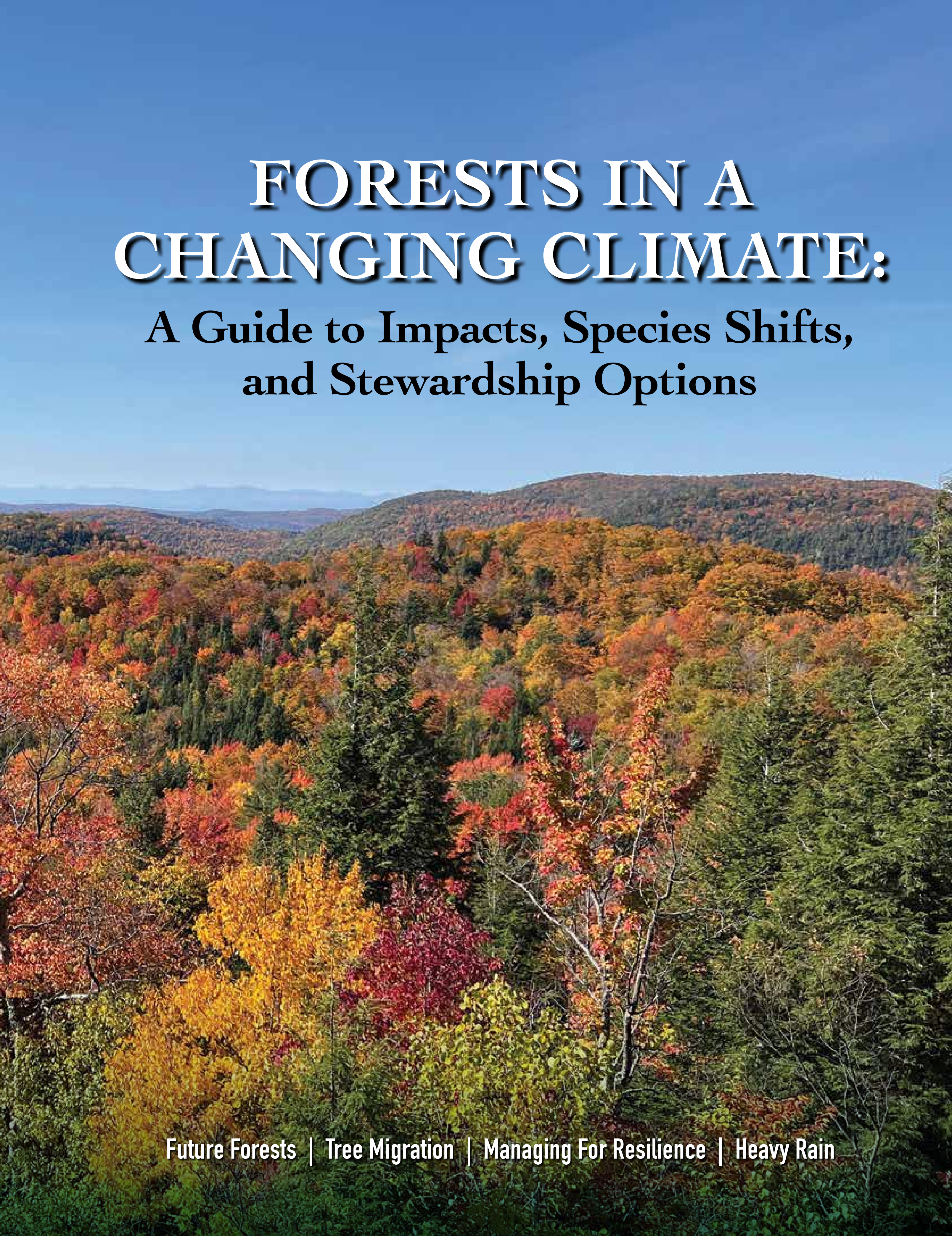
FORESTS IN A CHANGING CLIMATE:

A Guide to Impacts, Species Shifts, and Stewardship Options



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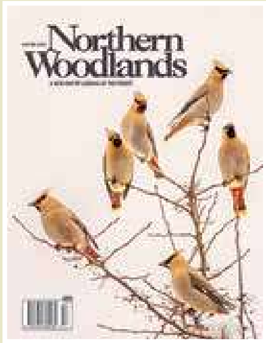

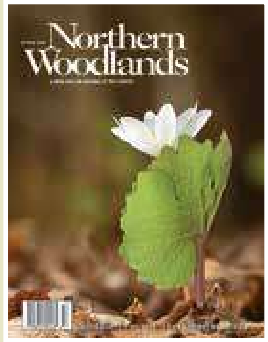

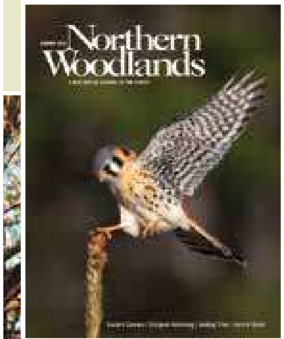

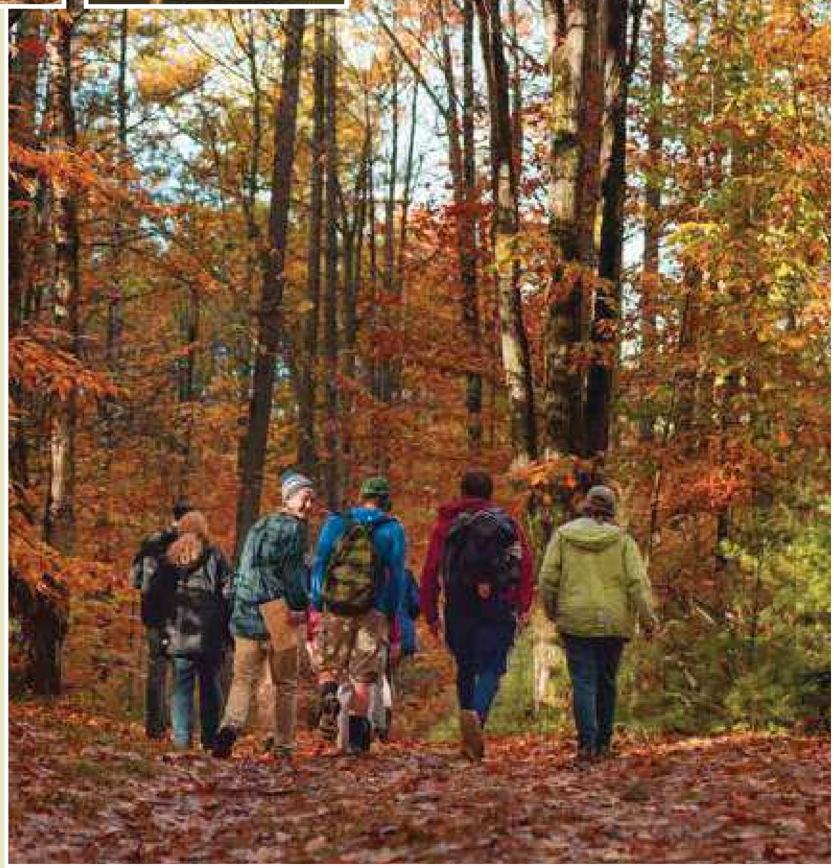

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INTRODUCTION

Forests across the Northeast are already experiencing the effects of a changing climate. Warmer winters, longer growing seasons, heavier rain events, drought, and shifting tree species distributions are altering how forests grow, regenerate, and respond to disturbance. Although these changes create new challenges for landowners and forest managers, they also present opportunities to steward forests in ways that support long-term resilience.

This four-part series that I wrote for *Northern Woodlands* magazine explores how climate change is affecting northeastern forests and what landowners and managers can do to help forests adapt. The articles examine the ecological impacts of changing temperature and precipitation patterns, how tree species may shift across the landscape in the future, the impacts of heavy rain events, and practical strategies for managing forests under increasing uncertainty. Together, the articles highlight the importance of maintaining diverse, structurally complex forests that can better withstand stress and continue providing essential ecosystem services such as clean water, wildlife habitat, carbon storage, recreation, and wood products.

The goal of this series is not to predict exactly what future forests will look like but rather to help landowners and communities better understand the processes already underway and to support informed, proactive stewardship. Climate change adds new considerations to forest management, yet many of the practices that promote resilience – protecting soils and water, encouraging species and age diversity, maintaining regeneration, and reducing vulnerability to disturbance – are also practices associated with healthy forests overall. Although uncertainty remains about the pace and extent of future changes, one thing is clear: the decisions made today will influence how forests respond in the decades ahead.

This project was made possible through a generous gift from the Virginia Wellington Cabot Foundation and financial support from the University of Vermont Extension, College of Agriculture and Life Sciences. The project benefited from collaborations with *Northern Woodlands* editor Elise Tillinghast, illustrator Erick Ingraham, and expert reviewers Maria Janowiak, Matthew Peters, Samantha Myers, and Erin Rodgers.

Alexandra Kosiba

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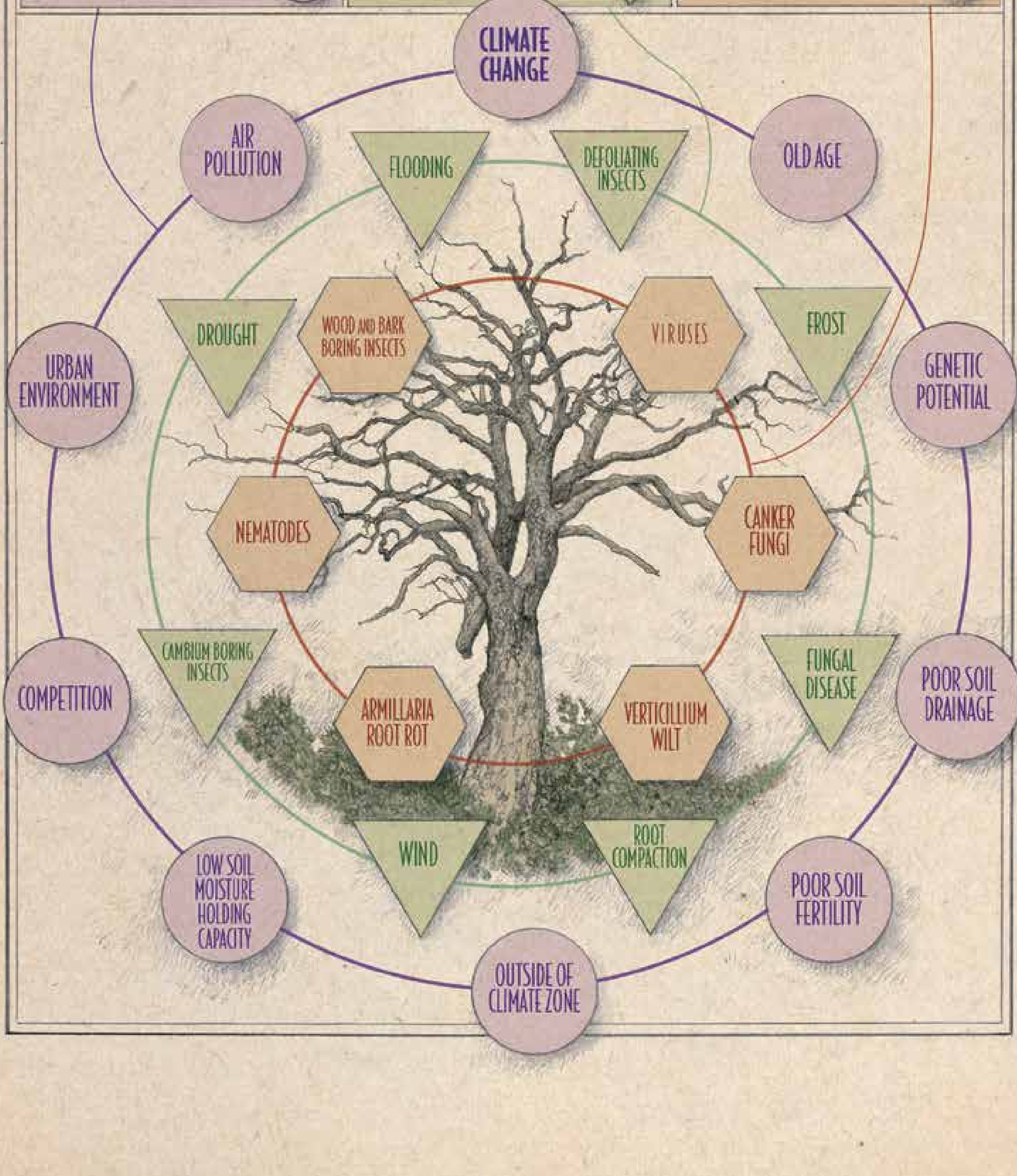
University of Vermont Extension

PROCESS OF TREE DECLINE

Multiple, interacting factors often contribute to a tree's decline. Climate change can add to – and intensify – this combination of factors.

Predisposing Factor	Inciting Factor	Contributing Factor
Character of the tree or its environment Predisposes tree to other stressors Long-term impact May not be noticeable	Typically caused by a physical or biotic stress Very damaging to predisposed tree Short-term impact Often very noticeable	Typically caused by opportunistic insects and pathogens Long-term impact Often very noticeable



CLIMATE CHANGE IMPACTS ON NORTHEASTERN FORESTS

By Alexandra Kosiba. Illustrations by Erick Ingraham.

This article is the first in a four-part series that focuses on climate change impacts and adaptation in forests. A companion series published last year focused on forest carbon. Alexandra Kosiba, a forest ecologist and tree physiologist, is an assistant professor of forestry at University of Vermont Extension. She specializes in climate change impacts to trees and forests and ways that foresters and landowners can incorporate climate change considerations into their decision-making and planning.

It's hard to ignore the changes in the weather we've been experiencing. Winters aren't as cold as they used to be, spring is arriving earlier and fall later, and when it rains, it pours. These changes reflect long-term shifts in the climate. Since 1970, the average annual temperature in the Northeast has risen more than 3 degrees Fahrenheit.[1] This temperature increase is greater than what has been observed for the contiguous United States (2.5 degrees) and the global average (1.7 degrees), but less than for Alaska (4.5 degrees).[2] Depending on future greenhouse gas emissions, climate models predict that the region will experience an additional temperature increase of between 2 and 8 degrees by the end of the century.

As temperatures throughout the world continue to rise, a common pattern is that colder entities are warming faster than warmer ones. For example, Earth's poles are warming faster than the equator, winters are warming more rapidly than summers, and minimum temperatures are increasing faster than maximum temperatures. Because a characteristic of the Northeast's climate has been historically cold and snowy winters, a loss of cold conditions is one of the region's greatest changes.

Predicting the impacts of these changes on forests is complex. Some tree species, in some locations, will benefit, while others will face declines in health and population. For the most part, trees do not die of a single cause, but rather succumb to the combined impact of multiple stressors. A challenge of climate change – and one of the reasons its specific effects can be hard to predict – is that it acts as a "threat multiplier." What this means is that changes in temperature and precipitation can exacerbate other stressors on trees such as insects, diseases, competition from invasive plants, nutrient limitations, and deer browsing.

1 *In this article, the "Northeast" is defined as New York and the New England states. This differs from some larger climate assessments in which the northeast climate region also includes New Jersey, Pennsylvania, Delaware, and Maryland. Climate data retrieved from ncei.noaa.gov/access/monitoring/climate-at-a-glance/statewide/time-series*

2 *nca2023.globalchange.gov*

3 *epa.gov/climate-indicators/climate-change-indicators-length-growing-season*

Lengthened Growing Season

As temperatures rise, the last spring frost arrives earlier than it used to, and the first fall frost comes later. These changes have resulted in a growing season that has lengthened by an average of two and a half weeks in the Northeast since 1895.[3] Some parts of the region have experienced larger increases. For instance, Connecticut has seen the growing season increase by a month.

An extended growing season benefits some tree species by providing more time for photosynthesis. Trees can use this additional energy to grow more, stow away sugars and nutrients, and invest in energy-costly processes, such as making seeds or defense chemicals against pests.

But an extended growing season also introduces challenges. A longer growing season allows some insect species to have more generations per year or to grow larger. When these insects are species that feed on trees, they have the potential to cause unsustainable damage to their hosts. For insects that are beneficial to trees, there is concern that the pace of climate change may lead to phenological mismatches, including divergences between flowering times and the return of pollinators.

Earlier spring conditions and start to the growing season can also elevate the risk of frost damage to newly emerging leaves and flowers. Such an event happened on May 18, 2023 in parts of the region. This freezing event caused noticeable damage to the leaves, flowers, and buds of many trees and shrubs. Whether a tree or shrub suffered from freezing damage depended on both its species and location. Because species leaf out and flower at different times, some late-emerging species, such as beech and oak, were at a more vulnerable developmental stage than earlier emerging species, such as maples. Most frost-damaged trees were able to produce a second set of leaves, although in some cases where leaf buds were also damaged, the new leaves that emerged were small and misshapen, resulting in reduced photosynthesis for the remainder of the growing season. To re-flush a second set of leaves requires use of energy reserves, possibly resulting in less capacity for growth and other important processes. Damage to flowers or flower buds meant that many trees and shrubs did not produce fruit or seeds this past year, which affects not only regeneration potential, but the wildlife that depend on those food sources.

In fall, warmer temperatures, particularly warm nights, can impact trees by delaying the developmental processes that are critical to preparing for winter, including acclimation to below-freezing temperatures. We observe this impact as a late fall foliage season, more muted leaf colors, and unsynchronized timing of peak color among species. Wreath makers are reporting that the timing of needle set in balsam fir, a signal that the tree is preparing for winter dormancy, is occurring later, which can make it more difficult to harvest boughs in time for the holidays.

Milder Winters and Altered Snow Dynamics

Warming in winter has outpaced that of summer, spring, and fall, increasing an average of 4.9 degrees in the Northeast since 1970[4]. This shift alters snow dynamics, leading to more rain than snow, a reduced snowpack, and a shorter snow season. Warmer temperatures may also result in an increase in wet and heavy snow events, which can break tree branches and topple saplings. Although snowfall is variable across the region and from year-to-year, overall snowfall is decreasing, a greater proportion of winter precipitation is falling as rain, and there are more winter days with bare ground.

Changes in the snowpack impact forest ecosystems in various ways. Snow insulates soil, minimizing freeze-thaw cycles and freezing depth. More frequent soil freeze-thaw events and deeper soil freezing can damage the fine roots of trees along with other organisms that live in the soil. Because fine roots are responsible for absorbing nutrients and water from the soil, damage to them restricts water and nutrient transport to the branches, which leads to reductions in vigor and growth. Deeper soil freezing and more freeze-thaw cycles can also cause soil nutrient losses, particularly of nitrogen, which is critical for all life in the forest.

4 *ncei.noaa.gov/access/monitoring/climate-at-a-glance*

Additionally, variations in snowfall affect the subnivean zone – the sheltered area between the forest floor and the bottom of the snowpack. Many wildlife species, such as grouse, mice, and voles, use the subnivean zone as protection from cold temperatures, bitter winds, and predators. Less snow reduces the depth of the subnivean zone, and in some years, it may not exist.

However, for other species of wildlife, a decline in snow may be beneficial. Because white-tailed deer have difficulty traveling in deep snow, deer populations historically have been restricted from the northern parts of the region. If snowpack declines in these locations, it is expected that deer may become more common. Because in winter deer eat tree seedlings and other understory plants, expansion of deer range could cause new impacts to the forests in these locations.

Warmer temperatures in late winter and early spring can also lead to an earlier melting of the snowpack. The melting of the snowpack is an important water source for trees when they are coming out of dormancy and beginning to leaf out. When trees suck up water through their roots, they reduce flood impacts and cycle water back into the forest. Thus, if peak streamflow occurs before trees begin to leaf out, there could be a greater risk of flooding early in spring and a lack of water availability when trees need it most.

Fewer Frigid Cold Winter Nights

Consistent with the pattern that cold entities are warming faster than warm ones, since the 1970s the Northeast's minimum winter temperature has risen a whopping 5.8 degrees compared to a 3.9 degree rise in maximum winter temperature. This means that we are not experiencing the same frigid lows as we did in the past, which has implications for the ecological processes of forests.

Plant and tree species have different abilities to resist injury during exposure to cold temperatures. These differences in cold tolerance limit where each species can grow. For example, balsam fir, one of the region's most cold-hardy trees, can withstand temperatures at least as low as -75 degrees. We can find balsam fir on mountain summits and throughout the coldest parts of the region. In contrast, tulip poplar suffers cold damage when exposed to temperatures below -20 degrees. Tulip poplar grows mostly in the southern part of the region and cannot survive in cold locations in the north. Because the minimum winter temperature at a location is the basis for plant hardiness zone maps, the USDA recently updated the zones to reflect increases in winter low temperatures due to climate change.

As minimum winter temperatures continue to rise, changes in hardiness zones are not limited only to plants. Many insects may be able to expand their ranges. For example, hemlock woolly adelgid is a small, invasive insect in the Northeast that feeds on the needles of hemlock trees, causing declines and mortality. Because the insect is not sufficiently cold hardy to survive in northern New England and New York, its range has been limited to the southern part of the region. However, as the climate warms, it is expected that hemlock woolly adelgid will be able to expand northward.

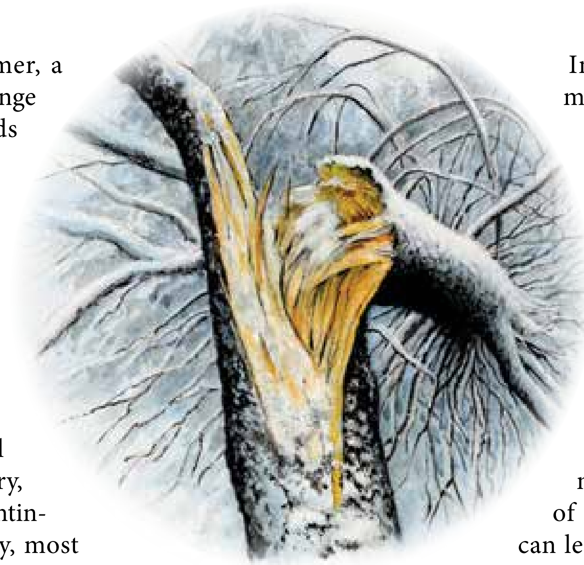
Warmer Summer Nights and Possibility of Heat Waves

Although winters have warmed faster than summers, the average summer temperature has increased by 2.2 degrees since 1970,[5] and in the future, we'll experience more hot summer days with the potential for longer heat waves. Heat waves can be problematic for trees if they coincide with low water availability, in what are called "hot droughts." Hot droughts dry both the air and the soil. When this occurs, trees can lose water from their leaves, which can cause the collapse of the tree's water-carrying tissues – a process known as "hydraulic failure."

Another trend is that summer nights are warming faster than summer days, which is consistent with the trend of minimum temperatures warming faster than maximum temperatures. Warmer nights mean fewer cool mornings and therefore a smaller diurnal temperature range, which is the difference between the warmest and coolest temperatures experienced

5 ncei.noaa.gov/access/monitoring/climate-at-a-glance

in a 24-hour period. In summer, a reduced diurnal temperature range can elevate metabolic demands for trees and increase nighttime water loss, potentially affecting tree growth and overall health.



More Rain and Heavier Rain Events

The Northeast has witnessed a 15-percent increase in annual precipitation over the past century, with projections indicating a continuation of this trend. Seasonally, most of this increase is occurring in summer and fall, while winter and spring have seen much less change.[6] As mentioned earlier, a greater proportion of winter precipitation is falling as rain rather than snow due to warmer temperatures.

More rain can benefit trees by increasing water availability, but prolonged periods of cloud cover reduce sunlight and, therefore, a tree's ability to photosynthesize. More wet days can create ideal conditions for the proliferation of foliar fungi and other diseases. Typically, these leaf diseases are not deadly for a tree, but they reduce photosynthetic capacity and often cause premature leaf drop. If foliar diseases persist for multiple growing seasons, and especially if they're coupled with additional stressors, trees may experience health declines or even mortality.

Not only has total precipitation increased, but heavy rainfall events have become more common. Most climate models indicate that this trend will continue. Heavy rainfall events that deposit multiple inches of rain pose challenges to forests, causing different impacts depending on the location and soils. In low-lying and flat areas, heavy rain can lead to more frequent and severe flooding. Following an extreme rain event, soils may remain water-logged because of a high water table or slow draining. Tree species that are adapted to wet areas, such as willows and cottonwoods, can tolerate water-logged soils, but upland species, such as sugar maple and white pine, may suffer. For this latter group, prolonged wet soils can cause root mortality and health declines. Saturated soils can also make trees more susceptible to being knocked over by strong winds.

In sloped terrain, heavy rain may mean that soil cannot absorb water quickly enough, and instead, water flows over the surface of the forest floor. Overland flow accelerates downslope, and in doing so it transports leaf litter, twigs, soil, and nutrients. Loss of leaf litter and soil can expose the fine roots of trees, causing them to be damaged or to dry out after the rain has subsided, in turn affecting the trees' ability to take in nutrients and water. Large amounts of soil erosion and nutrient leaching can lead to sedimentation in streams and lakes, negatively affecting water quality. Heavy rain events can also damage roads and trails, especially where there are culverts or drainages that are not able to accommodate the extreme flows.

Increased Possibility of Drought

Despite the overall increase in rainfall, warmer temperatures and longer periods of time between rain events can lead to drought. Warmer air can hold more water vapor than cooler air, and higher temperatures cause water to evaporate from the surface of leaves and soil more easily. Other site factors, such as the presence of earthworms and a lack of leaves, wood, and other dead organic matter on the forest floor, can further exacerbate soil drying. Because precipitation patterns are highly variable across the region and site conditions strongly affect hydrology, we will likely see that drought affects some areas, while other locations have ample moisture.

Although seasonal droughts are a normal occurrence in our region, if they become more extreme or frequent, they could cause stress to trees and forests. Dry soils are particularly harmful to seedlings that have not yet developed a deep root system. Trees can regulate water loss from their leaves by closing their stomata, which are small pores on the surface of leaves that allow the intake of carbon dioxide and release of oxygen and water. When a tree closes its stomata to reduce water loss on dry days, the tree's ability to capture carbon dioxide and to photosynthesize is also reduced. Trees can withstand dry periods by relying on stored carbohydrates and

6 ncei.noaa.gov/access/monitoring/climate-at-a-glance

water, but only as long as their resources last.

Some tree species are more tolerant of drought than others. Thicker, waxier leaves, smaller or needlelike leaves (such as those of pine trees), as well as trees that are shorter in height, are examples of traits that can make certain species more drought tolerant than others.

Drought conditions can also make some trees more susceptible to other stressors, such as insect infestations. For example, drought stress can reduce a tree's ability to produce and transport defense chemicals, which can then make the tree susceptible to wood-boring beetles, whose entry holes may be exploited by opportunistic decay fungi. As discussed earlier, hemlock woolly adelgid may be able to exist in new locations as winters continue to warm. In addition to this climate impact, the occurrence of drought can make hemlock trees more likely to succumb to the adelgid's feeding.

Prolonged droughts may also lead to an increased risk of forest fires. However, fire itself is not always a threat to forests. In fact, some forest types in the Northeast are adapted to fire. This means that many of the tree and plant species that live in these communities rely on fire for reproduction or to be able to compete with other plants. For example, pitch pine has serotinous cones that remain closed until fire melts the resin that holds the seeds inside. Fire also creates ideal conditions on the forest floor for the pitch pine seeds to germinate. But decades of fire suppression have reduced this natural process. While fire can be beneficial to ecosystems adapted to fire, it could have more negative impacts on ecosystems that are not fire adapted or where fire affects human communities.

Possibility of More Wind and Ice Storms

The Northeast may face more severe weather conditions, including ice storms and damaging winds. These events can have detrimental effects to forests, causing limbs to break and trees to topple. These types of events can facilitate forest development, creating complexity and diversity. However, wind and ice storms have different impacts depending on the size and species of the trees. Stands with a single species or trees of similar size can suffer more extensive damage and take longer to recover than a multispecies, multi-aged stand. Wind and ice storms are often most problematic to our infrastructure, such as power lines, roads, trails, and sap lines in sugarbushes.

Adapting to Climate Change

Trees can't, of course, move to more favorable locations when local conditions become stressful. They must adapt to the new conditions or perish. Declines in forest health can have numerous negative secondary effects, including emissions of stored carbon into the atmosphere, loss of wildlife habitat and biodiversity, decreases in wood supply, and reductions in the many ecosystem benefits forests provide, such as controlling soil erosion and regulating water.

Although individual trees are not able to migrate, species of trees can move to more favorable locations through their progeny. Over millennia, forests have adapted to substantial climate changes, but the current rate of change poses special challenges. Climate change is generally expected to outpace the distance that seeds can move through natural migration.

In general, the future climate in the Northeast is anticipated to be more stressful for trees adapted to cold climates, such as balsam fir, northern white cedar, and black spruce, while those trees adapted to warmer conditions, such as red oak, tulip poplar, and bitternut hickory, may be able to grow in new locations. A deeper exploration of differences among tree species, as well as strategies we can take to steward forests under changing conditions, will be addressed in future articles.[7]

Special thanks to our reviewers of this article: Maria Janowiak, Acting Director – USDA Northern Forests Climate Hub, and members of the State Leadership Committee of the Securing Northeast Forest Carbon Program.

7 For more information on climate change and forests, visit uvm.edu/extension/forestry-climate-change.

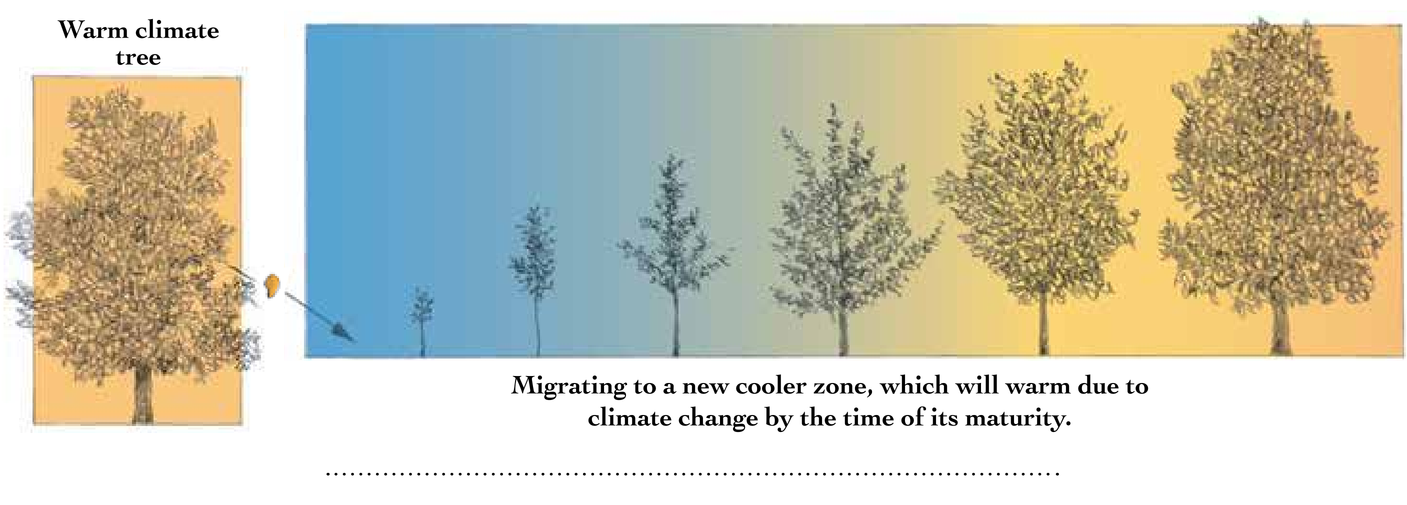
FUTURE CLIMATE-ADAPTED TREE SPECIES

By Alexandra Kosiba. Illustrations by Erick Ingraham.

This article is the second in a four-part series that focuses on climate change impacts and adaptation in forests. A companion series published last year focused on forest carbon. Alexandra Kosiba, a forest ecologist and tree physiologist, is an assistant professor of forestry at University of Vermont Extension. She specializes in climate change impacts to trees and forests and ways that foresters and landowners can incorporate climate change considerations in their decision-making and planning.

When we think about the impacts of climate change on our forests, it's crucial to understand that these changes will affect individual tree species differently. Some trees, in certain locations, will experience declines, while others will thrive. This variability stems from the unique physiology and ecology of each tree species, which determine the conditions in which the species grows and how it responds to environmental shifts. Consequently, as the climate changes, the composition of the forest community will also change.

To manage forests effectively in the face of climate change, we must grapple with several challenging questions. For instance, which species are most capable of adapting to changing conditions, and which ones may struggle? How might shifts in the forest community impact other objectives such as promoting wildlife habitat, carbon storage, flood prevention, and wood production? How rapidly can a forest change its tree species composition, and when is it appropriate to introduce new species? If we do choose to introduce new species, how far should we relocate these species within a forest to ensure their success?

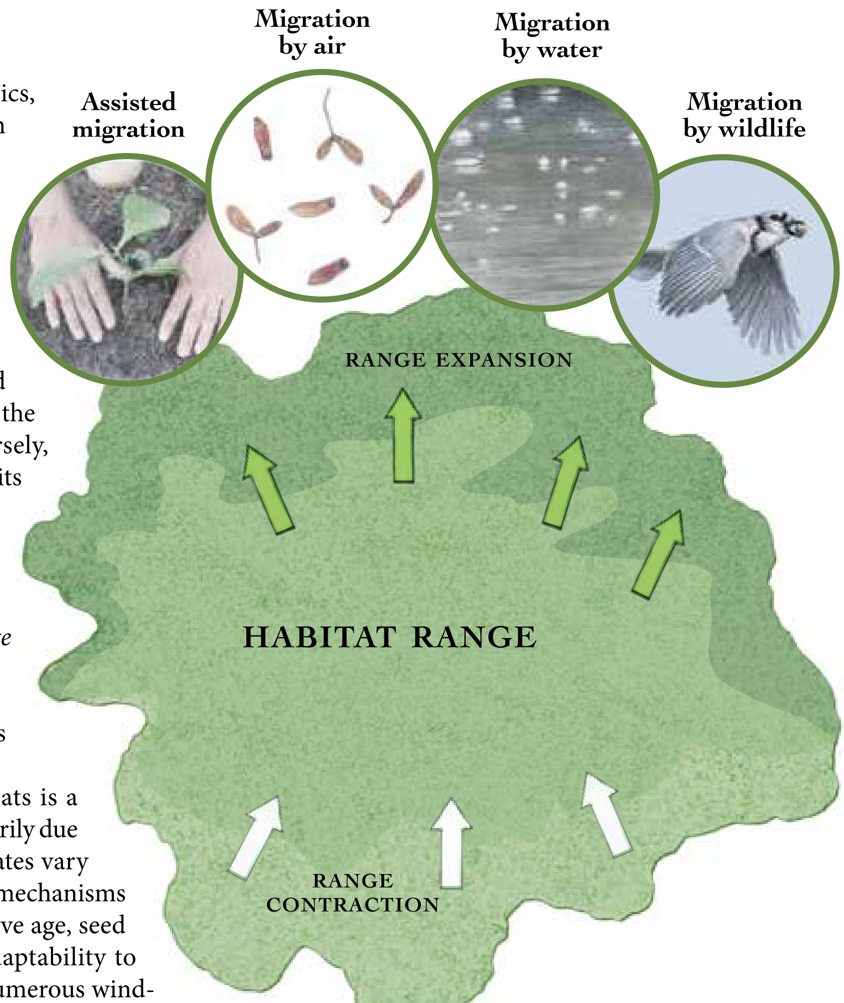


Migrating to a new cooler zone, which will warm due to climate change by the time of its maturity.

Trees on the Move

A combination of soil types, site characteristics, temperature tolerances, and precipitation levels collectively define a tree species' *habitat range* – the geographic area where all individuals of that species reside. As climate and environmental conditions change, the boundaries of this habitat range may contract or expand.

For instance, as temperatures rise, more of a tree species' seeds that disperse northward or to higher elevations may survive, allowing the species to establish in nearby areas. Conversely, at the southern edge or lower altitudinal limits of the habitat range, seeds may encounter less favorable conditions than in the past, leading to the decline and potential disappearance of the species from those areas. Scientists call these movements *range migrations*. More specifically, *range expansion* is when a species establishes in new habitats, and *range contraction* is when a species retreats from historical habitats.



Natural range expansion into new habitats is a process that spans multiple generations, primarily due to the slow maturation of trees. Migration rates vary among species, influenced by seed dispersal mechanisms (such as wind, water, or animals), reproductive age, seed production frequency and quantity, and adaptability to changing conditions. Species that produce numerous wind-dispersed seeds and reach reproductive age quickly may be able to move to new locations more rapidly. However, successful migration entails more than just arriving in a new habitat; seeds must find suitable conditions for germination, growth, and survival, including sunlight, water, and nutrients.

In the Northeast, a notable example of range migration is the recolonization of the region by trees following the last ice age. Starting around 12,000 years ago, pine, spruce, birch, larch, fir, and aspen began moving north into the tundra. Then came oak and hemlock. Later arrivals included beech, maple, and chestnut. Over millennia, northeastern forests developed and rearranged as species gradually migrated into the region, adapting to prevailing conditions along the way.

In contrast, range contraction can happen more quickly. Factors such as changes in temperature and precipitation, declines in snowpack, alterations in rainfall seasonality, soil drying, insects and diseases, competition from other plants, and heavy browsing by deer can all decrease seedling survival. When these stressors coincide with losses of older, seed-producing trees – such as mass infestations of invasive insects triggered by warming winters – a tree population may rapidly decline in part of its habitat range.

Over time, expansion at the leading edge and retreat at the opposite side can shift an entire tree species' habitat range across the landscape. These shifts, along with changes in other tree species' habitat ranges, shape forest communities.

Future-adapted Tree Species

In the Northeast, there are now more than 100 different native tree species, each with its own unique habitat range. While no two species have identical habitat ranges, we can categorize the region's trees into three broad groups to help us understand potential range shifts in response to climate change.

The first group comprises tree species with current habitat ranges that extend farther north, such that the Northeast sits along the southern end of their range. Species in this group include balsam fir, white spruce, quaking aspen, paper birch, northern white-cedar, pin cherry, black ash, and tamarack (larch). A warming climate poses challenges for this group because they are adapted to colder locations. Consequently, their ranges may contract northward or to higher elevations. We're already observing such shifts for species such as balsam fir, northern white-cedar, paper birch, and quaking aspen[1].

The second group includes species with the center of their habitat range in or near the Northeast, such as sugar maple, white pine, eastern hemlock, American beech, red maple, and yellow birch. These species may exhibit varied responses to climate change due to their wide distribution across the region.

The third group includes species with ranges extending south, with the Northeast being historically at the northern limit of their range. Examples include white oak, shagbark hickory, tulip poplar, eastern red-cedar, red oak, bitternut hickory, black cherry, and American sycamore. These species, adapted to warmer and more southerly areas, may expand their ranges farther into the region due to climate change.

Additionally, there is a fourth group to consider: species native to the mid-Atlantic states whose ranges do not currently extend into New England and New York. As the climate warms, these species may find new suitable habitat. This group includes more than 30 tree species, such as loblolly pine, pecan, eastern redbud, honey-locust, Virginia pine, and pawpaw.

Tree species likely to thrive and expand their range in the Northeast under future climate conditions are considered future *climate-adapted.* However, there's significant variation in suitability for different growing conditions within this group. For instance, the suite of tree species best suited to the future conditions in southwestern Connecticut differs from those for northern Maine. Factors such as soil, site characteristics, management goals, and future temperature and precipitation are essential considerations.

The Climate Change Tree Atlas

To offer insights into potential future habitats for tree species in the eastern United States amid changing climate conditions, the USDA Forest Service has developed a freely accessible online tool called the *Climate Change Tree Atlas*[2]. By analyzing data from 85,000 Forest Inventory and Analysis plots, scientists identified the current distribution of each tree species based on factors such as elevation, soil, and climate. Using future climate projections and statistical models, they predict potential suitable habitats for each tree species by 2100.

A tree species' future success isn't solely determined by changes in temperature and precipitation patterns. Individual tree species have certain traits that can contribute to their migration rates, as well as to their adaptability or vulnerability to disturbances and stressors. To provide insights to the potential of each species to reach new suitable habitats, the *Tree Atlas* uses a species' past migration rate to assess the likelihood that the species will be able to migrate to these new locations. Understanding these traits can inform conservation strategies and management practices to promote resilient forest ecosystems.

Additionally, traits such as fire tolerance and resistance to windthrow could contribute to a species' adaptability, while susceptibility to pests and diseases and sensitivity to animal browsing, for example, could hinder a species' future success. The *Tree Atlas* rates the traits of each species based on their positive or negative effects on adaptability compared to other species. For instance, balsam fir receives a negative adaptability score due to its susceptibility to pests and wood rot fungi, while eastern cottonwood gets a positive rating for its ability to endure prolonged flooding. Among our native species, red maple has the highest adaptability score, while black ash ranks the lowest. These adaptability scores can help us better understand how likely it is for a species to persist given a combination of stressors.

It's important to acknowledge that while the *Tree Atlas* aids decision-making, it doesn't encompass all aspects of tree physiology and ecology that influence species' responses to climate change. For example, there is considerable variability in traits within a species, leading to differences in growth, site tolerances, and adaptability among individuals. Natural selection can drive adaptations to new conditions, and some species can hybridize with related ones, producing offspring with beneficial traits for rapid adaptation.

For summarized lists of *Tree Atlas* species projections for different regions, see the Climate Change Response Framework[3]. Keep in mind that the reliability of the *Tree Atlas* projections varies by species, indicated by a reliability score. Generally, widely distributed species have higher reliability, while rare ones have lower reliability. Despite lower reliability, the model still offers insights into future changes, albeit with less confidence.

1 Fei et al. 2017. Divergence of species' responses to climate change. Science advances, 3(5).
2 https://www.fs.usda.gov/nrs/atlas/tree
3 https://forestadaptation.org/learn/resource-finder/climate-change-projections-individual-tree-species-new-england-and-northern and https://forestadaptation.org/learn/resource-finder/climate-change-projections-individual-tree-species-mid-atlantic-region

Barriers to Tree Migration

As noted above, numerous factors influence a tree species' ability to migrate, including land use changes, how quickly trees within that species attain reproductive age, seed viability, competition from other plants, weather patterns, herbivory, and insects and diseases. This means that even if a location offers suitable habitat for a tree species in the future, that species may not be able to become established there.

An unprecedented challenge trees face is that the climate is changing much faster than historical migration rates. Researchers estimate that following the last ice age, tree migration rates averaged less than 350 feet per year[4]. To match projected rates of climate change, trees may need to migrate much faster – up to 5 miles per year. Compounding this difficulty is the fragmentation of the landscape due to roads, farm fields, densely settled areas, and other intensive developments, which act as barriers to migration.

Given these obstacles, there is a substantial risk that certain tree species, particularly rare or uncommon ones, may fail to migrate to favorable locations quickly enough, and could experience population fragmentation and extirpation in parts of the Northeast. Widely distributed species such as sugar maple are unlikely to face complete habitat loss, but rapid climate change could lead to shrinking habitat ranges and declines in areas where they were once abundant.

Beyond the risk to individual species, there is concern that change is happening so rapidly, accompanied by numerous other stressors, that currently abundant tree species could decline faster than new species are able to establish, jeopardizing the forest's ability to sustain habitat and ecosystem services, including carbon storage and sequestration.

Assisted Migration of Tree Species

To address the impacts of rapid climate change on forests and individual tree species, some conservation groups, forest managers, and scientists are experimenting with assisted migration – planting tree species at new growing sites in anticipation of changing climate conditions. There are three general approaches.

Assisted population migration involves planting trees in new locations within a species' existing habitat range. This

4 Aitken et al. 2008. Adaptation, migration or extirpation: climate change outcomes for tree populations. Evolutionary applications, 1(1), pp. 95–111.

strategy is primarily used to enhance the resilience and adaptation of a forest to expected future conditions. An example of assisted population migration is collecting red oak acorns from a low elevation site and planting them at a higher elevation. In this scenario, red oaks growing at the lower elevation are adapted to a slightly warmer climate than currently exists at the planting location. Therefore, they may be better suited to the future conditions of the planting site.

Assisted range expansion involves planting trees in suitable areas just north of the species' current range in order to accelerate natural migration. This strategy may help to transition the species' composition of a forest to include a greater proportion of future climate-adapted species. An example is planting tulip poplar in a northern Massachusetts forest, just north of its current range.

Assisted species migration involves moving species far beyond their current range and what natural dispersal would allow over many decades. This strategy can help to conserve species with narrow habitat ranges or low migration potential. An example is planting Virginia pine in southeastern New York. Although the *Tree Atlas* projects some areas with future suitable habitat for Virginia pine in southeastern New York by the end of this century, there is a very low likelihood that the species will be able to migrate to this area without human intervention. Compared to other forms of assisted migration, this strategy has the highest risk of failure and potential for unintended consequences, such as inadvertently moving tree-infesting insects and diseases to new areas.

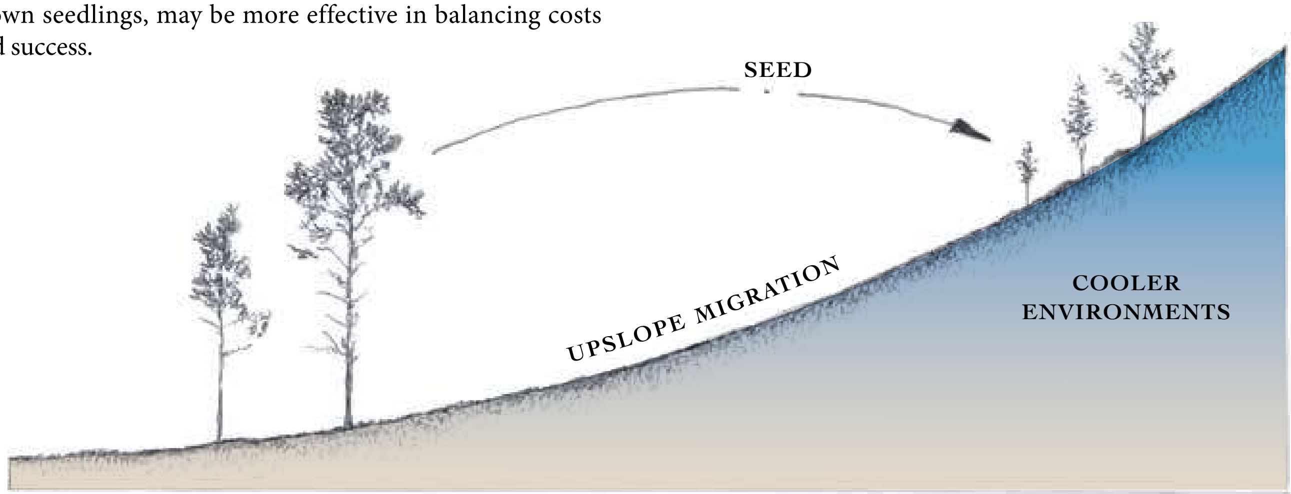
There are several challenges to assisted migration. Monitoring has revealed that although locally adapted trees may not always be well positioned for the future, they often outcompete transplanted young trees. Planting trees is also labor-intensive and costly, and these trees may require significant upkeep before they become established. Some evidence suggests that planting seeds, rather than nursery-grown seedlings, may be more effective in balancing costs and success.

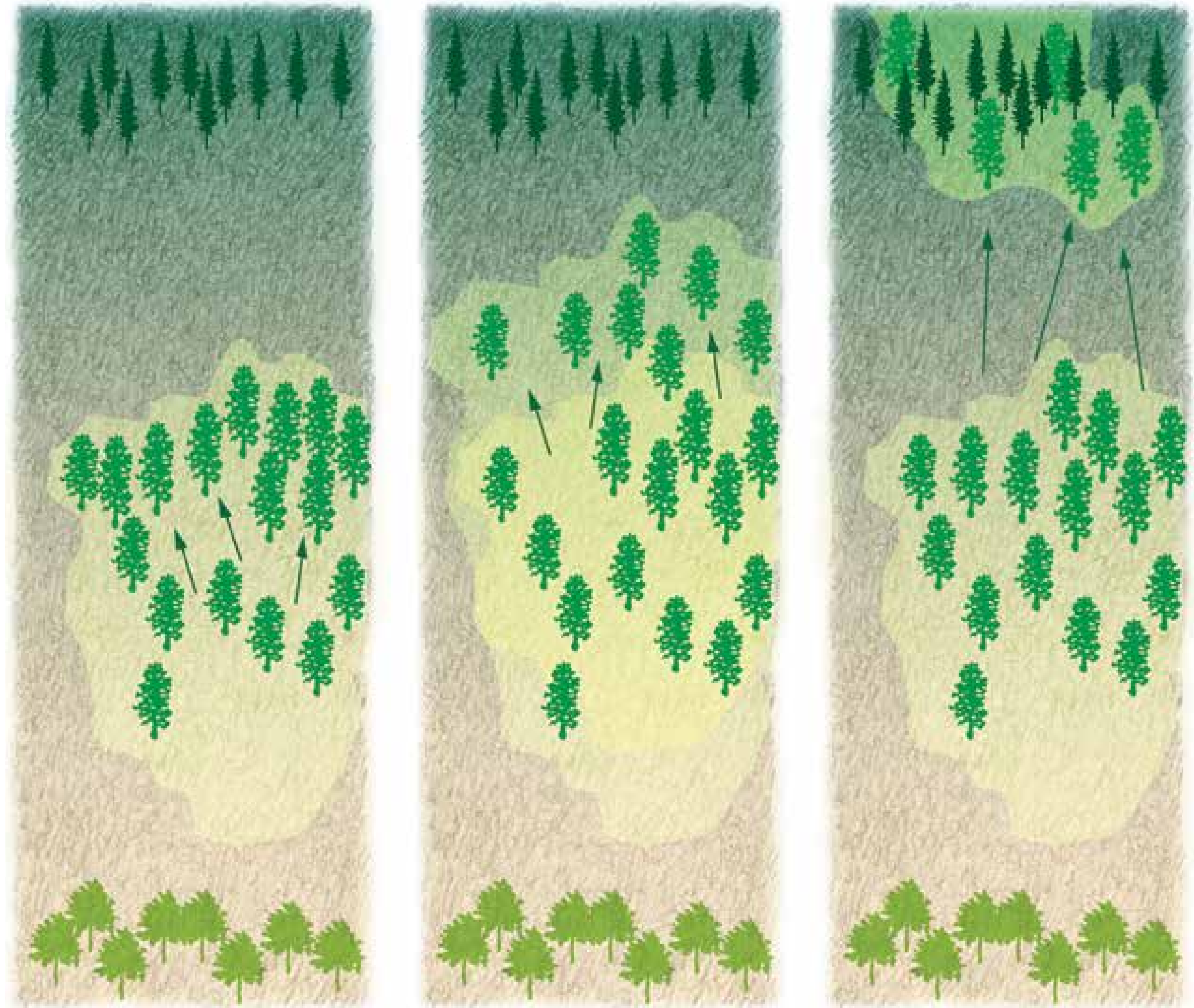
One key obstacle to assisted migration lies in the collection of the seed source, whether for direct planting or to grow seedlings. Given the trait variability within a species, it is crucial to select seeds originating from a variety of locations to enhance resilience to future conditions. Ideally, seeds should be sourced from locations that match the expected future climate of the planting site so that the seedling can both tolerate the current conditions as well as thrive in the future. However, implementing this approach can be difficult. Currently, most plant nurseries do not specify seed origin, and the overall availability of planting stock for many tree species is limited.

One of the biggest challenges with assisted migration is that the planted tree needs both to survive current conditions as well as future conditions that may be significantly different. Trees are unlikely to grow well if planted too far north from their origin, primarily due to their intolerance of cold temperatures. For example, U.S. Forest Service climate models indicate that by 2100, northern New Hampshire will have suitable habitat for pignut hickory, a species with high wildlife food value. However, northern New Hampshire is currently classified as belonging to a hardiness zone 3 (minimum winter temperature of -35 degrees Fahrenheit), and pignut hickory is only hardy to zone 5 (minimum winter temperature of -20 degrees F). As a result, planted pignut hickory in northern New Hampshire would likely suffer from cold injury in winter and may not survive long enough to experience more favorable climate conditions.

Managing Forests for the Future Climate

Understanding the effects of climate change on forest communities is essential for informed decision-making in forest management. By combining traditional forestry knowledge and practices with emerging climate science, we





Assisted Population Migration **Assisted Range Migration** **Assisted Species Migration**

can enhance the resilience of forest ecosystems. One strategy is to identify and promote future climate-adapted tree species.

The *Tree Atlas*, and the "Climate at a Glance"[5] site described in the prior article in this series, can help forest managers plan, manage, and plant for the future. However, specific site conditions and local factors are also important for selecting future climate-adapted species. Analyzing the tree composition of similar sites located at lower elevations or to the south can provide valuable insights into which species might succeed at your site in the future. Also keep in mind that because of the complex topography and weather patterns in the Northeast, certain locations such as north-facing slopes and cold air drainages may naturally remain cooler than their surroundings, supporting current tree species communities in the long term. Seeking the advice of a professional in your area, such as a forester or ecologist at your state forestry agency or local extension office, is an important next step.

The cascading impacts of these forest changes on other parts of the ecosystem are still uncertain. It is unclear how these shifts will affect the ability of our forests to sequester and store carbon, or to continue to provide many other essential ecosystem services. However, one thing is clear: greater greenhouse gas emissions stress trees more, forcing their ranges to shift larger distances and putting forests at greater risk. Despite this uncertainty, as forest stewards, we have enough information to be proactive and consider future tree communities in our management plans. We are wise to do so to ensure that our future forests continue to provide critical benefits to both nature and people.

Special thanks to our reviewers of this article: Maria Janowiak, Acting Director – USDA Northern Forests Climate Hub, and Matthew Peters, Ecologist, USDA Forest Service, Northern Research Station.

5 ncei.noaa.gov/access/monitoring/climate-at-a-glance

A comparison of different stages of forest development. At the top is a forest that lacks variation in tree size, species, and structure, and may be vulnerable to climate change impacts, disturbances, and other stressors. In the lower image, management interventions have created a more diverse and complex forest, with protections to soil, water, and biodiversity that can help build resilience.

MANAGING FORESTS FOR RESILIENCE

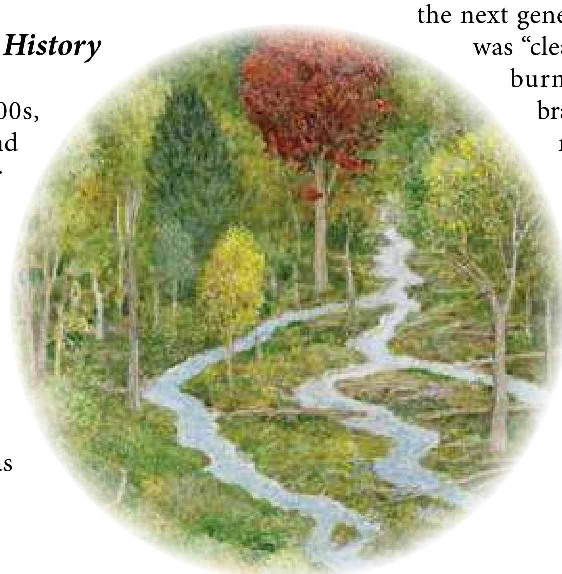
By Alexandra Kosiba. Illustrations by Erick Ingraham.

This article is the third in a four-part series that focuses on climate change impacts and adaptation in forests. A companion series published last year focused on forest carbon. Alexandra Kosiba, a forest ecologist and tree physiologist, is an assistant professor of forestry at University of Vermont Extension. She specializes in climate change impacts to trees and forests and ways that foresters and landowners can incorporate climate change considerations into their decision-making and planning.

As we consider how to best steward forests in a changing climate, it is important to recognize that there is no one-size-fits-all approach. Each forest has unique characteristics and conditions that influence its vulnerability to disturbances and stress. The current community, age, and structure of a forest reflect specific soil and site conditions, its elevation and climate, and the type and timing of past land uses. Understanding where your forest sits along a developmental pathway can help you incorporate climate-focused strategies to advance resilience in an uncertain future.

The Importance of Land Use History

Between the 1600s and late 1800s, more than 50 percent of forestland in the Northeast was cleared for agriculture and settlements. Many of the remaining forests were also subject to timber extraction. When people began to move westward and abandon farms, many fields began to revert to forestland. However, these second-growth forests did not possess the same characteristics as their predecessors. In some areas, livestock grazing caused soil compaction, while in other locations, plows had tilled and leveled soils. Although trees grew back, the species that dominated were those that easily established on open land, such as white pine and paper birch.



In subsequent decades, additional timber harvesting occurred in these second-growth forests as well as in forests that had never been fully cleared. Often, these practices were unsustainable. For example, *high-grading*, the practice of harvesting the largest, healthiest, and most valuable trees, simplified the mix of species, reduced the variety of tree sizes, and removed important sources of seeds for the next generation. Another common practice was "cleaning" the woods by removing and burning any dead trees and downed branches, which degraded biodiversity, reduced stormwater retention, and deprived soils of nutrients. This practice has left a legacy of deadwood deficiencies in many forests today.

Overall, the land use history in the Northeast has resulted in a forested landscape that is younger, less diverse, and less structurally complex than the forests that once dominated the region. Today, more than 80 percent of the region's forests are between 40 and 120 years old. While seemingly old to us, from an ecological perspective, these forests are young to middle-aged. Some of these forests may also have other evidence of past land uses, such as old roads or trails.

Climate Change and Forest Resilience

The impacts of climate change on forests will be both direct, through increases in temperature, rainfall, and extreme weather events, and indirect, through increased stress on trees, shifting disturbance patterns, and effects on pests, diseases, and invasive plants. Forests that are relatively uniform in tree age, species type, and canopy structure – and those with degradation from past land uses – may be more vulnerable to greater impacts under this pressure. *Vulnerability* is the degree to which a forest is susceptible to and unable to recover from climate change.

Conversely, forests with more diverse communities and complex structures are likely to fare better because they have more options for recovery. *Resilience* is the capacity of a forest to recover or adapt following disturbance or stress. Resilient forests typically have a diversity of tree species and ages, which allows them to accommodate change and to continue as forests after experiencing disturbances or stress. Different species and ages of trees have varying stress tolerances and disturbance susceptibilities. Although a resilient forest may not retain the same species or appearance as it did before a disturbance, it will continue to provide essential services such as clean air and water, wildlife habitat, recreational opportunities, timber resources, carbon sequestration and storage, and flood prevention.

Other features of resilient forests, as seen in old-growth forests, include the presence of large trees, ample deadwood in various stages of decay (both standing dead trees and downed logs), and intermittent gaps in the forest canopy. These canopy gaps support a wide diversity of regenerating trees and a broad wildlife community and food web. For example, canopy gaps promote plant species such as shrubs and brambles that can enhance the diversity of forest birds that, in turn, help regulate insect populations.

Due to the region's past land use, many forests are at a developmental stage with a dense, uniform overstory canopy and few sun-filled gaps. Without variation in the canopy, there are limited opportunities for a diverse community of new trees to establish if the current overstory trees decline from climate stress or other disturbances. These forests may also have other characteristics that increase vulnerability, such as a lack of deadwood to slow and retain stormwater, invasive plants that hinder tree regeneration, or old access roads that can cause soil erosion on steep slopes.

Recognizing the importance of land use history on forest development, we can make stewardship decisions that enhance forest resilience to climate change through adaptation. Climate adaptation involves preparing for and responding to anticipated climate change impacts by reducing vulnerabilities and advancing forest resilience through restoration, planned enhancements, and avoided degradation. For all forest types, promoting and maintaining resilience over time requires a clear appraisal of the risks and opportunities presented by climate change and other stressors, including an understanding of how local site conditions and management history might make a particular forest more or less vulnerable to climate change impacts.

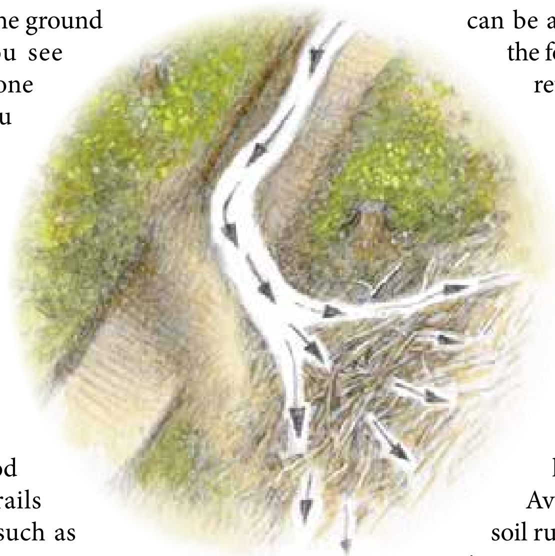
Assessing Risks and Vulnerabilities

A critical step in long-term planning is to assess possible vulnerabilities to climate change and other stressors to guide which management strategies might be best to lessen possible impacts. One helpful way to do this is to look at the forest in three horizontal layers: the overstory, the area between the ground and overstory, and the forest floor.

Start by looking up at the overstory trees. Are the trees of similar size or species? Do the trees have small, narrow canopies? Are they growing very close together such that little light reaches the forest floor? These are some conditions that may increase your forest's vulnerability to extreme events and disturbances.

Next look at the area between the ground and the overstory trees. Do you see only a few tree saplings, or only one or two different species? Do you see invasive plants or extensive evidence of animal browsing on twigs and stems? These are some conditions that may affect the ability of your forest to remain a forest in the future.

Last, look at the forest floor and consider what's damaged or missing. Are there areas of soil erosion or rutting? Is there an absence of logs and other deadwood on the ground? Do roads and trails lack water diversion structures, such as water bars, dips, or culverts? These are some conditions that can affect the soils and water quality of your forest. Take the time to go to different areas of your forest and repeat this three-layer assessment. Once you've evaluated the condition of these layers in different areas of your forest, you can begin to consider actions that you might take to improve resilience.



Managing Forests for Resilience and Adaptation

Where you identify possible vulnerabilities, you can take steps to advance the resilience of your woods. A toolbox approach is highly effective, allowing you to prioritize and combine different strategies. Here are 10 key strategies to promote resilience and to support the goal of managing forests for carbon benefits, as detailed in last year's forest carbon series:

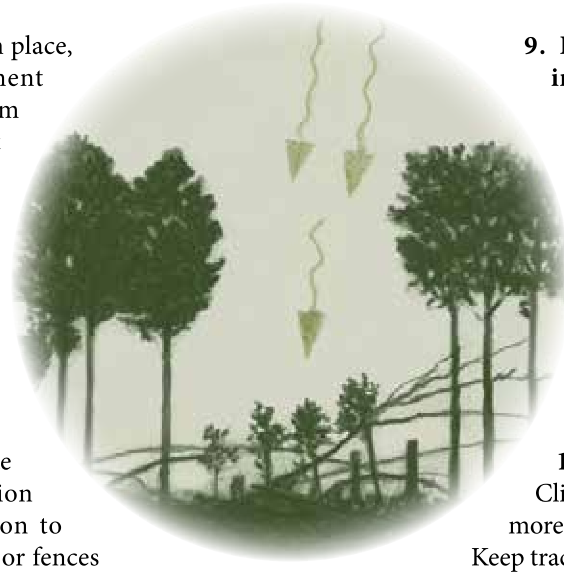
1. Keep forests as forests. The Northeast loses forestland to other land uses every year. Connected forests allow species to move as conditions change, promoting biodiversity. Preserve your forest through estate planning, conservation easements, or other methods.

2. Slow, spread, and sink water. Climate change is bringing more rain and stronger storms, which can cause soil erosion and nutrient loss. Use water diversion structures such as water bars or dips on roads and trails, and ensure culverts or bridges can handle extreme flows. Minimize water channelization by diverting water into depressions or flat areas where the water can be absorbed more slowly. Deadwood on the forest floor can also help slow down and retain water, especially when positioned perpendicular to the slope. Close out old, unused roads or trails to prevent erosion. Walking in your woods during or after heavy rainfall can help you see where water travels to identify problem areas.

3. Protect soils and water quality. Soil and water quality are crucial for long-term forest health. Plus, in most northeastern forests, more than half of the stored carbon is in the soil. Avoid traveling on wet roads to prevent soil rutting, compaction, and erosion. When using equipment in the woods – whether for logging, trail building, or recreation – minimize impacts by using equipment designed to reduce damage, working when the ground is dry or frozen, or using bridges and logs on trails. Pay particular attention to minimizing impacts of soil near waterbodies. Protect water sources and sensitive soils, such as areas that are wet, clayey, or mucky. A good strategy is to maintain plants and trees along waterways, wetlands, and steep slopes to stabilize soils.

4. Enhance species diversity and structural complexity. As noted previously, forests that have uniform age and a simple canopy structure are less well positioned to adapt to change, and are more vulnerable to single, forest-wide disturbance events. You can use forest management, including timber harvests and noncommercial cutting, to increase the number of species present in the woods and to create more variation in the forest's structure. When considering complexity, analyze the larger landscape: Are there similar or different conditions in adjacent areas to your property? For example, if the surrounding area is mostly mature forest, creating a few canopy gaps can help create landscape diversity and act as steppingstones for certain species.

5. Increase deadwood. Standing dead trees and downed logs promote resilience by protecting soils, retaining water, and cycling nutrients. Plus, deadwood provides food and shelter for many organisms. Try to keep dead trees and logs where they are. Although the best deadwood comes from trees that die of natural causes, you can create more deadwood by felling trees and leaving them in place, pushing them over with equipment to create tip-ups, or girdling them (cutting a ring around the trees but not felling them) if they're situated where they do not pose a hazard to passersby or future management. Think about ways to increase deadwood across a range of species, sizes, and conditions.



6. Manage other stressors. Climate change may make other stressors more impactful. Control or eliminate invasives, and pay special attention to preventing invasives' expansion to new areas. Use dead tree branches or fences to protect young trees from animal browsing, or consider promoting deer hunting.

7. Encourage successful regeneration. Key to forest resilience is ensuring that there are multiple generations of trees in the woods. Retain a diversity of large, healthy trees as a source of pollen and seed for the next generation. Promote tree regeneration by creating canopy gaps and other conditions necessary for successful seedling establishment. Consult with a forester to select a gap's size based on the forest type, site characteristics, and desired species and consider whether you need to provide certain ground conditions to promote the establishment of some species. If you are struggling to get natural regeneration, you may consider planting trees. If so, talk to a professional about which species to grow and how to acquire them.

8. Promote future-adapted species. As described in the previous article in this series, climate change will affect tree species differently. Consider maintaining and promoting species that are projected to be adapted to future climate conditions. For example, on warm, dry sites, favor species adapted to warmer conditions, such as oaks, hickories, and pines. Retain healthy, vigorous trees already adapted to your site and able to withstand its projected climate impacts. If planting trees, consider including species that might be better adapted to the future conditions of your woods.

9. Protect the rare, unique, and important. In addition to climate change, we are also facing a biodiversity crisis due to habitat degradation and loss. Help to promote biodiversity by protecting rare species, natural communities, or unique landscape features that you have in your woods. You can also use forest management techniques to improve wildlife habitat.

10. Monitor and reevaluate. Climate change will continue to bring more unexpected and extreme events. Keep track of changes in your woods by noting shifts in seasonal events, stressors, and management outcomes. Consider taking photos of certain locations to monitor changes. Utilize available resources and technical assistance, and keep your forest management plan updated or create one with a forester's help.

Conclusions

We live in uncertain times, but there are ways to make decisions that foster forest resilience and adaptation. Adapting forests to climate change involves understanding and managing the unique conditions and characteristics of each forest. By enhancing diversity and complexity in our forests, we can help them continue to provide essential ecosystem services and mitigate climate change impacts. Prioritizing adaptation actions that provide co-benefits to both people and ecosystems will help ensure the sustainability and health of our forests in the face of a changing climate. A growing number of resources are available to support you as you steward your forest into the future.

Special thanks to our reviewer of this article: Samantha Myers, Fellow – USDA Northern Forests Climate Hub and Forest Adaptation Specialist – Northern Institute of Applied Climate Science and the University of Vermont.

Resources

Kosiba AM. 2024. *12 Steps for Climate Resilience: Managing Your Forest with Climate Change in Mind.* www.uvm.edu/sites/default/files/UVM-Extension-Cultivating-Healthy-Communities/forestry/Climate_12Steps_Flyer_2024.pdf

Northern Institute of Applied Climate Science. Adaptation Workbook
https://adaptationworkbook.org

Keeping Your Woods Healthy in the Years Ahead. 2021.
www.uvm.edu/sites/default/files/UVM-Extension-Cultivating-Healthy-Communities/forestry/resources/KeepingYourWoodsHealthy_VT.pdf

Catanzaro P., D'Amato A., and Huff E.S. 2016. *Increasing Forest Resiliency for an Uncertain Future.* www.uvm.edu/sites/default/files/UVM-Extension-Cultivating-Healthy-Communities/forestry/resources/IncreasingForestResiliency.pdf

HEAVY RAIN AND UPLAND FOREST

By Alexandra Kosiba. Illustrations by Erick Ingraham.

This article is the last in a four-part series that focuses on climate change impacts and adaptation in forests, supported by the Virginia Wellington Cabot Foundation. A companion series published last year focused on forest carbon. Alexandra Kosiba, a forest ecologist and tree physiologist, is an assistant professor of forestry at University of Vermont Extension. She specializes in climate change impacts to trees and forests and ways that foresters and landowners can incorporate climate change considerations in their decision-making and planning.

Natural depressions in the forest floor, including those left by upturned tree roots, collect water from heavy rain events.

One of the most significant climatic changes that we've experienced in the Northeast is an increase in the frequency and intensity of rainstorms. With these downpours comes a heightened risk of destructive floods, especially in hilly and mountainous areas, where runoff moves swiftly downslope, washing out roads, inundating farm fields, and damaging buildings.

Water bars divert runoff from road and trail surfaces into areas where water can spread and sink into the soil.

Defining Heavy Rain Events

In order to understand and describe how precipitation patterns are changing, it's important to have a reliable way to compare weather events over time. Unfortunately, common terms that meteorologists and others use to describe heavy rainstorms – for example, "excessive," "extreme," and "heavy" rain events – do not have universal definitions. The Environmental Protection Agency simply defines heavy rain as rainfall that significantly exceeds what is typical for a given location.[1] One way you can gauge a heavy rain event in your location is if more rain falls in a day than is typical in a month. Across much of our region, this is about 3 inches of rain falling within a day. However, lesser amounts of rain may cause damage similar to that of heavy rain events, if they fall in a short amount of time.

Another common way to describe intense rainstorms and other significant weather events is by referring to their return interval, that is, the average number of years between events of comparable size based on historical data. For example, a "100-year rainstorm" means a storm of such intensity that it has only a 1 percent chance of occurring in any given year. However, this description is problematic because, in a period of rapid climate change, historical data about weather patterns is of limited use for making future predictions.

There are several ways to examine how heavy rainfall is changing over time. Heavy rain events may occur more frequently, with greater intensity (individual events drop more rain), or at a different time of the year. For example, a location might experience more heavy rainfall in winter now compared to the past.

In response to recent storms, many north-eastern communities are taking steps to reduce impacts. These efforts include enlarging road culverts, elevating houses, and installing rain gardens that collect and filter water from parking lots.

Yet other important contributions to reduce flood damage occur upstream. Upland forests play a crucial role in absorbing water and reducing the impacts of heavy rain. Stewards of these forests can enhance this ecosystem benefit and boost their land's resilience to climate change by taking actions that help slow down, spread out, and sink water.

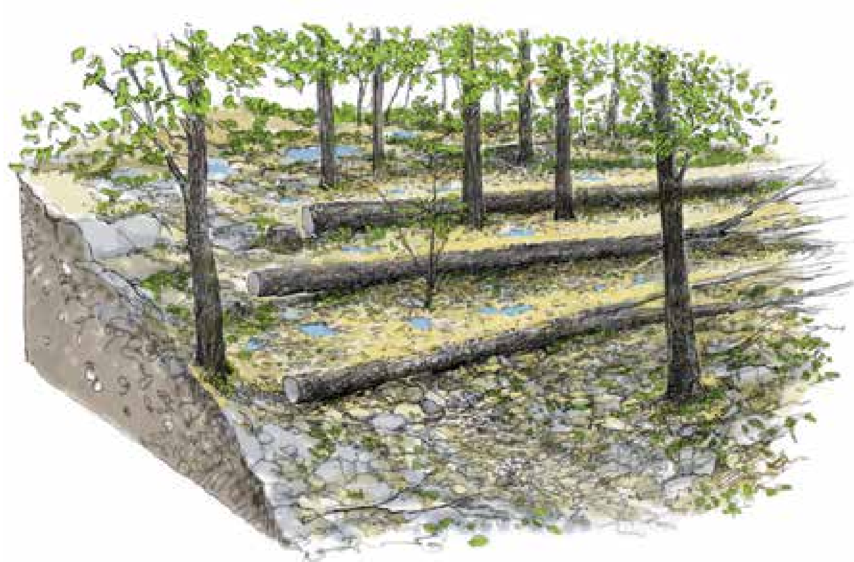
A Forecast for More Heavy Rain Events

A study published in 2017 in the journal *Theoretical and Applied Climatology* looked at changes in the magnitude, frequency, and seasonality of heavy rain events across the United States. The authors found that nearly all of the Northeast has experienced an increase in the frequency of heavy rain events.[2] Some areas in the region have also experienced an increase in the magnitude of heavy rainfall events, meaning that heavy rainfall events in recent years have deposited more inches of rain in each event compared to past years. These changes have been observed primarily in spring, summer, and fall.

1 www.epa.gov/climate-indicators/climate-change-indicators-heavy-precipitation#tab-2

2 Mallakpour and Villarini. 2017. Analysis of changes in the magnitude, frequency, and seasonality of heavy precipitation over the contiguous USA. Theoretical and Applied Climatology, 130, pp. 345–63.

Scientists expect this trend to continue as the planet warms. With each degree Fahrenheit of warming, the atmosphere's capacity to hold water vapor increases by about 4 percent.[3] This higher moisture content increases the odds that more intense precipitation events will occur. A report by Dartmouth College researchers, published last year in the scientific journal *Climatic Change*, projects that by the end of the 21st century, total rainfall in the Northeast will increase by 10 percent and that the number of heavy rainfall events will double. The report predicts that the most affected regions will be central New York, the Lake Champlain Basin, and northeastern Maine.[4]



Contour-felled trees slow surface water runoff and trap leaves, twigs, and soil.

The Impact of Heavy Rain Events in Forests

How heavy rain events affect forests depends primarily on location, topography, and soils. Lowland forests that occur in flat areas often experience flooding and waterlogged soils following a heavy rainstorm. Upland forests, with sloped terrain and soils that drain easily, are less likely to experience flooding but are vulnerable to soil erosion and loss of soil nutrients. In these upland forests, when rain falls faster than it can be absorbed by the soil, the excess rainfall becomes runoff, which flows over the forest floor. This runoff accelerates as it moves downslope, finding the path of least resistance.

Past land use may have degraded a forest's capacity to absorb and store water. For example, past agricultural use may have left a legacy of flattened forest floors that lack deadwood. An uneven forest floor with depressions, undulations, and dead plant material has more capacity to slow down and soak up runoff. Forest roads and trails also can be problematic if they channelize water. Many forest streams in our region lack an abundance of logs and other dead plant material that would naturally accumulate over centuries. The lack of these materials in streams can be due to the relatively young age of many of the region's forests as well as the cultural practice of intentionally "cleaning" streams of dead logs and branches. We now recognize that deadwood in streams provides critical ecological functions, including reducing downstream flood impacts. Without this material, streams can act as high-speed channels that incise streambeds over time.

Across the forest floor and in streams, water speed matters, both because it reduces the opportunity for runoff to seep back into the soil and because faster moving water causes more damage. Every time water doubles in speed, it can exert four times as much force. As water moves downslope, it can become strong enough to wash away leaf litter and soil, expose tree roots, dislodge rocks, and topple trees. Even relatively small flows, moving sufficiently fast, can carry large objects, including logs and boulders, and cause significant damage to both forests and downstream infrastructure.

Strategies You Can Use to Slow, Spread, and Sink Water

Walking through the woods during or immediately after a rainstorm can help you identify areas where water travels, moves debris, or causes erosion. You can then address these problem areas by making changes to slow, spread, and sink water. These actions can help move water into depressions where it can be absorbed, increasing the infiltration of runoff into the soil.

One strategy you can use to help address runoff is to place logs and other downed wood on the forest floor in such a way that they deflect, slow, and pool runoff. You can also implement a technique called contour felling, which involves cutting down and leaving trees perpendicular to the slope.

Other effective tactics to reduce soil erosion and to trap sediment and debris are to maintain trees and other plants in a

3 www.ncei.noaa.gov/news/warming-earth-also-wetter-earth
4 Picard et al. 2023. Twenty-first century increases in total and extreme precipitation across the Northeastern USA. Climatic Change, 176(6), p. 72.

wide buffer area along streams, wetlands, and other waterbodies and to restore natural stream conditions through strategic wood addition. This practice involves adding large, downed trees to streams to counteract the effects of past erosion and human alterations to stream channels. These logs create debris dams that slow water flow, re-engage the floodplain, reduce soil erosion, improve water quality, and create habitat for fish and other wildlife. With these structures in place, stormwater can flow more slowly over the streambanks, dissipate energy, and sink into the soil. It is important to consult with an expert if you are interested in strategic wood addition, as there are some important considerations based on the stream's width and slope, and this practice requires adherence to local regulations.

To prepare forest roads and trails for heavy rain events, install culverts and bridges large enough to accommodate extreme flows – and regularly inspect them to ensure they remain free of mud and debris. If sections of roads or trails are used infrequently, consider converting these structures to low water crossings, such as fords, which are designed to be overtopped during high water flows and require less cost and maintenance compared to culverts. On sloped sections of roads and trails, use water bars or broad-based dips[5] to divert water from the traveled surface. The required spacing of these water diversion structures, and which type is best, will depend on the road's slope and layout. Refer to your state forestry office for best management practices or consult with a forester.

Also consider closing out old roads and trails in the forest that you no longer use. You can add dead logs and branches in the old road or trail to reduce channelization and runoff, or if you are able to access the area with equipment, consider installing water bars or removing the compacted road surface entirely. Keep in mind that even if a road or trail hasn't yet experienced runoff or erosion issues, the increasing frequency and intensity of heavy rain events means that this could change. Being proactive can help avoid costly fixes in the future.

Resources

As with so many forest management decisions, expert guidance can help you determine what is achievable for your land and how to move forward efficiently with implementation.[6] If you're interested in exploring these flood reduction strategies, consider reaching out to a local service or county forester, or visit your nearest Natural Resources Conservation Service (NRCS) office. As noted above, expert guidance is especially important for stream restoration projects. For example, strategic wood addition requires careful planning during installation to maintain streamside integrity and prevent logs from dislodging during high flows, and may require permits. The NRCS offers technical assistance and cost-sharing opportunities for this work, along with other strategies mentioned in this article.

While we can't prevent heavier rainstorms, we can adapt. By understanding how water moves through our forests and employing methods to slow, spread, and sink it, we can enhance forests' resilience to heavy rain events and reduce the risk of damage on-site and downstream. Together, we can take meaningful steps to protect our landscapes and communities from the impacts of intense weather.

Strategic wood additions in streams slow, spread, and filter floodwater.

Special thanks to our reviewers of this article: Samantha Myers, Fellow – USDA Northern Forests Climate Hub and Forest Adaptation Specialist – Northern Institute of Applied Climate Science and the University of Vermont; and Erin Rodgers, Vermont/Massachusetts Program Manager, Trout Unlimited, Northeast Coldwater Habitat Restoration Program.

5 Broad-based dips are like water bars in that they direct water off the road and into a discharge area but are designed to allow vehicles to pass over them more easily.
6 For more information on strategies, see Shannon et al. 2019. Adaptation strategies and approaches for forested watersheds. Climate Services, 13, pp. 51–64.

GLOSSARY

Adaptability
The ability of a tree species to adjust to or recover from disturbance and environmental stress. Adaptability varies among species based on traits such as shade tolerance, methods of seed dispersal and reproduction, habitat specificity, and tolerance to drought, wind, ice, insects, browsing, disease, and temperature extremes.

Adaptation
Actions taken to help forests cope with changing climate conditions, such as promoting diverse tree species, improving water management, or preparing for future weather extremes.

Assisted Migration
The intentional movement of tree species or seed sources to locations expected to become suitable under future climate conditions.

Assisted Population Migration
Moving trees or seeds within the species' current range to help forests adapt to future conditions. Example: planting seed from warmer locations at cooler sites expected to warm over time.

Assisted Range Expansion
Planting a species just beyond its current range to help it migrate more quickly as the climate changes.

Assisted Species Migration
Moving tree species far beyond their current range to areas projected to become suitable in the future. This approach carries greater ecological risk and uncertainty compared to assisted range expansion and assisted population migration.

Biodiversity
The variety of living organisms in a forest, including plants, animals, fungi, and microorganisms.

Browsing
Feeding by deer or other animals on tree seedlings, saplings, and understory plants. Heavy browsing can limit regeneration and alter forest composition.

Canopy Gap
An opening in the forest canopy that allows sunlight to reach the forest floor. Gaps promote regeneration, support a diversity of tree age classes, create habitat for wildlife, and improve resilience by helping forests recover from disturbances such as storms or insect outbreaks.

Canopy Uniformity
A forest condition where trees are similar in size and age, creating a dense, closed canopy with relatively low structural complexity and habitat diversity.

Carbon Sequestration
The process by which trees and forests absorb and store carbon dioxide from the atmosphere.

Carbon Storage
The amount of carbon stored in forest vegetation, soils, and deadwood.

Channelization
When water becomes concentrated into narrow flow paths, such as roads, trails, or ditches, increasing runoff speed and erosion risk.

Climate Change
Long-term shifts in temperature, precipitation, and weather patterns caused largely by greenhouse gas emissions.

Climate Change Tree Atlas
An online tool developed by the USDA Forest Service that projects how suitable habitat for eastern tree species may shift under future climate conditions.

Co-Benefits
Additional positive outcomes from a management action beyond its main goal.

Cold Hardiness
A tree species' ability to survive low winter temperatures.

Composition
The mix and relative abundance of tree species in a forest. Forest composition is influenced by soils, topography, climate, disturbance, succession, and land use history.

Connected Forest Landscape
A network of forested areas that allows species movement and ecological processes to function.

Contour Felling
A practice where trees are felled perpendicular to the slope to slow runoff, trap soil and leaves, and reduce erosion.

Culvert
A structure that allows water to pass beneath a road or trail. Properly sized culverts help reduce washouts during heavy rain events.

Deadwood
Non-living woody material in a forest, including standing dead trees ("snags"), downed logs, branches, and twigs. Deadwood provides important ecosystem benefits such as wildlife habitat, carbon storage, water retention, nutrient cycling, and seedbeds for regeneration.

Developmental Pathway
The pattern of forest growth and change over time, shaped by site conditions, disturbance, climate, and land use history.

Disturbance
An event that damages trees or alters forest conditions. Examples include windstorms, ice storms, wildfire, drought, insect outbreaks, and flooding.

Diurnal Temperature Range
The difference between the warmest and coolest temperatures within a 24-hour period.

Drought
A prolonged period of below-normal water availability that stresses trees and forests. See also Hot Drought.

Ecosystem Services
Benefits forests provide to people and communities, such as clean water, flood reduction, wildlife habitat, carbon storage, and recreation.

Erosion
The movement or loss of soil caused by water, wind, or gravity. Heavy rain and fast-moving runoff can increase erosion in forests.

Extirpation
The disappearance of a species from part of its historical range, even though it still exists elsewhere.

Extreme Weather Events
Unusually severe weather such as intense storms, heavy rainfall, or heat waves that can damage forests.

Fine Roots
Small roots responsible for absorbing water and nutrients from the soil. These roots are especially vulnerable to soil freezing, erosion, and drought.

Fire-Adapted Forest
A forest ecosystem where periodic fire is a natural and beneficial process that helps maintain certain plant and tree species.

Floodplain
The relatively flat area next to a stream or river that can temporarily store floodwater during high flows.

Foliar Disease
Disease that affects tree leaves or needles, often reducing photosynthesis and causing premature leaf drop.

Forest Conversion
The permanent loss of forest due to land-use change such as development or agriculture.

Forest Floor
The layer of organic material covering the soil surface, including fallen leaves, twigs, decomposing wood, and other plant material. The forest floor stores water and nutrients, supports fungi and soil organisms, and provides important sites for seed germination and regeneration.

Forest Fragmentation
The breaking up of forests into smaller, isolated patches by roads, development, or agriculture, making it harder for species to migrate and ecosystems to function naturally.

Freeze-Thaw Cycles
Periods when temperatures alternate above and below freezing, typically during fall, winter, and spring. Increased freeze-thaw cycles can damage fine roots and soils, especially when snowpack is limited.

Future Climate-Adapted Species
Tree species expected to perform well under projected future climate conditions because they tolerate warmer temperatures, drought, or changing disturbance patterns. These species often have broad habitat tolerances and good dispersal ability.

Girdling
A practice used to create standing dead trees ("snags") by cutting through the bark and cambium layer around the stem, interrupting the flow of water and nutrients. Girdling can help increase habitat and structural complexity in forests.

Greenhouse Gases
Gases such as carbon dioxide (CO_2) and methane (CH_4) that trap heat in Earth's atmosphere. Human activities, especially the burning of fossil fuels, have increased greenhouse gas concentrations and contributed to climate change.

Growing Season
The period between the last spring frost and the first fall frost when plants actively grow.

Habitat Range
The geographic area where a tree species naturally occurs and can survive.

Hardiness Zone
A geographic classification based on average minimum winter temperatures used to estimate which plants can survive in an area.

Heavy Rain Event
A rainfall event that significantly exceeds what is typical for a location and may lead to flooding, erosion, or infrastructure damage.

High Grading
A harvesting practice that removes only the largest or most valuable trees while leaving behind lower-quality trees. High grading can reduce forest health, diversity, regeneration potential, and long-term resilience.

Hot Drought
A drought combined with unusually high temperatures, which increases water stress on trees.

Hydraulic Failure
The collapse of a tree's water transport system caused by severe drought stress.

Indirect Climate Impacts
Secondary effects of climate change, including increased pests, disease, and invasive species.

Infiltration
The process by which water soaks into the soil rather than flowing across the surface.

Invasive Species
Non-native introduced plants, animals, insects, and diseases that spread aggressively and can harm forest ecosystems.

Land Use History
The past human activities such as agriculture, logging, or grazing that influence current forest composition, soils, and structure.

Legacy Effects
Long-lasting impacts of past land use or disturbance that continue to shape forest conditions.

Migration Rate
The speed at which a tree species expands into new areas over generations.

Monitoring
The process of regularly observing and tracking forest conditions over time to evaluate changes and guide management decisions.

Overstory
The uppermost layer of the forest canopy formed by the tallest trees receiving the most sunlight.

Phenological Mismatch
A disruption in timing between connected species or events, such as flowers blooming before pollinators arrive.

Phenology
The timing of seasonal biological events, such as leaf-out, flowering, or migration.

Photosynthesis
The process by which plants use sunlight, water, and carbon dioxide to produce energy and grow.

Range Contraction
When a species disappears from parts of its historical habitat range because conditions become unsuitable.

Range Expansion
When a species successfully establishes in new areas outside its historical range.

Regeneration
The process of establishing new trees through seedlings, sprouts, or planting.

Regeneration Limitation
The failure of new trees to establish successfully because of insufficient seed, limited light, browsing pressure, drought, competition, or other unfavorable conditions.

Resilience
The ability of a forest to resist disturbance, recover from stress, and continue providing ecological functions over time.

Return Interval
The average number of years between weather events of a similar size or intensity, such as a "100-year storm."

Runoff
Water that flows across the ground surface when rainfall exceeds the soil's ability to absorb it. Also called "overland flow."

Second-Growth Forest
A forest that regrows naturally after major disturbance such as clearing, farming, or heavy logging. Most forests in the Northeast are second-growth forests.

Seed Dispersal
The movement of seeds away from parent trees by wind, water, or animals.

Serotinous Cones
Cones that remain closed until exposed to heat from fire, which releases the seeds.

Snowpack
Accumulated snow on the ground during winter. Snowpack helps insulate soil and stores water that becomes available in spring.

Soil Compaction
Compression of soil that reduces pore space, limiting water infiltration and root growth.

Soil Rutting
Grooves or depressions created by vehicles or equipment traveling over wet soils. Rutting can increase erosion, reduce infiltration, and compact soil.

Stomata
Tiny pores on leaves that allow trees to exchange gases and regulate water loss.

Strategic Wood Addition
The practice of placing large logs or woody material into streams to slow water, reduce erosion, reconnect floodplains, and improve habitat.

Stressors
Factors that contribute to tree decline or reduce forest health. Stressors may include drought, poor soils, insects, disease, invasive species, frost, flooding, or heat. Climate change can intensify many existing stressors and increase forest vulnerability.

Structural Complexity
The diversity of tree sizes, ages, canopy layers, deadwood, and spatial arrangement within a forest.

Subnivean Zone
The sheltered space between the forest floor and the bottom of the snowpack used by wildlife during winter.

Threat Multiplier
A factor, such as climate change, that worsens the impacts of other stressors like pests, drought, or invasive species.

Tip-Ups
The exposed root mound and soil left behind when a tree is uprooted by wind or other disturbance. Tip-ups create microsites that increase structural and habitat diversity in forests.

Toolbox Approach
A management strategy using multiple complementary practices to improve forest resilience.

Upland Forest
A forest located on well-drained, sloping terrain that sheds water downslope to wetlands, streams, or lowland forests.

Vulnerability
The degree to which a tree, species, or forest is susceptible to damage and unable to recover from stressors or climate impacts.

Water Bar
A drainage structure used on roads or trails to divert runoff off the traveled surface and reduce erosion.

Water Diversion Structures
Structures like water bars or culverts that redirect runoff to reduce erosion.

Waterlogged Soil
Soil that remains saturated for long periods, reducing oxygen available to tree roots and stressing some tree species.

Windthrow
Trees uprooted or broken by strong winds.

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NEXT STEPS FOR LANDOWNERS

If you're interested in incorporating climate change considerations into your forest stewardship, there are professionals and resources available to help. A good first step is connecting with your local stewardship, county, or district forester through your state forestry agency or university extension service. While titles and programs vary among states, these professionals share a common role: helping landowners understand their forests, identify management goals, and navigate available programs, technical assistance, and educational resources.

Depending on your property, goals, and interests, you may also choose to work with a private consulting forester. Consulting foresters can help conduct a forest inventory, develop a long-term management plan, identify climate vulnerabilities, and recommend strategies that support forest resilience and stewardship objectives.

One of the most important actions a landowner can take is keeping forestland forested. Conserving forests helps maintain wildlife habitat, protect water quality, store carbon, and sustain the many ecological and community benefits forests provide. Many states and conservation organizations offer programs and tools to support long-term forest stewardship, conservation planning, and family land transfer.

Climate change can feel overwhelming, but forest stewardship is a long-term process. Landowners do not need to implement every strategy at once. Small, thoughtful actions – such as improving regeneration, protecting soils and water, promoting species diversity, or learning more about your woods – can collectively increase forest resilience over time.

Some useful first steps include:

- Walking your woods regularly to observe changes over time
- Learning which tree species are regenerating successfully
- Identifying areas vulnerable to erosion, flooding, or drought stress
- Maintaining or increasing tree species and age diversity
- Consulting with a forester about long-term management goals
- Exploring cost-share and technical assistance programs

Here are some links that may be helpful:

Find a forester in your state:

Connecticut Department of Energy & Environmental Protection Service Forestry
https://portal.ct.gov/DEEP/Forestry/Service-Forestry-in-CT

Massachusetts Department of Conservation & Recreation Forest Stewardship Program
www.mass.gov/info-details/forest-stewardship-program

Maine Forest Service District Foresters
www.maine.gov/dacf/mfs/policy_management/district_foresters.html

University of New Hampshire Cooperative Extension County Forester Program
extension.unh.edu/countyforesters

New York Department of Environmental Conservation Forest Stewardship Program
https://dec.ny.gov/nature/forests-trees/private-forest-management#Forest_Stewardship_Program

Rhode Island Department of Environmental Management Forest Stewardship Program
https://dem.ri.gov/natural-resources-bureau/agriculture-and-forest-environment/forest-environment/forest-stewardship

Vermont Department of Forests, Parks and Recreation County Forester Program
https://fpr.vermont.gov/forest/list-vermont-county-foresters

Conservation-Based Estate Planning Resources

Connecticut: https://portal.ct.gov/DEEP/Forestry/Legacy/Estate-Planning-Resources-and-the-Forest-Legacy-Program

Massachusetts: www.MassWoods.org/legacy

Maine: www.forest.umaine.edu/legacy

New Hampshire: www.extension.unh.edu/resource/estate-planning-nh-woodlot-owners

New York: www.nyfoa.org/resources/plans-contracts

Rhode Island: https://web.uri.edu/rhodeislandwoods/legacy/future-ownership/

Vermont: www.vhcb.org/forestland

Natural Resources Conservation Service (NRCS)

Environmental Quality Incentives Program (EQIP)
www.nrcs.usda.gov/programs-initiatives/eqip-environmental-quality-incentives

Conservation Stewardship Program (CSP)
www.nrcs.usda.gov/programs-initiatives/csp-conservation-stewardship-program

Additional Resources

Kosiba, A.M. 2024. *12 Steps for Climate Resilience: Managing Your Forest with Climate Change in Mind*
https://go.uvm.edu/12steps

Keeping Your Woods Healthy in the Years Ahead. 2021
https://go.uvm.edu/woodshealthy

Catanzaro P., D'Amato A., and Huff E.S. 2016. *Increasing Forest Resiliency for an Uncertain Future.*
https://go.uvm.edu/forestresiliency