ❖ Where HWA is present, forest landowners and managers should avoid premature salvage cuts. Infested trees take years to succumb. Premature salvage may have unexpected consequences and will remove the potentially resistant trees. Premature cutting is particularly discouraged in deer wintering areas and near water.

*For the most up-to-date information on HWA, see http://www.vtinvasives.org/tree-pests/.

BOX 6. CONSIDERATIONS: *ASH AND EAB**

- EAB is a significant threat to all ash species. In hardwood stands with ash, focus growth on a variety of species. Where ash exceeds 20% of basal area, reduce the ash component. Residual stand-wide basal area targets should be consistent with appropriate silvicultural guides. Retain other species in greater numbers to maintain adequate stocking if removing substantial amounts of ash. Do not preemptively liquidate and eliminate ash from the forest mix. Where appropriate, continue to manage and regenerate ash.

- A federal quarantine restricts the movement of nursery stock, green lumber, chips, and other woody material of the genus *Fraxinus*, as well as any non-coniferous firewood from EAB-regulated areas. Ash logs have been allowed to move within quarantined areas. Shipping logs from within a quarantined area to a mill outside the area is possible, but requires compliance with quarantine restrictions. Moving firewood is the primary human-caused activity that increases the rate of spread of the insect.

*For the most up-to-date information on EAB distribution and quarantines, see http://www.aphis.usda.gov/plant_health/plant_pest_info/emerald_ash_b/index.shtml.

ASH INFESTED WITH EAB SHOWING BARK BLONDING DUE TO WOODPECKER FEEDING ON INSECTS.

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Glossary

Adaptation: Actions to moderate the vulnerability of forests to climate change, position forests to become more healthy, resistant, and resilient and when appropriate, facilitate ecosystem responses to climate change.

Adaptive capacity: The ability of a system (a forest, species or management) to adjust to changes in the environment, to reconfigure with minimum loss of function.

Adaptive silviculture: Integrating climate change adaptation into silvicultural planning and on-the-ground actions (Nagel).

Adaptive management: A forest management approach for addressing uncertainty through an iterative process of planning, implementation, assessment of success and adjusting the process to improve the chances of successfully achieving forest management goals. It is a tool for learning and improving long-term management outcomes while achieving short-term outcome based on current knowledge.

Assisted migration: One of a variety of methods of actively managing landscapes to develop forests more compatible with a projected future climatic condition. Several synonyms include: translocation (intentional movement of a species from one location to another), assisted colonization (introduction of a species and management to ensure successful establishment), managed relocation (intentional act of moving species, populations, or genotypes to a location outside a target's known historical distribution for the purpose of maintaining biological diversity or ecosystem functioning), and species rescue (a means to rescue species threatened under climate change).

BioFinder: A map and database identifying Vermont's lands and waters supporting high quality ecosystems, natural communities, habitats, and species that was developed by the Agency of Natural Resources and partners to advance stewardship and conservation efforts.

Biological legacies: Living organisms that remain after a disturbance (e.g., a harvest, a natural disturbance) and provide a unique function; a potential seed source for the species and genotypes from past generations; characteristics that improve forest health and/or adaptation to future conditions.

Complexity: landscape, forest: Stand structural complexity is the number of different attributes present and the abundance of each of these attributes (e.g., foliage arrangement, canopy cover, tree diameter, tree height, tree spacing, tree species, stand biomass, understory vegetation, and deadwood). Whereas landscape complexity is a dynamic mosaic of stands at varying stages of development; each stand having a tree age and size structure that benefits certain species' assemblages and differs in the ecosystem services provided.

Conserve the stage: An approach used by conservation groups to identify the geophysical characteristics that control total diversity, locate these characteristics on the landscape, and conserve these locations with the assumption that over long timescales these areas will most likely protect species in current and future climates.

Herbivory: The eating of plants; browse by deer, moose and other forest-dwelling animals.

Landscape connectivity: The degree to which the landscape facilitates or impedes movement among forest patches often based on the physical properties of the forest patches (e.g., size, number, distance between patches).

Mitigation: Steps taken to avoid or minimize negative environmental impacts, and in the climate change context, often referring to actions that reduce greenhouse gases.

Natural community: An assemblage of organisms, their physical environment, and the natural processes that affect them. As the physical environment is altered through climate change, the natural communities as we know them may change.

No-regret forestry: Silvicultural actions that attempt to adapt forests to climate change and promote a favorable forest health outcome regardless of climate impacts.

Novel forest: Association of species in forests without a present-day analog.

Passive management: Intentional forest adaptation that makes use of natural forest dynamics.

Refugia: Areas that are expected to escape ecological changes occurring elsewhere, promoting resilient ecosystems and providing habitat for relic populations. The size of the area, among other characteristics, will determine the likelihood of success in maintaining viable populations of a variety of species.

Resistant: Ecosystems that show little impact from repeated disturbances.

Resilient: Ecosystems that when impacted by low intensity disturbance have the capacity to quickly recover structure and function to levels similar to pre-disturbance condition.

Riparian zone restoration: Refers to a biodiversity, preventing erosion, protecting water quality, providing habitat and wildlife corridors, and protecting in-stream biota health. Restoration efforts are often interdependent with stream restoration projects such as: improving stream structure through physical restoration; removing stream barriers; vegetation restoration; restoration of soil biota (symbiotic myccorhizae, invertebrates, micro-organisms) may improve nutrient cycling and therefore stream water quality.

Silvics: The characteristics that define the life history, growth, behavior and ecology of a tree species and their environmental influences.

Silviculture: The theory and practice of influencing the establishment, composition, quality, structure and growth of forests.

Structure: horizontal, vertical: Vertical structure of a forest refers to the distinct layers including the forest floor, herbaceous and shrub layers, canopy and ages of trees. Horizontal structure refers to the landscape mosaic of forest ages.

Appendix A. Species-Specific Considerations

Tree species native to Vermont are susceptible to changes in climate as predicted through climate change models. Some currently abundant species will be less common, and minor species of our forests may become more abundant. Predictions presented here rely on tree silvics to model suitable future habitat for species under different climate projections. Although not considered in these predictions, each species also has a unique set of pre-existing stress agents that will likewise be affected by changes in climate.

Most research indicates that current natural community aggregations will become disaggregated as each species responds individually to new climatic conditions. Therefore, examining silvics of each tree species provides insights into adaptability and vulnerability under different climate predictions.

Our current understanding of species responses to climate projections comes from work by the US Forest Service (Prasad, et al. 2007). Using climate projections for the northeast they have modeled tree species responses. **Table 1** is an excerpt of Vermont tree species from the USDA Forest Service Tree Atlas (http://www.fs.fed.us/nrs/atlas/ and http://www.nrs.fs.fed.us/atlas/tree/). Each species is rated for current abundance in Vermont, and change in abundance based on expected future climate projections under low-emission scenario and high-emission scenario (i.e., future increases in greenhouse gas emissions and resulting temperature increases). Negative numbers mean reduced abundance and positive numbers mean increased abundance, relative to the current abundance. There remains much uncertainty in these projections, especially for less common species, so forest managers should remain cautious when implementing changes in species composition.

How to Read the Tree Atlas Table

Example: Yellow birch: current abundance is 5.34% of Vermont trees; predicted change under high emission scenario is a 66% reduction; predicted change under low-emission scenario is a 39% reduction in abundance.

Information on species silvics, current stress agents, climate-sensitivities, and overall adaptive capacity are compiled in this appendix. Expert knowledge of the authors on current silviculture was then developed into recommendations for building resistance and resiliency or assisting transitions of 30 species in the novel forest. Selection of 30 key tree species was made based on three criteria: (1) current or projected future abundance, (2) value as a timber species, and/or (3) value ecologically.

This is not an exhaustive review of silvics or stress agents but rather those details thought to be significant to future vulnerability. Additional resources are included in **Appendix C**. It should be noted that the information contained in the appendices may change as additional research improves our understanding of climate predictions and species adaptability. For access to this material and a searchable database, see http://fpr.vermont.gov/forest/ecosystem/climate_change.

TABLE 1. PREDICTED CHANGE IN TREE ABUNDANCE MODELED USING HIGH- AND LOW-EMISSION SCENARIOS FOR 30 OF VERMONT'S NATIVE TREE SPECIES IN ALPHABETICAL ORDER [*FROM* TREE ATLAS FOR VERMONT (Prasad, et al. 2007)]

Common name	Latin name	Current abundance in Vermont (% of trees)	High-emission scenario % change in suitable habitat (Gcm3AvgHiDif)	Low-emission scenario % change in suitable habitat (Gcm3AvgLoDif)
American basswood	*Tilia americana*	0.79	34	10
American beech	*Fagus grandifolia*	8.33	–56	–22
Balsam fir	*Abies balsamea*	7.96	–73	–62
Big tooth aspen	*Populus grandidentata*	0.84	–20	5
Bitternut hickory	*Carya cordiformis*	<0.01	9,500	3,000
Black (sweet) birch	*Betula lenta*	0.77	157	178
Black cherry	*Prunus serotina*	3.19	5	31
Black oak	*Quercus velutina*	0.21	1,695	629
Chestnut oak	*Quercus prinus*	0.2	1,440	600
Eastern cottonwood	*Populus deltoides*	0.06	3,483	1,400
Eastern hemlock	*Tsuga canadensis*	6.2	–32	10
Eastern hophornbeam	*Ostrya virginiana*	2.01	12	1
Eastern redcedar	*Juniperus virginiana*	0.12	3,675	975
Eastern larch	*Larix laricina*	0.02	–50	50
Eastern white pine	*Pinus strobus*	5.1	–29	–13
Northern red oak	*Quercus rubra*	2.13	119	100
Northern white-cedar	*Thuja occidentalis*	1.64	–40	–33
Paper birch	*Betula papyrifera*	3.57	–94	–47
Pignut hickory	*Carya glabra*	0.1	1,530	700
Quaking aspen	*Populus tremuloides*	2.71	–79	–23
Red maple	*Acer rubrum*	11.35	–18	4
Red pine	*Pinus resinosa*	0.33	–36	155
Red spruce	*Picea rubens*	4.7	–58	–51
Shagbark hickory	*Carya ovata*	0.16	644	238
Silver maple	*Acer saccharinum*	0.21	690	381
Sugar maple	*Acer saccharum*	14.28	–50	–32
Sycamore	*Platanus occidentalis*	<0.01	9,700	2,600
White ash	*Fraxinus americana*	4.2	4	22
White oak	*Quercus alba*	0.4	1,143	480
Yellow birch	*Betula alleghaniensis*	5.34	–66	–39

*Gcm3 = global climate model - greenhouse gas emissions and resulting climate changes.

Current abundance (2014) of 30 native tree species in Vermont forests

Major species	Common species	Uncommon species
•sugar maple	•black cherry	•bigtooth aspen
•red maple	•quaking aspen	•American basswood
•American beech	•northern red oak	•black birch
•balsam fir	•eastern hophornbeam	•white oak
•eastern hemlock	•northern white-cedar	•red pine
•yellow birch		•black oak
•eastern white pine		•silver maple
•red spruce		•chestnut oak
•white ash		•shagbark hickory
•paper birch		•eastern redcedar
		•pignut hickory
		•eastern cottonwood
		•eastern larch
		•bitternut hickory
		•sycamore

Changes in suitable habitat due to climate change that may result in changes in abundance for 30 Vermont tree species, based on a high emissions scenario model

Reduced abundance	No significant change	Increased abundance
•paper birch	•white ash	•American basswood
•quaking aspen	•black cherry	•northern red oak
•balsam fir	•eastern hophornbeam	•black birch
•yellow birch		•shagbark hickory
•red spruce		•silver maple
•American beech		•white oak
•eastern larch		•chestnut oak
•sugar maple		•pignut hickory
•northern white-cedar		•black oak
•red pine		•eastern cottonwood
•eastern hemlock		•eastern redcedar
•eastern white pine		•bitternut hickory
•big tooth aspen		•sycamore
•red maple		

CHANGES IN SUITABLE HABITAT DUE TO CLIMATE CHANGE THAT MAY RESULT IN CHANGES IN ABUNDANCE FOR 30 VERMONT TREE SPECIES, BASED ON A LOW-EMISSION SCENARIO MODEL

Reduced abundance	No significant change	Increased abundance
• balsam fir	• eastern hophornbeam	• American basswood
• red spruce	• red maple	• eastern hemlock
• paper birch	• big tooth aspen	• white ash
• yellow birch		• black cherry
• northern white-cedar		• eastern larch
• sugar maple		• northern red oak
• quaking aspen		• red pine
• American beech		• black birch
• eastern white pine		• shagbark hickory
		• silver maple
		• white oak
		• chestnut oak
		• black oak
		• pignut hickory
		• eastern redcedar
		• eastern cottonwood
		• sycamore
		• bitternut hickory

TABLE 2. TREE SPECIES GROWTH REQUIREMENTS

Species	Shade tolerant	Needs full sunlight	Needs moist soil	Drought tolerant	Tolerates low fertility	Needs fertile soil
American beech	X		X		X	
Balsam fir	X		X		X	
Basswood	X		X			X
Big tooth aspen		X		X	X	
Bitternut hickory	X		X			X
Black birch		X	X			X
Black cherry		X	X			X
Black oak		X		X	X	
Chestnut oak		X		X	X	
Eastern cottonwood		X	X		X	
Eastern hemlock	X		X			X
Eastern hophornbeam	X			X		X
Eastern larch	X		X		X	
Northern white cedar	X		X	X	X	X
Paper birch		X	X			X
Pignut hickory		X		X		X
Quaking aspen		X	X			X
Red cedar		X		X	X	
Red maple	X			X	X	
Red oak		X		X	X	
Red pine		X		X	X	
Red spruce	X		X		X	
Shagbark hickory	X			X		X
Silver maple	X		X		X	
Sugar maple	X		X			X
Sycamore	X		X		X	
White ash		X	X			X
White oak		X		X	X	
White pine	X			X	X	
Yellow birch		X	X		X	X

TABLE 3. CLIMATE CHANGE FACTORS AND PREDICTED TREE RESPONSE

Species	Hot summers	Increased winter or spring freeze/thaw	Edge of range	Increased droughts	Increased ozone	Extreme wind	Heavy snow or ice	Increased pest activity	Increased browse	Heavy precipitation
American beech	V	V	^	V^	O	V	V	O	O	^
Balsam fir	V	V	V	V	O	V	O	V	V	V
Basswood	O	O	^	V	O	O	V	O	V	O
Big tooth aspen	V	O	O	O	V	O	O	O	V	O
Bitternut hickory	O	V	^	O	O	O	O	O	V	O
Black birch	O	V	^	O	O	O	V	O	O	O
Black cherry	O	O	^	V	V	V	V	O	O	V
Black oak	O	O	^	O	V	O	O	O	V	O
Chestnut oak	^	O	^	O	O	O	O	O	V	O
Eastern cottonwood	V	V	O	V	V	V	O	O	V	V
Eastern hemlock	V	O	O	V	O	V	O	V	V	O
Eastern hophornbeam	O	O	^	O	O	O	O	O	O	O
Eastern larch	V	O	V	V	O	V	O	V	O	V
Northern white cedar	V	V	V	V	O	V	V	O	V	V
Paper birch	V	O	V	V	V	V	V	V	V	O
Pignut hickory	O	V	^	O	O	O	O	O	V	O
Quaking aspen	V	V	O	V	V	V	O	O	V	V
Red cedar	O	O	O	O	O	O	O	O	O	O
Red maple	O	O	^	O	V	O	O	O	O	O
Red oak	^	O	^	O	O	O	O	O	V	O
Red pine	^	V	V	O	O	O	V	V	O	O
Red spruce	V	V	V	V	V	V	O	O	O	V
Shagbark hickory	O	V	^	O	O	O	O	O	V	O
Silver maple	O	O	O	V	V	V	V	O	V	O
Sugar maple	V	V	O	V	O	O	O	V	V	V
Sycamore	O	V	O	V	V	O	O	O	O	O
White ash	V	V	^	V	V	O	O	V	V	O
White oak	^	O	^	V	O	O	V	O	V	O
White pine	O	O	O	^	V	V	V	O	V	^
Yellow birch	V	V	V	V	V	V	V	V	V	V

V = negative response; ^ = favorable response; O = no significant impact.

American beech

Species characteristics & site preferences

A major species in Vermont forests and among the top 10 in abundance. Regeneration by this species dominates some forests. Very shade tolerant. Site preferences include: pH 4.1-6.0; cooler, moister slopes, but adaptable to and competitive on dry sites. Seldom found on limestone sites, loamy texture soils with high humus, or alluvial bottom lands. Tolerates low nutrient sites, and is competitive regardless of moisture. Genetic variability can be low, as some beech forests can be from single parent as a result of root sprouting; however, some individuals are resistant to beech bark disease. Stomates adapted to open and close quickly depending on light (and also moisture). Lives to 300-400 years.

Current stress agents

Diseases include: beech bark disease, Nectria cankers, 70 decay fungi, Armillaria, and broomrapes like beech drops *(Epifagus virginiana*). Insect pests include: forest tent caterpillar, saddled prominent, fall webworm, variable oakleaf caterpillar(where the preferred host, white oak, is not present), beech scale, oystershell scale. Vulnerable to uprooting on shallow slopes. Tolerant to ozone. Not favored as deer browse. Very intolerant to flooding. Higher than average summer temperatures may be unfavorable for growth. Vulnerable to spring frost.

Guidelines for "Beech Mast Production Areas": http://fpr.vermont.gov/forest/forest_health/insects_diseases.

Vulnerabilities & Adaptability

American Beech is most vulnerable to ice damage, beech bark disease and to forest management strategies that select against or try to eliminate it from stands. Tree architecture and brittle wood have been shown to make it more susceptible to heavy damage from ice loads. It is competitive on dry sites, is at the northern edge of its range in Vermont, and is a successful propagator through root and stump sprouts. Management guidelines for beech bark disease and wildlife have been developed for Vermont.

Regeneration Considerations

Seed crop at 2 to 8-year intervals. Beechnuts require 1 growing season to mature. Seeds fall after 1st heavy frost. Germination requires a cold dormancy. Best on mor or mull humus soils, not flooded. Adaptable to low nutrient sites such as low calcium, so regeneration may have an advantage over species such as sugar maple. Most of annual height growth is between May 10 and June 10.

Silvicultural Recommendations

Maintain American Beech in groves for wildlife, especially where soils are not conducive to timber production. Maintain high stand density where weather is intense to protect stems from damage. In areas with invasive plants, beech vegetative regeneration from sprouting could be competitive.

Balsam fir

Species characteristics & site preferences

A cold-loving species dominating upper elevation forests and areas in northeastern forests of Vermont. Shade tolerant. Grows best on sites with pH 6.5-7.0, but adaptable to lower pHs. Soil moisture is the most important predictor of site index. Can adapt to low fertility. Grows on a wide range of organic and inorganic soils. Grows where mean annual precipitation is between 30-43 inches. Vulnerable to flooding due to shallow roots. Full sun needed. Outcompetes shade tolerant hardwoods. Grows best in the eastern part of its range in southeastern Canada and the Northeastern United States. This area is characterized by cool temperatures and abundant moisture. Genetic variation appears to be clinal and continuous and related to altitudinal gradient and both east-west and north-south geographic gradients. Typically lives to 80 years, but up to 200 years. At 70 years, more or less, more than 50% of trees have root or butt rot.

Current stress agents

Moose browse susceptible in northeastern Vermont, but future moose population may move north. Diseases: Very susceptible to 6 species of root and butt rots. Insect pests: Major pests are balsam woolly adelgid, spruce budworm, and hemlock looper (sudden outbreaks in over-mature fir stands and impacts are exacerbated in damp areas). Shallow roots make it vulnerable to wind or drought. Vulnerable to acid deposition through nitrogen inputs which act as fertilizer preventing hardening off for winter. Fire vulnerable due to thin resinous bark, crowns very flammable; creates hot fires; deadwood creates fuel; least fire resilient of softwoods; seeds burn, so is slow to re-establish.

Vulnerabilities & Adaptability

Balsam Fir is most vulnerable to droughty soil and desiccation, especially during germination and early seedling establishment (6 inches or greater). Balsam fir is susceptible to root and butt rot, especially when injured or growing slowly, as in overstocked stands or droughty sites. Balsam woolly adelgid, a soft shelled scale insect predicted to increase under climate change conditions, causes tree mortality. Where climate change increases soil moisture, balsam fir would be more adaptable than other species.

Regeneration Considerations

Begins after 20-30 years with good seed crops at 2 to 4-year intervals. Flower buds usually open in late May or early June before vegetative buds but have been reported flowering as early as April. Germination requires warm soil. Seedlings considered established at 6 inches in height.

Silvicultural Recommendations

Maintain wind resilient stands by light thinning. Use shorter rotations on appropriate sites to reduce chances for decay. Regeneration will require harvest methods that keep soil moist (small patch or strip cuts). Areas affected by balsam woolly adelgid generally require salvage cuts. Climate predictions greatly reduce balsam fir populations over the next 40 years and near elimination of the species from Vermont by the end of the century. Forest management plans should include identifying sites suited as refugia and working towards restoration of balsam fir in sites more resilient under climate change (e.g., coves; north aspects; low elevation, moist sites), which would not include gravelly, well drained soils, nor sites with standing water.

Basswood

Species characteristics & site preferences

An uncommon species in lower elevation hardwood forests. Shade tolerant. Less shade tolerant than its common associate, sugar maple, but vigorous sprouting and rapid sprout growth allow it to compete very well if already established in a stand. Grows best on deep moist soils, but is also found on coarse soils and exposed ridges. Calcareous soils are often associated with the presence of basswood, but it grows on soils ranging in pH from 4.5 to 7.5. Basswood is classified as a nitrogen-demanding species because it grows poorly on sites deficient in nitrogen. Most commonly grows on north- and east-facing slopes. Grows faster than most other northern hardwood species. On the same site, basswood often exceeds sugar maple and yellow birch in site index by 5 feet and beech by 10 feet. Development is vigorous from sprouts as well as seed. Leaves are high in nitrogen, calcium, magnesium, and potassium and contribute most of these nutrients to the forest floor. Recent studies suggest that the genus *Tilia* in eastern North America should be considered a single, but highly variable, species. In sampling *Tilia* from Quebec, Canada, to Lake County, FL, no apparent morphological discontinuities between populations were found to justify delimitation at the species level. Lives to 100-400 years.

Current stress agents

Diseases: butt rot following wounding. Insect pests: linden borer, but no serious defoliators. Drought sensitive. Fire sensitive species but will sprout vigorously. However, mature sugar maple-basswood forests are very resistant to burning. Intermediate sensitivity to sulfur dioxide, tolerant of ozone and hydrogen fluoride. Susceptible to browse from rabbits and when high deer densities.

Vulnerabilities & Adaptability

Basswood's ability to vegetatively sprout and grow quickly may help it to adapt to climate change, but the species may be limited by its preference for calcareous sites.

Regeneration Considerations

Basswood has good seed crops nearly every other year. Seed-bearing age for basswood generally ranges from 15 to 100 years. Flowering generally occurs in June but can begin in late May or early July, depending on latitude and annual variations in temperature. Fruits ripen in September and October and are soon dispersed by mechanisms such as wind, gravity, and animals. Seeds show a pronounced dormancy and generally germinate poorly regardless of seedbed conditions. Shading aids the establishment and initial survival of basswood seedlings. Heavy shade limits growth and development of seedlings, and vigorous growth is unlikely under the forest canopy. Likewise, higher soil temperatures found in forest openings are suitable for greatest growth of basswood seedlings. Seedlings develop a long taproot then lateral roots.

Silvicultural Recommendations

Basswood seeds show a pronounced dormancy and generally germinate poorly regardless of seedbed conditions. Regeneration of basswood from seed in natural conditions is difficult; however basswood sprouts prolifically. Given the uncertainty of regeneration success, basswood trees should be retained in forests to provide diversity and seed source.

Big tooth aspen

Species characteristics & site preferences

Big tooth aspen usually grows in even-aged mixed stands, most commonly with quaking aspen. Big tooth aspen is most prevalent on drier upland sites. Vegetative reproduction is common and results in rapid growth. Shade intolerant, cannot reproduce in the shade. Prefers well-drained, light-textured soils. Grows on a range of soil nutrition and is generally found below 2,000 feet of elevation. Big tooth aspen competes well on disturbed sites. Height growth is rapid enabling trees to outcompete other species. Lives to 70-80 years, and up to 120 years.

Current stress agents

Browsed heavily by deer and moose. Diseases: *Fomes ignarius*, *Armillaria mellea*, *Hypoxylon canker*, and *Nectria canker*. Insect pests: forest tent caterpillar, gypsy moth, and poplar borer Shallow and wide-spreading roots may be 2-3 times length of stem on first year seedlings. Root suckers may be found 30 feet from the stem. Tree susceptible to windthrow due to shallow roots. Sensitive to sulfur dioxide pollution. Some ozone sensitive clones have been observed. Very susceptible to fire but roots are resistant. Big tooth aspen grows under variable conditions across its range, with the greatest limiting factor being seed germination. Seed is viable for only 2-3 weeks and needs moisture for germination.

Vulnerabilities & Adaptability

Big tooth aspen is quite shade intolerant and seed viability is very short. While it can be maintained through vegetative sprouting, seedling establishment requires knowledge of seed years so that site scarification and small canopy gaps (one-half to 1 acre) can be established to take advantage of the limited number of weeks when seeds will succeed. The small gaps provide sufficient light while maintaining soil moisture needed for early summer germination. Increased small scale disturbance under climate change could benefit regeneration if there is enough moisture for the early summer germination. Although emerging gypsy moth larvae may have better survival in warm springs, population outbreaks seem to be avoided due to the fungus *Entomophaga maimaiga*.

Regeneration Considerations

Good seed crop every 4 years. Seed viability is only 2-3 weeks. Seed are produced on trees as young as 20 years. Flowers on female trees are very early in the spring before the leaves come out. Moist, exposed mineral soil is required. Germination rate is high on exposed mineral soil, but there is high seedling mortality. Growth of established seedlings is rapid. Survival of root suckers is good. Fast growing but shade intolerant.

Silvicultural Recommendations

Maintain big tooth aspen in stands as a wildlife species (good cavity tree) and allow self-adaptation for future timber production. Where moisture is limited, coppice regeneration should be encouraged.

Bitternut hickory

Species characteristics & site preferences

This is a long-lived, fast growing tree capable of reproducing vegetatively. Suppressed trees respond well to overstory release. Can hybridize with shagbark and pignut hickories. Variable site preference. Found on rich, loamy or gravelly soil. Grows in low wet woods and along borders of streams to gravelly uplands. Lives to 200 years, and is the shortest-lived of all the hickories.

Current stress agents

Not affected by severe diseases but has many of the problems common to most hickories; these include mineral streaks and sapsucker induced streaks that degrade lumber; branch galls. Insect pests include: potentially hickory bark beetle, especially in drought years. Tap roots on young trees aids against drought and wind damage. Bitternut hickory is wind firm. Nitrogen deposition response results in decreased growth. Highly susceptible to deer browse. Susceptible to fire at all ages. Is fast growing with reproduction via stump/root sprouts, so may outpace invasive plants.

Vulnerabilities & Adaptability

Trees are susceptible to frost, which may limit northern migration, in the short term. One competitive edge is its longevity and tolerance to competition and moisture variability. Seedlings can withstand short-term drought due to its long taproot. It grows on a range of sites from bottomland to dry upland and also reproduces vegetatively. Bitternut hickory is currently found only in the valleys of Vermont and is not a commercial species beyond the niche market, but is projected to increase in abundance with climate change.

Regeneration Considerations

Does not produce seed until about 30 years of age. Optimum seed production between 50-150 years. Fruit ripens in September and October and is dispersed from September through December. Disseminated by gravity. Seed germination requires some overstory shade and moisture. Seedlings develop a long taproot. Saplings respond well to release and can grow in the understory for long periods. Can produce fast-growing stump and root sprouts.

Silvicultural Recommendations

Silvicultural recommendations are to leave legacy hickory in harvested stands to provide a long-term seed source and to allow self-adaptation. Bitternut hickory may be planted in riparian restoration projects, which would assist the species in moving beyond its current range.

Black birch

Species characteristics & site preferences

Opportunistic, long-lived intermediate, capable of rapid growth and heavy colonization where provided moderate light. Intolerant of shade. It grows best on moist, well-drained soils. Sweet birch grows primarily on three soil orders: Spodosols, Inceptisols, and Ultisols. Trees favor medium to high fertility and pH, and moist protected slopes. It is also found on a variety of less favorable sites with rocky coarse-textured or shallow soils. Genetically it is closely related to yellow birch. Trees live 150-250 years, but highly site dependent.

Current stress agents

Diseases include: several fungi attack living trees and stems frequently become highly defective at an early age, particularly on droughty infertile sites and on trees of sprout origin (*Phellinus ignarius*, *Nectria galligena*, *Armillaria*). Insect pests include: moderately susceptible to bronze birch borer on weakened trees such as from ice injury, birch skeletonizer and gypsy moth. Defoliation is not common.Generally windfirm. Dense, fast growing seedlings can outcompete invasive plants. Unknown ozone sensitivity; there is conflicting evidence. Seldom browsed as it is not a preferred species for deer. Sensitive to fire but fire could increase germination.

Vulnerabilities & Adaptability

Regeneration requires some shade to establish but once established, it is intolerant of shade. Where enough stems persist following a harvest, in most stands regeneration grows quickly enough to outcompete invasive plants in understory. Seed production is frequent.

Regeneration Considerations

Large seed crops are produced every 1 or 2 years. Seed production begins when trees are about 40 years old. Flowers in late spring, monoecious and borne in catkins. Seed fall is during mid- September through November. Seed dispersal is normally by wind and seeds may be blown some distance over crusted snow. Seedlings develop best during their early years with filtered sun, protected by side shade or light overhead shade. Saplings grow relatively rapidly. Competition is marginal; it is able to maintain but not increase proportion of stems in many stands over time.

Silvicultural Recommendations

It is important to tend early (thin) to provide full release of stems at an early age. Caution should be taken when clearcutting immature second-growth northern hardwood stands before an understory has developed, since this may be followed by an abundance of intolerant species with only a poor representation of black birch. Identify locations within a stand that could benefit from thinning, and recognize that boles will bend with heavy snow (reducing timber quality). Avoid micro sites that may be more susceptible to frost. Favor trees of seed origin rather than sprouts.

Black cherry

Species characteristics & site preferences

The largest native cherry tree found in Vermont. Intolerant of shade. Grows best on moist, well-drained soils and protected slopes, but is also found on a variety of less favorable sites with rocky coarse-textured or shallow soils. Although it can tolerate poorly-drained sites, productivity is reduced with increasing wetness. Although it does not seem to be very susceptible to winter kill, it is not found in upper elevations or colder areas. Saplings grow relatively rapidly. Competition is marginal; it is often able to maintain but not increase number of stems over time. Opportunistic, long-lived intermediate in successional stage, capable of rapid growth and heavy colonization where provided moderate light. Lives to 150-250 years, but typically less than 150 years.

Current stress agents

Diseases: several fungi attack living trees and stems frequently become highly defective at an early age, particularly on droughty infertile sites and on trees of sprout origin (*Phellinus ignarius*, *Nectria galligena*, *Armillaria*). Insect pests: moderately susceptible to bronze birch borer on weakened trees such as from ice injury, birch skeletonizer and gypsy moth. Defoliation is not common.Usually has a spreading and shallow root system restricted to the upper 2 feet of soil, but occasionally has sinker roots that are deeper. It is vulnerable to windthrow, especially on poorly drained soils, due to a tendency towards shallow roots and growth height above associated species. Sensitive to fire, however fire can increase germination. Sensitive to ozone; often used as a bioindicator plant due to its sensitivity. Seldom browsed by deer. Average drought tolerance. Certain plants interfere with black cherry regeneration through allelopathy: flat top aster, rough stemmed goldenrod, bracken fern and wild oatgrass release chemicals that interfere with black cherry growth and development.

Vulnerabilities & Adaptability

Black cherry is vulnerable to both drought (especially regeneration) and flooding. This species needs early tending to eliminate competition. As range of black cherry moves north, cherry may have fewer defects.

Regeneration Considerations

Good seed crops every 1-2 years. Trees are monoecious, flowering in late spring. Black cherry flowers are white, solitary, and borne in umbel-like racemes. The flowers are perfect and are insect pollinated. Seed fall is during mid-September through November, and is dispersed by wind. Seed production begins when trees are about 40 years old. Late spring frosts may damage the flowers before they open, and frosts occasionally cause large numbers of newly set fruits to fall from the pedicels without maturing. A moist seedbed is required. Shade improves germination, and is poorest in full sun. Best growth in early years when there is filtered sun, so caution should be taken when removing the overstory before an understory has developed.

Silvicultural Recommendations

Silvicultural recommendations are to leave legacy black cherry during harvesting to provide a long term seed source and to let it self- adapt. Black cherry is an inelastic species (does not respond well to release), so silvicultural recommendations are to provide full release early on and continually, and to create gaps. Once in the superstory it will grow well. Also grows well in upper elevations with low deer population.

Black oak

Species characteristics & site preferences

A long-lived, hardy tree needing advanced reproduction to perpetuate. Intolerant to shade as seedling, intermediate as older stem. Prefers well- to excessively -well drained upland sites, and is outcompeted on mesic sites. Best growth is on well drained silty clay to loam soils. Tolerates hot dry conditions, but is more competitive in moderate climates. Coppice sprouts in full sun and is capable of rapid growth proportional to vigor of parent stem. Overall it is not a very competitive species due to browsing and lack of shade release. It is most competitive on xeric sites. Lives to 100-200 years.

Current stress agents

Highly susceptible to deer browse. Diseases include: concern over oak wilt, which spreads by root grafts or sap feeding beetles. Insect pests include: gypsy moth and forest tent caterpillar. Moderately sensitive to ozone. Wind firm. Highly susceptible to invasive plant competition with regeneration.

Vulnerabilities & Adaptability

Black oak is stressed by drought, poor sites, or defoliation which can be inciting or declining factors. Often succumbs to secondary agents. In the absence of fire it is not competitive with other species. Successful regeneration requires advanced regeneration of 4 to 5 foot height. Although emerging gypsy moth larvae may have better survival in warm springs, population outbreaks seem to be avoided due to the fungus Entomophaga maimaiga.

Regeneration Considerations

Consistent seed producer and during heavy seed years, surplus acorns are fed on heavily by various animals. It is monecious, flowering in April to May, and is wind pollinated. Seed germinates in the spring, grows slowly, and is not competitive unless well established at time of harvest.

Silvicultural Recommendations

Silvicultural recommendations are to retain species on sites it currently occupies. Climate change may increase suitable habitat, making this species more competitive than others on droughty sites. Refugia are the sites where it grows now, such as in sand plain forests.

Chestnut oak

Species characteristics & site preferences

A long-lived, uncommon species in Vermont found growing on rocky ridges. Intermediate shade tolerance. Grows best in rich well drained soils along streams, although it is found growing on dry infertile soils and rocky ridges, often with a south or west aspect, as well. Competitive on poor and/or droughty sites with abundant light, otherwise not very competitive. Sprouts more competitive than seedlings. Without disturbance, succeeded by shade tolerant trees. Considered a long-lived tree, with 300-400 years possible.

Current stress agents

Susceptible to deer browse, but less favored than other oaks. Diseases include: susceptibility to most of the diseases of oaks including oak wilt and bacterial leaf scorch. Insect pests include: forest tent caterpillar, gypsy moth, oak skeletonizer, and variable oak and slug caterpillars. Heavy defoliation can be detrimental to long term health. Unknown sensitivity to ozone as there is conflicting evidence. Well adapted to fire and resistant to fire damage. Fire facilitates later seed germination. Higher incidence of fire damage and associated decay than other oaks throughout the Appalachians, although its inherent resistance to heartwood decay is greater than that of white, northern, red, black, or scarlet oak. Highly susceptible to invasive plant competition as it is easily outcompeted due to poor growth of seedlings and saplings.

Vulnerabilities & Adaptability

Hardy tree but faces regeneration threat from invasive plants. Although emerging gypsy moth larvae may have better survival in warm springs, population outbreaks seem to be avoided due to the fungus Entomophaga maimaiga.

Regeneration Considerations

Good crops of seed infrequent and highly sought by wildlife. Monoecious and spring flowering. Seed matures in one growing season, drops during September to October. Seed germinates in the fall. Seedling establishment and survival reduced greatly by intermediate shade. Superior ability to sprout from stumps.

Silvicultural Recommendations

Silvicultural recommendations are to keep it where it is growing. Refugia are the sites where it grows now.

Eastern cottonwood

Species characteristics & site preferences

Cottonwood tends to be linearly distributed along streams. Differences in climate, soils, day length, and exposure to pests result in genetic differences among these populations. Gene flow to downstream portions of the population may occur as a result of Shade intolerant and cannot reproduce in shade. Seed beds below cottonwood overstory are unsuitable except along riparian areas where soil is deposited annually. Prefers terraces with well drained but moist soils. Requires abundant moisture and tolerates spring and fall flooding well, but will not tolerate extended flooding in the growing season. One of the tallest trees east of the Rockies. On the best sites in the south it can grow five feet per year for the first 25 years with 1-inch diameter growth per year. Lives to 100-200 years, but structurally sound trees live to about 70 years.

Current stress agents

Susceptible to rabbit and deer browse, and to beaver damage. Very little incidence of disease.Insect pests: problems in plantations with cottonwood leaf beetle, twig borer, and stem borer. Roots are shallow and wide spreading so is susceptible to wind throw. Sensitive to ozone. Recovery from ice or wind damage is good since branches resprout. Susceptible to fire. Fire kills trees of all ages.

Vulnerabilities & Adaptability

Vulnerable to drought, fire, and flooding during the growing season.

Regeneration Considerations

Germination must be almost immediate upon falling from the tree. Needs an exposed mineral soil that is very moist, almost flooded to germinate. Produces seed on trees as young as 10 years, but optimum mature age is between 30-40 years. Water disperses seeds for long distances along rivers and streams. Seed matures variably throughout the summer. Requires moist seedbed. High germination rate, but needs mineral soils exposed. Seedlings grow very slowly at first, but advances rapidly after about 3 weeks. Cuttings will easily propagate. This is a very fast growing tree, on best sites can grow up to five feet per year.

Silvicultural Recommendations

Retain as a riparian edge species. Give trees an opportunity to self- adapt. Potentially assist migration into riparian areas. In some cases trees may need protection from beaver damage using physical barriers (fencing or tree shelters) and chemical barriers (pepper spray).

Eastern hemlock

Species characteristics & site preferences

An abundant, long-lived conifer species often found lining stream banks. Very shade tolerant Prefers cool moist to very moist, well drained sites, so has been restricted to regions with cool, humid climates. Lives up to 400 years.

Current stress agents

Susceptible to deer browse. Insect pests: hemlock woolly adelgid, hemlock looper, and hemlock borer (especially on stressed trees). Rooting patterns are determined, to a great extent, by site conditions. Where the water table is near the surface, root systems are shallow. On better drained soils, a deeper root system will develop. Wind susceptibility is dependent on location. Sensitive to sulfur dioxide pollution. Variable response to ozone. Extremely sensitive to drought, especially seedlings.

Department of Forests, Parks and Recreation, Hemlock Wooly Adelgid in Vermont-Recommendations for Landowner Response:
http://fpr.vermont.gov/forest/forest_health/insects_diseases.

Vulnerabilities & Adaptability

Extremely vulnerable due to both climate sensitivity and climate change favoring the spread of hemlock woolly adelgid. Climate vulnerability is largely due to potential drought effects.

Regeneration Considerations

Trees are monoecious, flowering in late April to early June. Pollen is wind dispersed and fertilization is complete in about 6 weeks. During this time, the pollen is extremely sensitive to drying and is often the cause of seed failure. Seed are wind dispersed. Requires a mixture of organic and mineral soil with 70-80% crown cover (shade). First year seedlings are sensitive to surface soil drying and high temperatures. Seedlings are fully established when 3-5 feet tall. Early growth is slow; 2 to 3-inch diameter saplings may be 200 years old. Growth during the pole size stage also tends to be slow. Hemlock can remain overtopped and suppressed for many years.

Silvicultural Recommendations

Current silvicultural strategies to address the potential threat from HWA include: Thin stands to maintain healthy vigorous hemlock trees. Avoid root disturbance by cutting in winter, or, if necessary, in groups or strips. As HWA advances, try to maintain some mature hemlock where possible and think about advance regeneration. If a harvest becomes necessary due to HWA, in stands where advance regeneration is not present and deer browsing is not an issue, consider a 2-3 stage shelterwood. Thinning stands may result in decline unless light thinning in winter. Regeneration of hemlock requires scarification and moisture retention. Favorable regeneration sites include old dead logs. Hemlock is considered established when 3-5 feet tall.

Eastern hophornbeam

Species characteristics & site preferences

A small short lived tree that occurs scattered in the understory of hardwood forests. Grows on a variety of soils. It is slow growing and has nutrient-rich foliage. Very shade tolerant. Best development with soils that are in loam or loam-modified texture classes, and surface soil pH ranges from 4.2 to 7.6. Conditions are highly variable across its range. In our region it seems to grows best under dry, nutrient rich conditions on well-drained soils. Intolerant to flooding. Leaves are high in calcium and nitrogen compared to other species growing at the same locations.

Current stress agents

Relatively free of insect and disease problems. Deep, irregular root systems make this a wind firm tree. Susceptible to intense fire. Susceptible to acid deposition effects. Browsed only incidentally by deer.

Vulnerabilities & Adaptability

Trees are resistant to weather extremes, are shade tolerant, and grow on a wide range of soils which may increase its adaptability. Eastern hophornbeam is vulnerable to fire.

Regeneration Considerations

Wind disseminated pollen. Catkins appear at the same time trees break bud, and full bloom is about one month later. Fruit completes development during the summer and ripens by the end of August (in the north) or October (in the south). Trees reach maturity at around 25 years. Seeds germinate the following spring after ripening. Flexible seedbed requirements. Slow growing.

Silvicultural Recommendations

Although a minor component of forests, retain for diversity and adaptability.

Eastern larch

Species characteristics & site preferences

A deciduous needle-bearing tree growing on wet organic soils. Very intolerant to shade. Tolerates a wide range of soil conditions, but grows most commonly on nutrient poor wet-to-moist organic soils such as sphagnum and woody peat. This is a wide ranging small to medium sized deciduous conifer that is a pioneer or early seral species in bogs, and occasionally found on upland sites. It is capable of vegetative reproduction through layering. Lives to 100-200 years.

Current stress agents

Low susceptibility to browse. Diseases: larch decline complex.Insect pests: larch casebearer (which may be responsive to below normal May rainfall), larch sawfly, and eastern larch beetle. Shallow, wide-spreading roots, moderately susceptible to wind damage. Shallow root system makes it susceptible to drought. Easily killed by fire, though usually grows on wetter sites less prone to fire

Vulnerabilities & Adaptability

Not a major species in Vermont. Because it prefers cool sites and is susceptible to drought, may be vulnerable under climate change scenarios.

Regeneration Considerations

Good seed crops every 3-6 years. Trees are monoecious, with small, solitary male and female flowers appearing in spring at the time needles break bud, late April to early May. Seed production begins at 12-15 years with large quantities of seed produced by 40 years. Abundant light and constant water levels. Seedlings are easily killed by “damping off” within the first 6-8 weeks after germination, and are also susceptible to drowning, drought, and inadequate light. The growth rate of tamarack depends on both the nutrient status and moisture-aeration conditions of the site. On water-covered stagnant peatlands, trees grow slowly. With abundant light, eastern larch is one of the fastest growing conifers on uplands in the boreal (including Alaska) and northern forest regions; on peatlands it outgrows any other native conifer.

Silvicultural Recommendations

Silvicultural recommendations are to retain eastern larch where it is currently growing, and keep these sites as eastern larch refugia.

Northern white cedar

Species characteristics & site preferences

A long-lived tree growing on rich and moist sites. Tolerant to shade. Grows best on limestone derived soils in cool, moist sites, but is intolerant to flooding. Occurs in both pure stands and as minor species in mixed stands of hardwoods or other softwoods. Lives to 300-400 years.

Current stress agents

Heavy browsing by deer. Diseases: cedar heartwood is frequently attacked by fungi; trees on xeric and basic sites have a moderate resistance to decay, whereas cedar on acid and wet sites has a very low resistance. Redheart rot caused by *Stereum sanguinolentum* invades boles follInsect pests: arborvitae leafminer, an occasional problem, but otherwise relatively free from insect pests. Weak wood makes it susceptible to wind, ice, and snow breakage, particularly when the heartwood is attacked by fungi. Shallow, wide spreading roots make it susceptible to wind damage on some sites. Tolerant of ozone and sulfur dioxide pollution. But growth and health limited by acid soils with high aluminum concentrations. Seedlings are especially susceptible to drought; tree susceptibility to drought especially on shallow soils.

Consider consulting "Silvicultural Guide for Northern White-Cedar, GTR-NRS-98, 2012" for more specific details on the managing northern white-cedar.

Vulnerabilities & Adaptability

Moisture requirement, especially during early establishment of regeneration will be one of the vulnerabilities this species faces with climate change. Also, establishment can be difficult in areas with heavy browsing pressure from deer, moose and hare. Young, fast-growing trees and those growing in the shade are less attractive to the leafminers. Other stress factors to consider are lack of wind firmness on wet soils or following canopy opening, and breakage of limbs and boles to ice, rain and snow.

Regeneration Considerations

Good seed crops at 2-5 year intervals. Trees are monoecious and flower in mid-April to mid-May. Seed production begins when trees are 6 years old, becoming optimum at 75 years, and declines after 300 years. Germination requires constant moisture and warm temperatures; prefers decaying wood or mineral soil seedbed. Moisture is the most important factor for seedlings during the first few years. Saplings are generally slow growing and attain less height than common associates.

Silvicultural Recommendations

For the most part it is best to avoid disturbance through harvesting to allow it to self-adapt. Where managing for timber the silvicultural guide distinguishes between areas with or without heavy browse. Cedar requires down material for regeneration, so avoid whole tree harvesting or retain abundant down material. Intermediate treatment may be needed. Wind throw is a concern when thinned to low density. Thinning not recommended for trees with <33% or >50% of crown length.

Paper birch

Species characteristics & site preferences

A medium-size deciduous tree that is short-lived, opportunistic, intolerant to shade, and a pioneer species on disturbed areas forming nearly pure stands. It is a common associate in conifer-hardwood mixed forests on cool, moist sites. Intolerant to shade. Best development and growth occurs on the deeper well-drained to moderately well-drained soils. Paper birch site index is highest when growing on moist and nutrient enriched habitats. This is a nutrient-sensitive species. Also grows on a wide range of sites and in the northeast tends to be more abundant on the drier sites than on wet or poorly drained sites. Competition is a problem for this shade intolerant species. Six varieties are known, two of which grow in Vermont: typical paper birch and mountain paper birch. Trees rarely live more than 140 years.

Current stress agents

Diseases include: quite prone to stem decay and foliage diseases such as Septoria leaf blight. Insect pests include: moderately susceptible to a birch leaf miners, bronze birch borer, Asian long horned beetle, birch skeletonizer, and forest tent caterpillar. High winds will break the tree bole more often than uprooting tree. Responds well after fire though not fire dependent for establishment. Moderately sensitive to ozone. Susceptible to browsing by moose and deer. Generally shallow-rooted and drought sensitive.

Vulnerabilities & Adaptability

Under climate change scenarios populations in Vermont may be confined to northern and higher elevation sites, but susceptible to extremes of climate including drought, wind and ice.

Regeneration Considerations

Good seed crops at 2 year intervals. Seed production begins at 15 years, is optimal at 40 years and declines after 70 years. Sensitive to moisture, temperature, light, and seedbed condition. Seedlings will not grow on soils with pH less than 5.0. Young paper birch grows rapidly. Individual trees often have a diameter of 8 inches after 30 years. Seedling, sapling, pole, and sawtimber-size trees have all responded to fertilizer treatments in recent studies.

Silvicultural Recommendations

Competition is a problem for this shade intolerant species. Clearcutting stands in the northeast that are less than 100 years old often results in high competition with Rubus and pin cherry. Longer rotations could be advantageous by diminish seed bank of these competing species. Retain as a component of forests where possible. Patch clearcuts are recommended to regenerate paper birch.

Pignut hickory

Species characteristics & site preferences

This is a long-lived species that forms long tap roots which enable drought resistance and wind firmness. Intolerant to shade in the northeast, but studies indicate it is tolerant to shade in the southeast. Prefers well drained upland soils. Soil preference is variable but responds to increased soil fertility. Can grow at lower levels of nitrogen than ash or basswood. Tolerates variable moisture regimes. Three varieties are recognized; two of which (*Carya glabra* var. glabra and *Carya glabra* var. megacarpa) may occur in Vermont. Lives to 200-300 years.

Current stress agents

Sapsucker damage is common. Diseases include: *Poria spiculosa*, a trunk canker. Insect pests include: potentially hickory bark beetle, especially in drought years. Tap roots with few laterals on young trees make trees windfirm. Responds to increased soil fertility so would be negatively affected by acidification. Susceptible to fire at all ages. Adaptability may be limited by frost, but late flowering may be advantageous for seed production. Choose northern provenances for assisted migration

Vulnerabilities & Adaptability

Benefits from longer growing season which will help adaptability, but it's not likely to be major component of Vermont's forest.

Regeneration Considerations

Good seed crops occur at 1-3 year intervals. Optimum seed bearing age is 75-200 years, with a maximum of 300 years. Fruit ripens in September and October and the sweet nuts are disseminated in September through December by gravity and dispersed by animals. Seed have 50-75% germination success. Seed germination requires some overstory shade and moisture, and winter dormancy. Seedling growth is slow and produces a long taproot, persisting in older trees. Sapling diameter growth is rated slow. Can be found growing in association with black gum and hackberry in moist sites, and black oak and post oak on drier sites.

Silvicultural Recommendations

Pignut Hickory is a minor component of the Vermont forest and found only in a few locations in southwestern Vermont. This species should be favored for retention.

Quaking aspen

Species characteristics & site preferences

Fast-growing, short-lived tree suited to a wide variety of sites. Very shade intolerant. Grows best on moist sites but grows on a wide range of sites. Prefers well drained sandy loam soils. Aspen has a high nutrient demand for calcium, magnesium, potassium and nitrogen. Grows where annual precipitation exceeds evapotranspiration. Lives to 30-100 years.

Current stress agents

Diseases include: Hypoxylon canker, and is susceptible to trunk decays. Insect pests include: forest tent caterpillar, large aspen tortrix, gypsy moth and satin moth. Several wood boring species attack the stem and weaken it. Aspen clones tend to have flat, lateral, root systems that develop root sinkers. Seedlings have a variable root system. Well adapted to fire. Quaking aspen populations decrease where fire is suppressed. Fire creates suitable seed bed for aspen regeneration from seed. Sensitive to sulfur dioxide pollution. Sensitive to ozone. Browsed by moose and deer. Aspen has the capacity to regenerate from sprouting and therefore may outgrow invasive plants, or at least be competitive. Resistant to ice storm damage.

Vulnerabilities & Adaptability

Aspen is susceptible to drought, subject to wind throw, and a preferred browse species. It does, however, have the ability to vegetatively regenerate, and its positive response to early thinning may be an asset.

Regeneration Considerations

Good seed crops every 4-5 years. Primarily dioecious, flowers appear mid-March to April before leaves expand. Wind pollinated, seeds mature 4-6 weeks. Wind and water dispersal of seeds occurs. Moisture during short seed viability. Fire creates suitable seed bed for aspen regeneration from seed. Few aspen seedlings survive due to short period of seed viability, unfavorable moisture during seed dispersal, high soil surface temperatures, and unfavorable chemical balance of some seedbeds. Aggressive pioneer species, but does not compete well if overtopped. Very fast growing and responds well to thinning. Root sucker propagation has the advantage of local adaptation well suited to microsites, but the potential disadvantage of lack of adaptive capacity to new climatic conditions.

Silvicultural Recommendations

Higher temperatures and late season drought projections will adversely affect aspen. Sites that maintain soil moisture will be critical as aspen refugia, at some future point in time. Coppicing is the recommended regeneration method, giving it an advantage over invasive plant species. Aspen will also seed in after a fire.

Red cedar

Species characteristics & site preferences

An uncommon conifer tree usually growing in dry pasture sites. Intolerant to shade. Grows on a wide variety of soils and sites, but like most species, grows best on deep, moist, well-drained alluvial sites. Is not competitive with other hardwoods, so tends to be limited to drought-prone sites such as dry, exposed sites and abandoned fields. Trees tend to make soil more alkaline (due to high calcium content of the foliage), but trees themselves are less tolerant of alkaline soils than other drought tolerant trees and shrubs. Red cedar is a long-lived tree that does not heal well from wounds and does not self-prune. However, it has a low capacity for water loss and is able to sustain stomatal opening at low water potentials, which helps it adapt to dry environments. Lives to 150-300 years.

Current stress agents

Not valued as browse; however, when food is scarce, deer will heavily browse reproduction. Diseases: cedar apple rust. Insect pests: no serious insect problems. Tap root and lateral roots help make this a wind firm tree. Tolerant to sulfur dioxide and hydrogen fluoride pollution. Grows in areas with high ambient ozone. Newly established seedlings are subject to frost-heaving and winter injury. Competes well on poor site or thin soils, but is very susceptible to fire

Vulnerabilities & Adaptability

Extremely tolerant of drought, has a wide natural range and presently grows under a wide range of climatic conditions, making this species a possible strong competitor in a changing climate.

Regeneration Considerations

Good seed crops every 2-3 years, and has the highest seed production when 25-75 years old. Trees are dioecious, and cones form in late fall to be ready for pollination in late May to mid-June. Seed dispersal is in February to March. Seed dispersed by birds. Germination usually takes place during early spring of the second year after seed dispersal. Natural regeneration usually takes place on poor hardwood sites, along fence rows or in pastures. On dry sides, most seedlings are found in crevices, between laye First year seedlings produce long fibrous root systems but not much height growth. Once established, seedlings survive for extended periods under severe competition. Seedlings may be susceptible to frost. Growth depends on site quality and competition. It is not a competitive species.

Silvicultural Recommendations

Maintain this species when found in stands. Very little work has been done on the management of this species. Red cedar is generally considered a low quality tree for sawtimber production, so it is used for chips or bedding. It is known to be very susceptible to fire and therefore may require protection from fires.

Red maple

Species characteristics & site preferences

A versatile species that grows in a wide variety of sites. It is not as resistant to wounding as sugar maple. Intermediate shade tolerance. Thrives on a wide range of soil types, a diverse range of sites, and is tolerant of a wide range of moisture conditions from dry to wet. Trees are polygamo-dioecious (male flower trees, female flower trees and trees with both flower types), and one of the first trees to flower in spring. In Canada it is known to hybridize with silver maple. Genetic breadth allows for variation in range and More shade tolerant and longer lived than other early successional species such as aspen and pin cherry, but not as shade tolerant as sugar maple and beech. Lives to 100-300 years.

Current stress agents

Diseases include: nectria canker and eutypella canker. Susceptible to rot after stem injury, but there is a high genetic variability in decay susceptibility. Insects pests include: preferred host for Asian longhorned beetle. Sapsucker damage can lead to ringshake. Depends on soil depth. Ozone sensitive. Tolerant to intermediate in sulfur dioxide sensitivity. High susceptibility to deer and moose browse. Tolerates drought by postponing growth when conditions are dry, then producing a second flush of foliage when conditions improve, even after growth has stopped for 2 weeks.

Vulnerabilities & Adaptability

Red maple is extremely adaptable on a wide range of sites and commonly increases after disturbances, windstorms, fire, etc. However, it is susceptible to decay following injury. This may be a good tree for future climate conditions, but should not be used as a replacement for all other species, especially on spruce-fir sites.

Regeneration Considerations

Seed crops every year. Seeds dispersed in spring. Germination in early summer. Prefers mineral soil but will germinate even on conifer needles. Rapid growth on a range of site conditions. Rapid early growth up through the pole stage.

Silvicultural Recommendations

Trees respond well to thinning, but are susceptible to wounding. During single tree selections managers should look for trees with little or no defect on the bole and with well-healed branch stubs. Red maple is competitive in group and patch cuts. Red maple as a species has been increasing in stocking levels in Vermont. Managers need to carefully consider this when making decisions that will create conditions for red maple regeneration.

Red oak

Species characteristics & site preferences

Red oak establishment follows white pine in old agricultural sites or in areas affected by fire. Lateral growth happens in episodes when moisture, light and temperature are favorable, so multiple growth flushes will occur in the same growing season. Intermediate tolerance to shade. Grows on deep, well drained loams to silty clay loams, with and especially deep A horizon (ravines). Site preferences range from very dry to moderately moist sites, on northern or eastern aspects and on lower slopes. Growth under forest canopies often results in top-kill of saplings. New sprouts grow from buds near the root collar. This resprouting can happen over and over again. Competition is a problem with red oak when trying to regenerate. Lives to 200–400 years.

Current stress agents

Highly desired as deer browse. Diseases include: bacterial leaf scorch, oak wilt, and anthracnose. Insect pests include: forest tent caterpillar, gypsy moth, oak leaftier, oak skeletonizer, two-lined chestnut borer, and twig pruner; and acorn insects such as nut weevils. Susceptible to oak decline due to combined effects of defoliation and drought. Tolerant of ozone and sulfur dioxide. Sensitive to soil aluminum toxicity indirectly from acid deposition. Taproots anchor trees against wind damage. Susceptible to invasive plant competition.

For more information on oak regeneration one source is: http://www.nrs.fs.fed.us/pubs/gtr/gtr_nrs33.pdf

Vulnerabilities & Adaptability

Over- browsing from deer and moose, and competition from invasive plants are two key vulnerabilities. Red oak is a species that should have suitable habitat and be very adaptable. Consider promoting, selecting for and retaining red oak, especially on low nutrient sites where sugar maple will not grow well. Control deer and moose populations to avoid regeneration failures. Deer exclosures may be helpful.

Regeneration Considerations

It is monoecious and trees of 25 years old may flower. Most abundantly flowers when 50 or more years. Acorns mature in 2 years. Good crops happen every 2-5 years. Crown size is important in determining if a tree is a good seed producer. It takes about 500 acorns to yield one, 1-year-old seedling. Many acorns are consumed by insects, squirrels, rodents, deer, and turkey, and as many as 80-100% of acorns can be destroyed. Seedlings needs light intensity of 30% to reach maximum photosynthesis.

Silvicultural Recommendations

Shelterwood systems have been suggested for this species, but it is important to note that the final removal cut should not be carried out unless there is adequate advance regeneration of red oak. In addition, stands may need early tending to prevent red oak saplings from being out competed.

Red pine

Species characteristics & site preferences

Mostly found in plantation settings in Vermont. Very intolerant to shade. Red pine commonly grows on dry soils with low fertility and well-drained sandy to loamy-sand soils. Trees grow poorly on potassium deficient soils, but can grow on soils deficient in nitrogen and phosphorus. Growing season precipitation ranges from 15-25 inches. A 30-day summer drought is common in western portions of its range. Native to areas with cool-to-warm summers and cold winters. Becomes more shade intolerant with age or as the environment becomes warmer. Thinning may stimulate root grafts. Susceptible to saturated soils. Red pine is one of the most genetically uniform species. Lives to 200-300 years.

Current stress agents

Minimal browse. Diseases: scleroderris canker, annosus root rot, and shoot blights. Insect pests: several species of sawflies that are currently limited by low temperatures, European pine shoot moth, pine gall weevil, pine bark adelgid, red pine scale, and potentially pine shoot beetle. Usually has a well-developed root system making it wind firm. Root grafting is common and may be a pathway for disease transmission, but may also sustain weak trees during a drought and provide increased wind firmness. Vulnerable to acid deposition, sensitive to sulfur dioxide pollution, but tolerant to ozone. Subject to breakage and windfall from ice, sleet and wind. Red pine thrives in a fire regime of alternating high intensity, stand replacing fires at long intervals (one to two centuries), and actually decreases when fire is suppressed.

Vulnerabilities & Adaptability

Red pine is subject to breakage during wind and ice storms. Regeneration is susceptible to drought. Once established it can grow on dry sites low in fertility. This is a species that is tolerant of fire.

Regeneration Considerations

Good seed crops occur at intervals of 3-7 years. Cone production per tree increases as stand density decreases. Red pine is monoecious, flowering between April and June. It takes two seasons for the cones to develop and 60% of the cones can be lost between the first and second seasons. Actual fertilization occurs in July of the second season (13 months after pollin Cones open best on hot, still autumn days when there is little wind to carry the seeds far. Prefers mineral soil or burnt duff. Grow slow in the wild, especially if they are shaded.

Silvicultural Recommendations

Not commonly found growing in natural stands in Vermont, so where it is growing naturally it should be maintained or protected.

Red spruce

Species characteristics & site preferences

Among the top 10 species in abundance in Vermont, generally found in upper elevation forests. Tolerant to very tolerant to shade. Prefers cool, moist sites with sandy loam soils and pH 4.0-5.5, but tends to grow on many sites unfavorable to other species. Grows where January temperatures are –8° F to 30° F and July temperatures are between 52° F and 80° F. Drought and frost heaving are major causes of mortality during the first year. Soil surface temperatures of 115° F, even for a short time can cause heavy mortality of seedlings. Seedlings are considered established when six inches tall. Although it is shade tolerant, balsam fir and some hardwood species that produce heavy shade can out-compete red spruce for overstory positions. Low genetic variability. Red spruce under suppression retains its ability to respond to release with a growth rate approaching that of open-grown trees. Lives to 400 years.

Current stress agents

Diseases: *Armillaria mellea* and *Inonosus tomentosa* occasionally attack red spruce. Insect pests: spruce and other bark beetles, spruce spider mite, and spruce budworm (especially in stands with balsam fir). Shallow roots make it vulnerable to wind throw and drought. Winter injury as an indirect result of acid deposition is a major stress factor. Ozone sensitive at high elevations.

Vulnerabilities & Adaptability

Of its associates red spruce is one of the last species to start height growth in the spring. Slow seedling development is easily outcompeted by hardwoods and herbaceous plants. However, seedlings can survive several years of shading and still be released.

Regeneration Considerations

Good seed crops are produced every 3-8 years. Trees mature at 35-45 years old and begin cone production. Seed dissemination between October and March. Mineral soil, rotten wood, or shallow duff and adequate moisture are needed for germination. Seeds usually germinate between May and early July. Seedlings in open areas can undergo high mortality due to high temperatures.

Silvicultural Recommendations

A major recommendation is to promote wind resilient trees by thinning stands. When regenerating red spruce it is recommended to use methods that leave some shade to prevent the seedlings from extreme heat exposure or moisture loss. Competition from balsam fir and other hardwoods may make pre-commercial thinning necessary. Small groups and single tree selection can be used for this species; however single tree selection is not recommended on secondary softwood sites. Considerations should be given to those areas where this species can be maintained in refugia since suitable habitat may be reduced for red spruce in the future.

Shagbark hickory

Species characteristics & site preferences

A common associate in oak forests, this long-lived species is wind firm, drought resistant, and has variable (i.e., adaptable) site requirements. It is able to reproduce vegetatively via stump and root sprouts. After seedling establishment it is drought resistant. Moderately tolerant to shade. Suppressed understory responds well to overstory release. Prefers fertile, rich sites, and is most commonly found on calcareous sites. Moisture requirements are variable and it is found on a range of sites. Often found growing in floodplain forests and clayplain forests in Vermont. Moderately tolerant to competition and suppressed trees in the understory respond well to release. Life expectancy is 200-300 years.

Current stress agents

Diseases include: *Poria spiculosa* (stem canker). Insect pests may include hickory bark beetle. Tap roots on young trees make this a wind firm species. No ozone injury symptoms reported. Browse damage can be heavy with high deer populations. May not be outcompeted by invasive plants because it is able to persist for years in the understory and then respond well to release. Intolerant of fire at all ages.

Vulnerabilities & Adaptability

Vulnerabilities include deer browse, seed predation and limited seed dispersal. It is a long-lived, drought resistant species likely capable of site adaptability.

Regeneration Considerations

Good seed crops every 1-3 years. Optimum seed bearing age is 60-200 years. Disseminated by gravity and animals. Seed have 50-75% germination success. Needs a moderately moist seedbed for germination. Seedlings have long tap root, and may persist in the understory. Saplings may persist for years in the understory and then respond well to release. Hybridizes with other hickory species. There is considerable morphological diversity.

Silvicultural Recommendations

Identify legacy trees and retain. Because of delayed maturity (seed production) until 40 years old, maintaining trees for the long term improves opportunity for seed production and seedling establishment. Leave harvested tops whole for browse protection. Conserve forests where shagbark hickory occurs and allow to naturally adapt. Plant in riparian restoration areas to assist in expanding range.

Silver maple

Species characteristics & site preferences

Silver maple is a valued tree in riparian forests, able to survive long periods inundated in flooded areas. Shade tolerance ranges from moderately tolerant to very tolerant depending on site quality and location. Best growth is in better drained moist areas. Found most often on alluvial soils associated with streamside and riparian sties. Because the blooming periods of silver and red maple overlap there is a possibility of natural hybridization between them. Lives to 200-250 years.

Current stress agents

Susceptible to deer browse. Diseases: Verticillium wilt and Armillaria root rot. Insect pests: host to Asian long horned beetle. Root system is shallow and fibrous. Rated by some as sensitive to ozone. This bottomland species not well adapted to survive fire even though it sprouts. Susceptible to competition from knot weed and other riparian area invasive plants.

Vulnerabilities & Adaptability

Vulnerabilities include intolerance to competition and susceptibility to wind and ice storms. However, silver maple's ability to withstand flooding gives it a competitive advantage.

Regeneration Considerations

Silver maple is the first maple to bloom in spring, beginning as early as February and extending into May. Fruit and seed develop rapidly and are usually mature within 3 weeks of pollination. Seed ripening and dispersal ranges from April to June. Seeds require no stratification or pretreatment and are capable of geminating immediately at maturity. Young seedlings are most successful on moist mineral soil with considerable organic matter. Seedlings require 2,000 - 2500 hours (nearly 3 months) of chilling to break dormancy. On upland soils silver maple is highly intolerant of competition. Seedlings can be competitive because they tolerate prolonged periods of inundation. Growth of young trees is seriously affected by competition from other vegetation.

Silvicultural Recommendations

Recommendations for silver maple: Encourage this species in riparian areas.

Sugar maple

Species characteristics & site preferences

This is currently one of the most abundant species in Vermont. It is a long-lived species that is exceptional in its ability to compartmentalize wounds. Very shade tolerant. Site preferences include: well-drained loam soils rich in organic matter; high nutrient requirement, especially calcium; moist soil with growing season precipitation of 15-40 inches. Average temperature ranges: January 0-50° F and July 60-80° F. Trees require 2,500 hours (about 3 months) of continuous chilling to break bud dormancy. Lives to 300-400 years.

Current stress agents

Diseases include: sapstreak, Armillaria, Eutypella, and anthracnose. Insect pests include: forest tent caterpillar, saddled prominent, maple leaf cutter, maple trumpet skeletonizer, pear thrips, sugar maple borer, Bruce spanworm, and is a host to Asian long horned beetle. Depends on soil depth. Tolerant to ozone, sulfur dioxide, and hydrogen fluoride. Sensitive to acid deposition induced leaching of soil calcium. Susceptible to deer browse. Roots rely on arbuscular and ectotrophic mycorrhizae that can be sensitive to drought.

Vulnerabilities & Adaptability

Key vulnerabilities include: moisture requirements, root damage, regeneration issues due to deer browsing and invasive plants. Vermont soils are richer than those of surrounding states, so we expect to keep sugar maple as a focus species for Vermont. Sugar maple will do best now and in the future if growth is concentrated on moist, site 1 and 2 stands. Coves would make ideal refugia, if other site conditions are favorable.

Regeneration Considerations

Seed crops at 1 to 4-year intervals. Tree maturity at 22 years. Seeds require moisture stratification of 35-90 days. Germination depends on cool temperatures, beginning at 34° F and will not germinate when temperatures reach 50° F. Seedlings are very shade tolerant and produce a root exudate that inhibits growth of competing yellow birch. Soil moisture is important to seedling survival, so overstory canopy shade is needed until good root systems are established. Understory trees take advantage of early spring leaf off; 90% of annual growth occurs within a 2 to 3-week period before overstory leaf out. Growth of saplings and pole size trees tends to be slower than most associated hardwood species. Saplings can tolerate suppression and respond to release.

Silvicultural Recommendations

Regeneration requires good soil moisture, so when harvesting, consider maintaining stocking above 60 ft^2/acre. Single tree and small group selection cuts would help maintain soil moisture for regeneration survival. In stands with a significant ash component, it may be advantageous to maintain a higher sugar maple basal area in the event that ash are attacked by emerald ash borer during the next rotation.

Sycamore

Species characteristics & site preferences

A tree of riparian forests with unusual flaking silver-green bark and large palm-shaped leaves. Classified as intermediate in shade tolerance. Grows best on sandy loams or loam with a good supply of ground water. Commonly grows on flood plains and sites with moist alluvial soils. It grows on moist sites but is intolerant of flooding during the growing season. On moist sites sycamore tends to maintain itself in subclimax–climax forest types. On drier sites sycamore usually has pioneer or transitional status. Geographic variation in sycamore is extensive. Sycamore is unique among North American tree species in displaying a strong north-south gradient in resistance to a killing stem canker disease. Lives to 250 years and occasionally 500 years.

Current stress agents

Low susceptibility to browse. Diseases: anthracnose and leaf scorch. Insect pests: low susceptibility. Deep rooted and wind firm. Sensitive to ozone. Buds are susceptible to late spring frost.

Vulnerabilities & Adaptability

Sycamore requires adequate moisture but is not tolerant to flooding. Warmer weather should improve growing conditions.

Regeneration Considerations

Trees are monoecious, flowering in May in the northern extent of the range. The fruit is a ball composed of many closely packed, long narrow fruits that ripen between September and October. Fruit remains on the tree over the winter, breaking up or falling off the following spring. Seeds are primarily wind disseminated with some dispersal by birds, and by water, depositing seeds on mudflats or sandbars. Seedlings must have direct sunlight to survive. Saplings have the ability to grow very fast. Also sycamore can sprout readily from the stumps of saplings and poles.

Silvicultural Recommendations

Retain where it currently grows. Presently in Vermont Sycamore is not an abundant species. When sycamore is found in a stand consider retaining to improve species diversity. Climate predictions for the future may provide suitable habitat for sycamore. This species may be considered for assisted migration in riparian areas.

White ash

Species characteristics & site preferences

Among our top 10 species in abundance in Vermont, it is a tree with deep furrowed bark, pinnate leaves, and blunt tipped twigs. Shade tolerant as a seedling becoming less tolerant of shade as the tree increases in age. Overall ranking is that of shade intolerant. White ash has demanding soil fertility and soil moisture requirements, preferring enriched sites. Most commonly found on fertile soils with high nitrogen and moderate to high calcium content. Water loving, but rarely found in swamps. It is intermediately tolerant of temporary flooding. Young ash may be abundant in the understory of northern hardwood stands, yet few grow into the overstory unless provided with light from above. Lives to 200-250 years.

Current stress agents

Diseases: ash yellows. Insect pests: a serious threat to ash survival is posed by emerald ash borer as it moves eastward. Ash is also host for the Asian long horned beetle. Generally forms a taproot that branches into a few larger roots, single lateral roots develop at intervals. Distribution of roots is strongly influenced by soil type. This is a ring porous, drought sensitive species. Larger trees are moderately susceptible to fire. Ash can seed in after a fire. Sensitive to ozone and used as an ozone bioindicator plant. Browsed on by moose and deer. Needs fertile soils high in nitrogen and calcium. Considered a pioneer species, shade intolerant.

Vulnerabilities & Adaptability

Emerald ash borer is expected to be the significant decline factor. Few trees seem resistant to EAB. Northern spread of ash yellows or witches brooms may currently be cold limited; freezing damage may lead to split bark and basal cankers, and decline is aggravated by drought.

Regeneration Considerations

Good seed crops occur every 3rd year. Trees are dioecious with flowers appearing with or just before the leaves in April or May. Pollen is wind carried (300') as are the seeds (400'). Seed production begins at age 20 optimal at age 40. Seeds germinate in the spring and require cold stratification. Seedlings require moist soil, humus or leaf litter in the spring for good germination. Seedlings can tolerate shade, but tolerance decreases with age.

Silvicultural Recommendations

Follow VT ash guidelines to manage ash in light of EAB. These guidelines will be modified as new information on insect locations and/or research sheds new light on management practices. Manage invasive plants in ash stands now so that if ash overstory declines, other tree regeneration has an opportunity to fill the niche.

Department of Forests, Parks and Recreation Ash Management Guidance for Forest Managers:
http://fpr.vermont.gov/forest/forest_health/insects_diseases

White oak

Species characteristics & site preferences

White oak is a long-lived slow growing hardwood. It grows slower than species such as red oak, sugar maple, black walnut or white ash, but faster than beech or hickory. Intermediate shade tolerance. Prefers thick A horizon soils. Not limited by soil preference except on very sandy soils where Grows on a wide variety of sites, except extreme driest or shallowest soils; prefers lower slopes facing north or east moisture is also limited. Major site factors influencing white oak growth are latitude, aspect, and topography. White oak has the ability to grow on all aspects and slopes within its range except extremely dry shallow ridges, poorly drained flats, and wet bottom land. Saplings are able to persist under a canopy for 90 years. Lives to 600 years.

Current stress agents

Susceptible to deer browse. Diseases include: bacterial leaf scorch and oak wilt. Insect pests include: forest tent caterpillar, gypsy moth, oak skeletonizer, orange-striped oakworm, variable oakleaf caterpillar, and oak slug caterpillar. The oak leafshredder, also known as the oak leaftier, prefers red oak, but will attack white, pin and black oak. Variable sensitivity to ozone and intermediate in sensitivity to sulfur dioxide. Deep fibrous roots make this tree wind firm. Seedlings start with a taproot. Moderately resistant to fire, white oak is well adapted to periodic fire.

Vulnerabilities & Adaptability

Favorable features include that this long-lived species has the ability to persist in the understory. White oak has the ability to grow on a wide range of sites, although it appears to be limited in elevation presently in the northern most part of its range.

Regeneration Considerations

Trees start bearing between 50 and 200 years. Acorn crops are good in years when the weather is warm for 10 days during flowering and then cool for 13-20 days afterward. Trees are monoecious; pollen dissemination hindered by wet weather, freezing temperatures or dry winds. Acorns germinate as soon as they fall to the ground in September or October. A humus layer is important to germination and early seedling growth. White oak is able to persist in the understory as a seedling and be released.

Silvicultural Recommendations

As with other oak species a key to maintaining and reproducing white oak is adequate advanced regeneration. Literature sources vary in how this is determined and the size of the advanced reproduction, but generally seedlings should be greater than 3 feet in height.

White pine

Species characteristics & site preferences

Relatively fast growing conifer populating former pastures. Intermediate tolerance to shade. Prefers well drained sandy loam soils but is competitive on poor sites and a broad range of moisture regimes. Saplings require partial light for growth. Regeneration is not competitive until fully established. Often this requires cultural work to outcompete hardwoods. Vegetative competition is a major problem. One of the fastest growing northeastern conifers. It grows on a wide range of sites, but is difficult to establish regeneration. Lives more than 200 years.

Current stress agents

Moderately susceptible to browse. Diseases: white pine blister rust, *Armillaria mellea*, and red ring rot. Insect pests: white pine weevil affects timber quality; there are roughly 277 insects and 110 diseases that attach white pine; the four most important to Vermont are listed. Prone to breakage in heavy wind. Sensitive to ozone. Highly susceptible to invasive plant competition. In invasive plant zones, dense invasive plants are often found in white pine understory.

See also Ostry, M.E.; Laflamme, G.; Katovich, S.A. 2010. Forest Pathology 40: 332-346; http://www.nrs.fs.fed.us/pubs/36134.

Vulnerabilities & Adaptability

White pine may be a short term winner, but a long term looser. It currently occupies many geographic zones and a variety of sites. White pine could be an adaptive tree but its lack of competitiveness as a seedling/sapling will require management to overcome.

Regeneration Considerations

Trees are monoecious, flowering from May to June. Cones mature during August and September of the year following pollination. First year seedlings are highly susceptible to drought. It takes 3-5 years to establish regeneration. First year seedlings are highly susceptible to drought. It takes 3-5 years to establish regeneration.

Silvicultural Recommendations

Reduce hardwood competition to support retention in a stand (in a mixed wood stand) by expanding gaps to allow for growth. Regeneration requires scarification and careful planning to coincide harvests with seed years. Multi-year timber harvests may allow seed year overlap with overstory removal. Cone production is visible starting a year before cone crop matures. A summer harvest would promote scarification and could be timed with seed crop. An extended rotation with 30-50 BA retention would protect regeneration from white pine weevil attack, when grown in a pure pine stands. In mixed woods, rely on gaps for regeneration. Leave seed trees (>30” diameter at breast height).

Yellow birch

Species characteristics & site preferences

A long-lived species abundant in northern hardwood forests especially in colder sites. Intermediate in shade tolerance and competitive but it can not regenerate under closed canopy. Grows best on moist, well-drained fertile loams in cool areas with abundant precipitation. In the Green Mountains grows better at lower elevations than higher and better on northeast aspects than southwest aspects. Lives to 150-300 years.

Current stress agents

Diseases include: *Nectria galligena*, *Inonotus obliquuos*, *Armillaria mellea*, and susceptible to decay organisms. Insect pests include: birch leaf miner, bronze birch borer, birch skeletonizer, birch leaf folder, and serves as a host to Asian longhorned beetle. Wind firm on deep well-drained soils, but subject to windthrow on shallow somewhat poorly drained or stony soils. Sensitive to ozone. Susceptible to high deer or moose browsing. Adaptable well-developed lateral root system capable of either spreading horizontally in shallow soils or penetrating to more than 5 feet under ideal conditions.

Vulnerabilities & Adaptability

Yellow birch is vulnerable to harvesting damage, which predisposes it to further disease organisms. This species needs careful planning when trying to regenerate in stands. Wind and drought could also affect survival.

Regeneration Considerations

Seed production begins at 30-40 years and is optimum at 70 years. Seed coat has germination inhibitor that's inactivated by light. Hardwood leaf litter detrimental to seed survival. Requires soil disturbance and canopy opening for regeneration. Germination on mineral soil or humus. Hardwood leaf litter is detrimental to seedling survival. Seedling growth is limited by inadequate fertility. Although it grows on somewhat acidic sites, it prefers fertile loam sites. It can not out compete grasses and herbaceous plants. Saplings require light from overhead, space for crown expansion, soil moisture, and nutrients to compete with common associates.

Silvicultural Recommendations

Yellow birch is a valuable species for both timber and wildlife. Group selection and shelterwood harvesting systems have been successful in regenerating this species. Cooler, moister sites may be areas where yellow birch will fare better under the stressors associated with climate change.

Table 4. Predicted change in tree abundance modeled using high and low-emission scenarios for all of Vermont's native tree species listed in alphabetical order [*from* Tree Atlas for Vermont (A. I. Prasad 2007-ongoing)]

Common name	Latin name	Current abundance in Vermont (% of trees)	High-emission scenario % change in suitable habitat (Gcm3AvgHiDif)	Low-emission scenario % change in suitable habitat (Gcm3AvgLoDif)
American basswood	*Tilia americana*	0.79	34	10
American beech	*Fagus grandifolia*	8.33	–56	–22
American elm	*Ulmus americana*	1.29	164	72
American mountain-ash	*Sorbus americana*	0.03	–100	–100
Balsam fir	*Abies balsamea*	7.96	–73	–62
Balsam poplar	*Populus balsamifera*	0.15	–100	–100
Big tooth aspen	*Populus grandidentata*	0.84	–20	5
Bitternut hickory	*Carya cordiformis*	<0.01	9,500	3,000
Black ash	*Fraxinus nigra*	0.72	–89	–40
Black cherry	*Prunus serotina*	3.19	5	31
Black locust	*Robinia pseudoacacia*	0.06	2,467	900
Black oak	*Quercus velutina*	0.21	1,695	629
Black spruce	*Picea mariana*	0.23	–100	–100
Black walnut	*Juglans nigra*	0.05	3,320	1,580
Black willow	*Salix nigra*	0.14	707	500
Boxelder	*Acer negundo*	0.19	300	63
Bur oak	*Quercus macrocarpa*	<0.01	10,300	2,000
Butternut	*Juglans cinerea*	0.02	350	550
Chestnut oak	*Quercus prinus*	0.2	1,440	600
Chinkapin oak	*Quercus muehlenbergii*	<0.01	7,100	400
Chokecherry	*Prunus virginiana*	0.09	–89	–67
Eastern cottonwood	*Populus deltoides*	0.06	3,483	1,400
Eastern hemlock	*Tsuga canadensis*	6.2	–32	10
Eastern hophornbeam	*Ostrya virginiana*	2.01	12	1
Eastern redcedar	*Juniperus virginiana*	0.12	3,675	975
Eastern white pine	*Pinus strobus*	5.1	–29	–13
Flowering dogwood	*Cornus florida*	<0.01	34,500	12,700
Gray birch	*Betula populifolia*	0.77	–22	–19
Green ash	*Fraxinus pennsylvanica*	0.12	683	33
Hackberry	*Celtis occidentalis*	<0.01	21,900	5,600
Honeylocust	*Gleditsia triacanthos*	<0.01	18,300	4,200
Jack pine	*Pinus banksiana*	0.06	–100	–33
Mockernut hickory	*Carya tomentosa*	0.08	1,225	325
Mountain maple	*Acer spicatum*	0.53	–100	–98

Common name	Latin name	Current abundance in Vermont (% of trees)	High-emission scenario % change in suitable habitat (Gcm3AvgHiDif)	Low-emission scenario % change in suitable habitat (Gcm3AvgLoDif)
Musclewood	*Carpinus caroliniana*	0.34	191	129
Northern red oak	*Quercus rubra*	2.13	119	100
Northern white-cedar	*Thuja occidentalis*	1.64	–40	–33
Paper birch	*Betula papyrifera*	3.57	–94	–47
Pignut hickory	*Carya glabra*	0.1	1,530	700
Pin cherry	*Prunus pensylvanica*	0.95	–96	–35
Pin oak	*Quercus palustris*	<0.01	2,200	1,600
Post oak	*Quercus stellata*	<0.01	30,000	700
Quaking aspen	*Populus tremuloides*	2.71	–79	–23
Red maple	*Acer rubrum*	11.35	–18	4
Red pine	*Pinus resinosa*	0.33	–36	155
Red spruce	*Picea rubens*	4.7	–58	–51
Sassafras	*Sassafras albidum*	<0.01	16,700	5,200
Scarlet oak	*Quercus coccinea*	<0.01	13,500	4,500
Serviceberry	*Amelanchier* spp.	1.29	33	53
Shagbark hickory	*Carya ovata*	0.16	644	238
Silver maple	*Acer saccharinum*	0.21	690	381
Slippery elm	*Ulmus rubra*	0.11	909	482
Striped maple	*Acer pensylvanicum*	2.53	–57	–29
Sugar maple	*Acer saccharum*	14.28	–50	–32
Sweet birch	*Betula lenta*	0.77	157	178
Sycamore	*Platanus occidentalis*	<0.01	9,700	2,600
Tamarack (native)	*Larix laricina*	0.02	–50	50
White ash	*Fraxinus americana*	4.2	4	22
White oak	*Quercus alba*	0.4	1,143	480
White spruce	*Picea glauca*	0.66	–71	2
Yellow birch	*Betula alleghaniensis*	5.34	–66	–39

Appendix B. Maximizing Forest Carbon Storage and Uptake

Vermont forests play an extremely important role in removing carbon dioxide from the atmosphere and providing a service by storing this as carbon in all parts of trees. The largest amounts of carbon are stored in large diameter trees. While forests are not the problem, they could serve as part of the solution to reduce excess atmospheric carbon dioxide.

Forest carbon management can be viewed as tiers of options, each addition contributing more towards maximizing the role of forests in mitigating climate change. Keeping lands forested is the first tier. Forestland stores and sequesters more carbon that other land uses and by maintaining forestland, there is opportunity to increase carbon sequestration.

Next are ways to maintain carbon during harvesting. There is always some carbon loss from forests associated with logging. Harvesting techniques that can avoid soil disturbance, keeping soil carbon storage intact, and promote rapid regeneration of the site following the harvest will minimize harvest-related carbon emissions and reduce the time-lag before forests again act as net carbon sinks.

The next tier of forest carbon management relates to the types of silvicultural methods employed. Every situation and forest will be different in the balance between management objectives and opportunities to maximize forest carbon uptake and storage. Current science on this topic allows forest managers to pick and choose methods that maximize forest carbon while also achieving landowner objectives.

Another tier of forest carbon storage options relates to the end product use for the harvested wood. Again, factors such as product markets and economics play a large role in determining types of products, but again, there are options that can improve or reduce the time and amount of carbon stored in harvested wood.

The final tier for maximizing forest carbon storage and uptake are those forests left undisturbed. There are exceptions to this in cases where stand-replacing disturbances reduce carbon stores.

Forest Management Options to Maximize Forest Carbon

- Planning your harvest to retain some of the large diameter trees for carbon storage.
- Extending the time between harvest entries or harvest rotations can be valuable for increasing net carbon storage.
- Favoring wood production for durable wood products rather than shorter life cycle products (e.g., wood chips, firewood) improves the storage life of forest carbon.
- Planning harvests to minimize soil disturbance prevents unwanted release of carbon from the forest floor and underlying soils.
- Encouraging rapid regeneration following a harvest minimizes the time that soils are exposed and subject to additional decomposition and carbon emissions.
- Expanding use of milling residuals and waste streams for thermal-driven wood energy use, combined with short rotation bioenergy woody crops (including hybrid willow and popular) for bioenergy production, provided the latter are not established on areas currently occupied by extant forests. Competition with food production is a major concern pertaining to short rotation bioenergy feedstocks on agricultural lands.

Forest Practices Currently Without Scientific Support as Carbon Emission Reduction Strategies

- Expanding the use of wood biomass energy will not reduce net greenhouse gas emissions, at least over the near to mid-term, if net harvest intensities increase. Wood bioenergy has many positives, such as enhanced energy independence, renewability, and economic incentives for working forests and open space conservation, that must be evaluated relative to this potential unintended consequence.

- Increasing harvesting intensity in extant forests to produce wood biomass energy will not reduce net GHG. Shorter rotations favor rapid rates of carbon uptake in younger forests, but come at the expense of existing carbon storage capacity.

  - ✓ Shortening rotations both as a carbon strategy and for climate adaptation has only limited science to support this. An exception is where disturbance frequencies (for events of moderate to severe intensity) are very likely to increase.

  - ✓ Short rotations run counter to forest adaptation strategies that promote "continuous cover" forestry and maintenance of structurally complex canopies to buffer below-canopy microclimate. Continuous cover forestry, structural retention, and extended rotations are most often recommended as strategies that can enhance resilience to change.

  - ✓ Shortened rotations and/or expanded harvests could contribute to net emissions reduction if employed carefully in select locations and as part of a comprehensive strategy also including conservation and extended rotations. This is true so long as the intensified management activities generate genuine substitution benefits (emissions reductions through product substitutions). That can be difficult to definitively substantiate from a market analysis perspective.

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Appendix C. Citations and Additional Literature Resources

Silvics of North America
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Conifers
http://www.na.fs.fed.us/spfo/pubs/silvics_manual/Volume_1/vol1_Table_of_contents.htm

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