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A review of forestry mitigation and adaptation strategies in the Northeast U.S.

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Abstract The forests of the Northeast U.S. will be significantly affected by climate change, but they also play a role in mitigating climate change by sequestering CO_2. Forest management decisions can increase forests' resilience and ability to adapt to altered precipitation and temperature patterns. At the same time, management strategies that increase carbon storage will help reduce climate disruptions. Because of climate change, foresters on managed lands should take into account changes in species composition, more frequent disturbances, potential changes in growth rates, and distorted insect and disease dynamics. Silvicultural prescriptions should emphasize low impact logging techniques, the perpetuation of structural complexity, legacy trees, extended rotations, and uneven aged management systems where appropriate. In order to maintain resilience as well as to store carbon, forests should be protected from land use conversion.

1 Introduction

Climate change has already caused a variety of measurable impacts on terrestrial ecosystems across the globe including greater run-off, earlier spring peak discharge, earlier spring events, changes in species ranges, and changes in disturbance regimes (Parmesan and Yohe 2003; Parmesan and Galbraith 2004; Wang and Chameides 2005; Alley et al. 2007; Intergovernmental Panel on Climate Change 2007). Alterations in temperature, rain patterns, disturbance regimes, and other natural conditions are affecting forest ecosystems. Moreover, the negative impacts of climate change are magnified by fragmentation of natural areas and spread of invasive species. However, effective management decisions can increase forests' resistance, resilience, and adaptation to the climate change and even help restore

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ecosystem patterns and processes in order to increase the forests' ability to sequester carbon (Millar et al. 2007).

1.1 Regional description

The Northeast region of the U.S. stretches from 47°N in the state of Maine to 39°N in Pennsylvania. The average temperature in the Northeast is 8°C. Winter temperatures average −4.3°C while summer temperatures average 19.6°C (National Climate Data Center 2008). The prevailing wind direction, from west-to-east, creates a continental climate except for coastal areas moderated by the Atlantic Ocean (Barrett 1980). On average, the region receives 104 cm of precipitation which is evenly distributed throughout the year (National Climate Data Center 2008). Elevations range from sea level to mountain tops above 1615 m, but much of the region is set on upland plateaus between 150 and 450 m (Barrett 1980). Glaciation created young soils which vary considerably across small spatial scales (Barrett 1980).

The Northeast U.S. includes three ecological provinces including Northeastern mixed forest, Adirondack-New England mixed forest-coniferous forest, and Eastern broadleaf forest (McNab et al. 2007). Major forest types in the region are white/red/jack pine (*Pinus sp.*), spruce/fir (*Picea sp./Abies sp.*), oak/hickory (*Quercus sp./Carya sp.*), and northern hardwoods (Eyre 1980). Spruce/fir forests dominate the inland areas of Maine as well as the mountain tops northern most portions of New York, New Hampshire, and Vermont. These forests have cold temperatures and relatively coarse, acid soils (Barrett 1980). Northern hardwood forests are dominated by maple (*Acer sp.*), beech (*Fagus grandifolia)*, and birch (*Betula sp.*) and cover lower elevations and southern portions of Maine, New York, New Hampshire, Vermont, and the northern portion of Pennsylvania. Northern hardwoods also include conifers (e.g., hemlock (*Tsuga canadensis*) and white pine (*Pinus strobus*)) in the mixture (Westveld 1956). Pine forests are found in the coastal areas of Maine and New Hampshire and much of central Massachusetts. Pine forest tend to occupy site with coarse textured, well drained soils (Barrett 1980). Oak/hickory forests occupy the southern most portions of the region. The oak/hickory forests are also considered a transitional forest type between the Northern hardwood type and the Appalachian hardwoods that dominate further south (Westveld 1956).

Much of the southern portion of Northeastern forests were cleared for agriculture in the early nineteenth century, leaving less than 1% of the forest cover in an old-growth condition (Cogbill et al. 2002). Currently much of the region has second or third growth forest that has yet to reach late seral stages (Irland 1999). Many areas suffer from poor forestry practices such as high grading in the oak/hickory and Northern hardwood types (Barrett 1980). There are about 32 million hectares of timberlands (areas where commercial timber could be produced) and about 1.6 million hectares of reserved forest where harvests are not permitted (Alvarez 2007). Approximately 36 million m^3 of wood are harvested annually of 89 million m^3 of net tree growth (Alvarez 2007).

More than 84% of the Northeast region's 53.6 million people live in urban areas mostly along the coast (US Census Bureau 2000). The large urban population of the region has driven an emphasis on preservation and recreation for forest land accessible to the urban public (Irland 1999). Forests managed for timber and other products tend to be farther inland and farther from population centers. More development is occurring in formerly rural or forested areas causing landscape fragmentation (Egan et al. 2007).

2 Climate change in the Northeast U.S.

Over the last century and particularly in the last few decades, the Northeast U.S. has become hotter and wetter. The Northeast has gotten warmer, particularly since 1970 at the rate of 0.65 to.75°C per decade (Hayhoe et al. 2007). The largest temperature increases have come during the winter, which has warmed at a rate of 0.70°C per decade over the last 35 years (Hayhoe et al. 2007). The Post-1970 warming should be put in the context of a global cooling period from 1946–1975, which was particularly noticeable in the eastern U.S. (Committee on the Science of Climate Change 2001). The growing season has increased since 1980 by approximately 1 week nationally, with greater increases in the western U.S. than in the eastern U.S. (DeGaetano 1996; Easterling 2002; Kunkel et al. 2004). In the Northeast average annual precipitation has increased by 9.5 mm over the last century, even accounting for droughts in the 1930s and 1950s (Easterling 2002; Hayhoe et al. 2007). Very heavy daily precipitation has also increased in the last century (Easterling 2002) and the decrease in the percent of precipitation the Northeast receives as snow has been most notable in northern and coastal areas (Huntington et al. 2004).

In the Northeast, model estimates for the increase in average minimum temperature (over the 1961–1990 average) are 1.0°C by 2030 and 3.2 to 5.0°C by 2100, and increases in average maximum temperature are very similar (New England Regional Assessment 1999). Using a high emissions scenario, summers in the Northeast will be 3.3 to 7.8°C warmer and winters will be 4.4 to 6.7°C warmer than historic averages by 2100 (Frumhoff et al. 2007). Total precipitation in the Northeast may increase in the range of 10 to 30% over the next century (New England Regional Assessment 1999; Frumhoff et al. 2007). Winter precipitation may increase 11 to 14% over the century with a greater proportion falling as rain rather than snow (Huntington et al. 2004; Hayhoe et al. 2007). A warming climate may cause snow to melt earlier in the year and therefore decrease sublimation and produce an earlier and larger peak runoff (Dankers and Christensen 2005; Hayhoe et al. 2007). Intense rain incidents are likely to increase as well, with more rain falling during an event and longer rain events. However, even with more rain there may be more frequent droughts because of the timing of precipitation (Frumhoff et al. 2007; Hayhoe et al. 2007).

3 Impacts

Climate change will likely have a wide array of impacts on forests, but the most well research impacts include range shifts, soil properties, tree growth, disturbance regimes, and insect and disease dynamics.

3.1 Range shifts

The concept of range shifts combines two ideas: suitable habitat and physical movement. To the extent that temperature dictates species range in the Northeast, those ranges will shift as the climate warms. Increasing temperatures may push species habitats higher in elevation. However, evidence for changes in tree line is still weak, perhaps because of seasonally different climate patterns, browsing, and abrasion (Wang and Wall 2003; Danby and Hik 2007). Mountain habitats are threatened by range shifts, loss of the coolest climatic zones on peaks, and genetic isolation of populations (Beniston 2003).

Natural plant movement is essentially limited to seed dispersal. Recent models suggest species such as loblolly pine (*Pinus taeda*) and southern red oak (*Quercus falcata*) might only move 10 to 20 km beyond their current range over the next century (Iverson et al. 2004). This rate of dispersal is comparable to estimates of post-glacial species range expansion (Davis 1981; Clark et al. 1998), but modern dispersal would tend to be slower than post-glacial rates because areas which had been recently freed from glaciers also would have been relatively free of competition and unfragmented (Overpeck et al. 1991; Muller and Richard 2001).

While species migration rates are relatively slow, changes in habitat suitability are predicted to be much more rapid (Malcolm et al. 2002; Iverson et al. 2008). Long-lived species can persist in locations that are no longer suitable and no longer permit regeneration (Franklin et al. 1992), which would slow changes in species composition due to climate change (Hansen et al. 2001). Where a mismatch between current tree distribution and habitat suitability occurs, forests will be under increased stress. Current species associations in the Northeast are relatively new and as ranges shift these associations will change (Whitehead 1979; Davis 1981). Generally, it is very difficult to include the complex interactions that determine species range in a model (Austin 2002). For example, initial estimates of the suitability of New Hampshire in 2100 for the Maple-Birch-Beech forest type were very low (Hansen et al. 2001), but more recent modeling rates it as relatively high (Prasad et al. 2007). However, in the Northeast over the next century the spruce-fir forest type is likely to decline in importance as will the Northern hardwoods type if emissions remain high (Iverson et al. 2008).

Climate change impacts will vary by region, species, and even site. For example, the number and severity of freeze/thaw events, which occur once or twice a winter, has increased due to climate warming and could cause dieback and decline in yellow birch (*Betula alleghaniensis*) in the Northeast (Bourque et al. 2005). Because of shifting habitat suitability and differential effects on species, current species associations are likely to change. Endangered species may suffer disproportionately from future range restrictions because their habitats have already been drastically reduced by development and human land use (Malcolm and Pitelka 2000). Similarly, species dependent on high-elevation ecosystems, such as Bicknell's thrush (*Catharus bicknelli*), are particularly sensitive to climate warming (Rodenhouse et al. 2008). A global review of hotspots of endangered species suggests that while endangered reptiles and amphibians may benefit from climate changes, birds and mammals may suffer (Hansen et al. 2001).

3.2 Tree growth

The additional CO_2 in the atmosphere may increase tree growth in the Northeast, but the increases may be limited by availability of water and nutrients, particularly nitrogen (Aber et al. 2001; Springer and Thomas 2007). A plant's water use efficiency can increase with elevated levels of CO_2, which reduces the impact of water stress (Aber et al. 2001; Nowak et al. 2004). Experiments have shown an approximately 12% increase in net primary productivity due to elevated CO_2 levels (Nowak et al. 2004; Hanson et al. 2005). Such increases in the Northeast are supported by some modeling efforts (Malcolm and Pitelka 2000; Ollinger et al. 2008). However, increases in primary productivity from CO_2 fertilization and longer growing seasons must be weighed against potential increases in drought stress, nitrogen deficits, and potential increased tree death due to more frequent wind storms (Saxe et al. 2001). Because of drought conditions, some researchers predict a decrease in leaf area of about 25% for temperate forests in the Northeast (Watson et al. 1998; Aber et al. 2001). Changes in growth may be determined by how much the climate warms with large temperature increases leading to growth reductions (Bachelet et al. 2001). An integrated model of the effects of tropospheric ozone, nitrogen deposition, elevated CO_2, and land use change in the Northeast indicate that in combination the positive and negative effects of these changes had little net effect on forest growth (Ollinger et al. 2002).

3.3 Soils

Soils are a key element in the climate change equation and perhaps the least well understood. Although models of soil organic matter decomposition predict increasing rates with increasing temperature, field measurements seem to contradict model results (Saxe et al. 2001). In addition to increases in CO_2 emissions, industrialization has increased the amount of nitrogen deposition. Nitrogen deposition from human activities may help forests that are nitrogen limited, but excess nitrogen deposition can lead to soil acidification and reduced nutrient availability to plants (Aber et al. 2001). Magnani and colleagues (2007) showed that once stand disturbance effects are factored out, nitrogen deposition is the most important factor in forest carbon sequestration. Similarly, even in areas where calcium depletion is not currently a problem, increased growth and species change may make calcium a limiting factor in forest growth (Huntington 2005). Additionally, heavy storms and more intense runoff may increase erosion and degrade soils in the Northeast (Frumhoff et al. 2007).

3.4 Disturbance regimes

The alteration of basic environmental conditions will cause changes in the disturbance regimes in the Northeast including hurricanes, windstorms, ice storms, droughts, and fires (Dale et al. 2001). Over the near term climate-driven natural disturbances may be even more important than the direct effects of climate change in causing abrupt or rapid forest ecosystem responses (Keeton 2007). Although current predictive capabilities are insufficient to model the processes that determine hurricane and windstorm frequencies, research does suggest that storms will become more frequent and more intense in the Northeast (Uriarte and Papaik 2007). Increasing frequency of storms would favor species that can respond to growing space released by blow down and snap-offs, such as hemlock (Uriarte and Papaik 2007). High levels of atmospheric CO_2 may result in reduced injury to trees during ice storms, at least in conifer species (McCarthy et al. 2006). Although the Northeast may get more rain because of climate change, there may be more frequent droughts because of the timing of precipitation. The combination of precipitation and temperature changes will lead to earlier peak runoff and may cause more frequent short and medium term droughts (Hayhoe et al. 2007). The frequency of fire in the future may change because of increasing temperature, more frequent droughts, and changes in species composition. Rising temperatures appear to be responsible for the increase in fires in the western U.S. and boreal forests (Flannigan et al. 2006; Westerling et al. 2006). Altered fire regimes will have cascading ecosystem effects. For example, species composition has been tied to fire frequency in the Northeast over the last 10,000 years (Clark et al. 1996; Carcaillet and Richard 2000).

3.5 Insect and disease dynamics

Temperature increases will shift insect ranges northward so new areas are affected, but at the same time some previously affected areas may no longer be suitable for some insects (Ayres and Lombardero 2000). A larger concern is the potential for climate change to disrupt predator–prey relationships and permit outbreak conditions (Logan et al. 2003). Research suggest that spruce budworm (*Choristoneura fumiferana*) outbreaks will be 6 years longer and cause 15% more defoliation because of climate change (Gray 2008). Climate change and shifts in suitable habitat may also increase plant stress and reduce resistance to insects and diseases. Global climate change is likely to exacerbate exotic species problems (Simberloff 2000). For example, hemlock woolly adelgid (*Adelges tsugae*) may be able to expand its range farther north with warmer temperatures (Evans and Gregoire 2007). Invasive species are well positioned to take advantage of range shifts because they tend to be site generalists, mature quickly, and have successful dispersal strategies (Williamson and Fitter 1996; Malcolm and Pitelka 2000; Hansen et al. 2001; Malcolm et al. 2002). Similarly, climate changes will change forest pathogen dynamics and may exacerbate some disease problems such as sudden oak death (*Phytophthora ramorum*) (Venette and Cohen 2006).

Climate change also interacts with other processes that are altering northeastern forests. Forest fragmentation, the conversion of forest to other land uses, makes forests more susceptible to alien species invasions, alters nutrient cycles, changes species composition, and affects species diversity (Foley et al. 2005; Schulte et al. 2007). Air pollution, other than greenhouse gases (GHG), may also add to the impact of climate change (Bytnerowicz et al. 2006).

4 Managing forests in the face of climate change

Forest management must be flexible given the uncertainty in predictions of temperature, precipitation, disturbance, and species interactions (Bodin and Wimana 2007; Millar et al. 2007). Silviculture is one of the primary tools available to land managers to guide forest development towards increased resistance and resilience to the impacts of climate change (Spittlehouse 1997; Spiecker 2003). Silvicultural prescriptions have aided with many other grave problems facing forests by restoring ecosystems (Allen et al. 2002; Shepperd et al. 2006), building resilience (Salonius 2007), managing native insects (Whitehead et al. 2003), dealing with invasive species

(Waring and O'Hara 2005), recovering from disease (Ostrofsky 2005), and mitigating species decline (Smallidge et al. 1991; Dwyer et al. 2007).

Many suitable habitats will move north or up elevation as the climate warms, leaving individual trees and whole forests outside of their optimal habitat. It may be preferable to focus on future desired forest functions rather than aiming for specific species mix (Chornesky et al. 2005; Larsen and Nielsena 2007). In the short term, shifting habitats are likely to manifest themselves as declines in species at the edge of their current range. Managers working in the southern portions of a range should not plan for growth rates for those species to continue at past rates in the next century. More complex models are available to help managers plan which species may be under particular stress in a given location such as the Climate Change Tree Atlas (Prasad et al. 2007; Iverson et al. 2008). Targeted plantings are able to match species to suitable habitat more rapidly than natural species migration and may be an appropriate adaptation strategy for shifting habitat suitability (Beaulieu and Rainville 2005; McLachlan et al. 2007).

Managers will need to balance activities that support current habitat communities with those that favor species more suitable to future environments. Current communities must be kept as healthy as possible to facilitate migration either northward or to higher elevations (Hansen et al. 2001). The uncertainties of climate change suggests silviculture strategies should maintain a diverse suite of species to hedge against lost of individual species (Lindner 2000). Maintaining or restoring species diversity can increase the likelihood that some species will flourish as the climate changes. In order to aid the dispersal of animal species whose suitable habitat has moved north, it may be more important to increase the habitat quality, including food, cover, and other resources, of the forest matrix, rather than to focus solely on habitat connectivity (Bailey 2007). Retaining legacy trees or groups help protect plant and animal communities that are under stress because of climate change, and under represented on the landscape (Salonius 2007). Even after legacy trees die, they contribute coarse woody material (CWM) which is often in deficient in Northeastern forest (Ziegler 2000; Keeton 2006). Climate change and associated changes in forest functions may even provide a window of opportunity for forest restoration. For example, increased frequency of fire in the Northeast may aid efforts to re-establish American chestnut (*Castanea dentata*) (Foster et al. 2002; McCament and McCarthy 2005).

As climate change increases the frequency and severity of some disturbances, managers will be forced to react more often to natural disturbances. To some degree, disturbances can be planned for. For example, areas that are particularly susceptible to blowdown from wind storms can be mapped and vulnerable stands can be managed for species more resistant to windthrow (Evans et al. 2007). Similarly, insect outbreaks tend to be species specific and stands can be managed to reduce the dominance of preferred species (Whitehead et al. 2003). Thinnings can be targeted to the most influential local disturbance, such as wind or drought, in order to encourage forest resistance (Bodin and Wimana 2007). In some cases, the most appropriate reaction to disturbance is to allow nature to take its course (Dale et al. 1998). However, in other cases societal concerns may dictate some sort of response such as salvage or replanting.

Climate change may foster the introduction of new invasives and exacerbate problems with non-native species already established in the Northeast. The best strategy with exotic species is to avoid their establishment through detection and eradication (Liebhold et al. 1995). Intact, diverse forest ecosystems may be more resistant to spreading exotic invasions (Jactel et al. 2005; Huebner and Tobin 2006; Mandryk and Wein 2006), although research is not conclusive on this point (Howard et al. 2004; Gilbert and Lechowicz 2005). Once established, the impact of exotic and native insects may be lessened by increasing individual tree vigor. Standard silvicultural approaches to increasing tree vigor such as crown thinnings have been shown to ease some insect infestations (Lee et al. 2002; Waring and O'Hara 2005). Conversion to different species composition may be necessary in certain severe infestations or particularly susceptible sites (Gottschalk 1993). Biological or chemical control may be possible or warranted in some cases where unique ecosystems or trees can be protected without damaging other resources (e.g., hemlock woolly adelgid Cowles et al. 2005).

The importance of maintaining favorable soil structure, organic matter, and nutrient availability will be increased by changing climate induced stress on forest ecosystems. For this reason whole tree harvesting is inadvisable on sensitive sites because of the risk of nutrient depletion (Akselsson et al. 2007). Removing tree boles instead of whole trees can leave 80% to 90% more nutrients on site (Stupak et al. 2008). In the Northeast, timber harvests often are timed to occur when soils are frozen to minimize compaction. Harvesting timber on frozen soil may become more difficult because of warmer winters (Henry 2008). However, forest soils may freeze more often due to reduced snow coverage and reduced insulation caused by climate change (Groffman et al. 2001). Thus far, research suggests that most harvest operations have little effect on soil carbon in the Northeast (Johnson and Curtis 2001; Hoover 2005), although harvests in spruce-fir forests that remove more than 80% of the volume caused soil impacts (Reinmann et al. 2005). On sensitive sites low impact logging techniques, such as directional felling or careful trail layout, protect soil nutrient resources (Hallett and Hornbeck 2000; Horn et al. 2007).

5 Managing forest for increase carbon storage

In addition to including climate change in forest management plans, foresters may also need to consider the amount of carbon stored in forests (Krankina and Harmon 2006; Ruddell et al. 2007; Moomaw and Johnston 2008). The North East State Foresters Association (2002) states that, in general, "management strategies that encourage larger trees, employ harvest methods that reduce waste and damage to residual trees, and minimize soil disturbance during harvest all improve carbon sequestration activities." Nationally forests, urban trees, and wood products combined account for up to 91% of the annual U.S. carbon storage (Woodbury et al. 2007). More specifically, about 6.9 Pg of carbon are stored in the Northeast's forests with 0.12 Pg of C sequestered annually (Potter et al. 2008). On average, each hectare of northeastern forestland holds 180 Mg of carbon of which 38% is alive above ground, 8% is alive below ground, 6% is in dead wood, 10% is in litter, and 38% is in soil organic material (Environmental Protection Agency 2006).

Extending rotations or entry cycles and increasing the length of time trees grow before harvest can capture more carbon on site (Liski et al. 2001; Sampson 2004; Stavins and Richards 2005; Bravo et al. 2008). A potentially large amount of carbon could be sequestered in a relatively short time period by increasing the rotation ages of softwood stands beyond financially optimal ages. Studies looking at increasing rotation ages 5, 10, and 15 years indicate 3 Mg/ha/yr CO_2 can be sequestered by increasing the rotation age of softwoods in the Northeast (Sohngen et al. 2007). However, in some forests shorter rotations can increase the carbon held in soils because of litter production and harvest residues (Liski et al. 2001).

Another option to increase carbon storage is to increase the structural complexity of forests. Structural complexity and carbon storage can be increased by preserving reserve trees, snags, and CWM (Harmon and Marks 2002; Park et al. 2005; Keeton 2006; Choi et al. 2007). Leaving reserve trees or groups adds to the current structural complexity of a stand and provides a source of CWM into the future (Keeton 2006; Salonius 2007). Uneven aged management is often used to promote structurally complex forests and may sequester more carbon. For example, uneven aged management stores 40 Mg/ha more carbon than clearcut even-age management in the oak-hickory and oak-pine communities of the Ozarks (Li et al. 2007) and up to 26 Mg/ha more than diameter limit cutting in Wisconsin (Strong 1997). Partial cutting also appears to be the best carbon sequestration strategy in boreal mixed species forests (Lee et al. 2002) and in the northern uplands forest type of New Brunswick (Neilson et al. 2007).

Reducing damage to the residual stand can help preserve forest productivity and hence carbon storage (Lee et al. 2002; Stavins and Richards 2005; Birdsey et al. 2006). Low impact logging has been shown to improve carbon storage and protect biodiversity in tropical forest (Putz 1996; Davis 2000). The type of trees cut, operator skill, and logging machinery used can reduce residual stand damage, minimize waste, and maximize harvest yields in Northeastern forests (Ohman 1970; Cline et al. 1991; Fajvan et al. 2002; Nebeker et al. 2005). Litter decomposition does not increase and carbon storage in soils is largely unaffected (change $<10\%$) by timber harvests (Strong 1997; Yanai et al. 2003).

In general fossil fuel use in forestry is negligible in comparison to the fate of carbon stored in trees (Chen et al. 2000; Finkral and Evans 2008). However, intensive silvicultural systems that involve site preparation and fertilizer require considerable fossil fuel inputs (Markewitz 2006). By using natural regeneration methods and low impact logging techniques, forestry-related fossil fuel use in the Northeast can be minimized.

5.1 Carbon storage in forest products

Any harvest reduces on site carbon storage, but depending on the fate of wood products harvested and the other materials or fuels the wood products replace, forest management can be a net carbon benefit (Harmon and Marks 2002; Schmid et al. 2006). A thin from below and a thin from the middle in Alleghany hardwoods increased the carbon stores 38 Mg/ha and 7.5 Mg/ha respectively when wood products were included (Hoover and Stout 2007). However, a shelterwood in a mixed species stand in Maine caused a net release of carbon, even with storage in wood products (Scott et al. 2004). The fate of wood products removed from the forest and the carbon emitted in the transportation and manufacture of wood products has a major impact on the carbon accounting for forest management. Solid wood and wood composite products store carbon for 45–100 years while wooden pallets have a half life of 6 years (Skog and Nicholson 1998; Houghton and Hackler 2000; Penman et al. 2003) and paper decays at a rate of about 10% per year (Houghton and Hackler 2000). For wood products that end up in landfills, decay may be incomplete. On average only 3% of the carbon in solid wood products and 38% of office paper are projected to ever be released from landfills (Gower 2003). There is also a potential benefit, reduction in GHG emissions, from substituting wood for more GHG-intensive building materials, or replacing fossil fuels with forest biomass for energy (Gustavsson et al. 2006; Eriksson et al. 2007). For example, wood-based houses may result in 20% to 50% less GHG emission than steel or concrete base houses over a 100 year life span (Upton et al. 2007). Conversion of forests to other land uses, and thereby reducing the size of forest parcels, can reduce the opportunity to sequester carbon in wood products because harvests may be limited on smaller parcels (Egan et al. 2007).

5.2 Forest preservation

Forest preservation in reserves plays an important role in preparing for climate change as well as storing carbon. Reserves and other unmanaged natural areas serve another important role in preserving habitat under additional stress from climate change and as well as genetic reserves. Genetic diversity will help species adapt to climate change (Rehfeldt et al. 2001; Parmesan and Galbraith 2004). The current forest reserve paradigm will be strained by climate change because as habitat moves, the reserve location may no longer offer habitats for the species and forest types that it was designed to protect (Halpin 1997).

Late successional or old growth reserves store larger amounts of carbon than young forests (Harmon et al. 1990; Law et al. 2003; Birdsey et al. 2006; Taylor et al. 2007). Mature forests can continue to sequester carbon even after they move into an old growth or late successional stage (Luyssaert et al. 2008). For example, a 200 year old hemlock forest continued to sequester 3.0 Mg/ha/yr (Hadley and Schedlbauer 2002).

6 Conclusions: toward a regional strategy

As temperatures in the Northeastern U.S. increase by 3.2 to 6.7°C and changes in precipitation create more frequent droughts, species ranges, soil properties, tree growth, disturbance regimes, insect impacts, and disease dynamics will all change. A regional climate change strategy for Northeastern forests must both respond to climate changes and increase carbon storage. The first priority must be to keep forests intact both to increase resilience as well as to store carbon because loss of forest land precludes other solutions. On public and other lands accessible for recreation, preservation will help store carbon because of the ability of mature forests to sequester carbon. On managed forest lands, working forest conservation easements can keep forest lands as forests while protecting their productive capacity (Perschel 2006).

Managed lands are crucial to a forestry strategy to address climate change. Harvesting forest products from Northeastern forests can reduce energy used in international shipping, reduce forest degradation in other areas of the world, as well as sequester carbon in products (Berlik et al. 2002). Similarly, low-grade wood from forests can be burned to generate heat and/or power and thereby offset fossil fuel use (Ciais et al. 2008; Marland and Obersteiner 2008). However, leaving low-grade wood in the forest can help store carbon (Park et al. 2005; Keeton 2007). Therefore, so these two benefits must be balanced, while also ensuring sufficient CWM is left on site to protect wildlife and site productivity.

On managed lands, foresters should take into account changes in species composition and more frequent disturbances, especially drought. Management should focus on maintaining forest function, not specific species mixes. Long term planning should consider current projections for decrease in suitability for the spruce-fir forest type and, in a high emission scenario, Northern hardwoods (Iverson et al. 2008). Across the region, silvicultural prescriptions should emphasize low impact logging techniques and the perpetuation of structural complexity by leaving legacy trees, extending rotations, and implementing uneven aged management systems where appropriate. Forest management that generates high quality forest product has carbon sequestration benefits because solid wood products hold carbon for a longer time than lower quality products.

A number of socio-economic factors will help determine the best climate change strategy for Northeastern forests that can be implemented. However, these factors are difficult to forecast. Regulations and markets will determine how a climate change strategy can be implemented, but markets are notoriously difficult to predict and even climate change regulations are uncertain. For example, it is not certain if the Northeast's Regional Greenhouse Gas Initiative will allot carbon credits for forestry management activities. Prices for wood products, carbon credits, and fossil fuels will influence the best balance of CWM to use for bioenergy and to leave in the woods for carbon storage. Public opinion will influence the mix of preservation and forest management across the landscape.

In addition to the uncertainty of socio-economic variables, questions remain about the magnitude of climate change and its impacts on forests of the Northeast. The complex effects of changes to basic fire regimes or disturbance patterns cast uncertainty on even the best modeling efforts. More basic ecological research is needed to help climate change strategy for Northeastern forests.

References

Aber J, Neilson RP, McNulty S et al (2001) Forest processes and global environmental change: predicting the effects of individual and multiple stressors. Bioscience 51(9):735–751

Akselsson C, Westling O, Sverdrup H et al (2007) Nutrient and carbon budgets in forest soils as decision support in sustainable forest management. For Ecol Manag 238(1–3):167–174

Allen CD, Savage M, Falk DA et al (2002) Ecological restoration of southwestern ponderosa pine ecosystems: a broad perspective. Ecol Appl 12(5):1418–1433

Alley R, Berntsen T, Bindoff NL et al (2007) Summary for Policymakers. In: Solomon S, Qin D, Manning M et al (eds) Climate change 2007: the physical science basis. Working group I contribution to the intergovernmental panel on climate change. Fourth Assessment Report, Cambridge, UK, pp 748–845

Alvarez M (2007) The state of America's forests. Society of American Foresters, Bethesda

Austin MP (2002) Spatial prediction of species distribution: an interface between ecological theory and statistical modelling. Ecol Model 157(2–3):101–118

Ayres MP, Lombardero MJ (2000) Assessing the consequences of global change for forest disturbance from herbivores and pathogens. Sci Total Environ 262(3):263–286

Bachelet D, Neilson RP, Lenihan JM et al (2001) Climate change effects on vegetation distribution and carbon budget in the United States. Ecosystems 4(3):164–185

Bailey S (2007) Increasing connectivity in fragmented landscapes: an investigation of evidence for biodiversity gain in woodlands. For Ecol Manag 238(1–3):7–23
Barrett JW (1980) The northeastern region. In: Barrett JW (ed) Regional silviculture of the United States. Wiley, New York, pp 25–65
Beaulieu J, Rainville A (2005) Adaptation to climate change: genetic variation is both a short- and a long-term solution. For Chron 81(5):704–708
Beniston M (2003) Climatic change in mountain regions: a review of possible impacts. Clim Change 59(1/2):5–31
Berlik MM, Kittredge DB, Foster DR (2002) The illusion of preservation: a global environmental argument for the local production of natural resources. J Biogeogr 29(10–11):1557–1568
Birdsey RA, Pregitzer K, Lucier A (2006) Forest carbon management in the United States: 1600–2100. J Environ Qual 35:1461–1469
Bodin P, Wimana BLB (2007) The usefulness of stability concepts in forest management when coping with increasing climate uncertainties. For Ecol Manag 242(2–3):541–552
Bourque CP-A, Cox RM, Allen DJ et al (2005) Spatial extent of winter thaw events in eastern North America: historical weather records in relation to yellow birch decline. Glob Chang Biol 11(9):1477–1492
Bravo F, Bravo-Oviedo A, Diaz-Balteiro L (2008) Carbon sequestration in Spanish Mediterranean forests under two management alternatives: a modeling approach. Eur J For Res 127(3):225–234
Bytnerowicz A, Omasa K, Paoletti E (2006) Integrated effects of air pollution and climate change on forests: a northern hemisphere perspective. Environ Pollut 147(3):438–445
Carcaillet C, Richard PJH (2000) Holocene changes in seasonal precipitation highlighted by fire incidence in eastern Canada. Clim Dyn 16(7):549–559
Chen W, Chen JM, Price DT et al (2000) Carbon offset potentials of four alternative forest management strategies in Canada: a simulation study. Mitig Adapt Strategies Glob Chang 5(2): 143–169
Choi J, Lorimer CG, Vanderwerker JM (2007) A simulation of the development and restoration of old-growth structural features in northern hardwoods. For Ecol Manag 249(3):204–220
Chornesky EA, Bartuska AM, Aplet GH et al (2005) Science priorities for reducing the threat of invasive species to sustainable forestry. Bioscience 55(4):335–348
Ciais P, Schelhaas MJ, Zaehle S et al (2008) Carbon accumulation in European forests. Nature Geoscience 1:425–429
Clark JS, Royall PD, Chumbley C (1996) The role of fire during climate change in an eastern deciduous forest at Devil's Bathtub, New York. Ecology 77(7):2148–2166
Clark Js, Fastie C, Hurtt G et al (1998) Reid's paradox of rapid plant migration: dispersal theory and interpretation of palaeoecological records. Bioscience 48(1):13–24
Cline ML, Hoffman BF, Cyr M et al (1991) Stand damage following whole-tree partial cutting in northern forests. Northern J Appl For 8(2):72–76
Cogbill CV, Burk J, Motzkin G (2002) The forests of presettlement New England, USA: spatial and compositional patterns based on town proprietor surveys. J Biogeogr 29(10–11):1279–1304
Committee on the Science of Climate Change (2001) Climate change science: an analysis of some key questions. National Academy, Washington, DC
Cowles RS, Cheah CAS-J, Montgomery ME (2005) Comparing systemic imidacloprid application methods for controlling hemlock woolly adelgid. In: Onken B, Reardon R (eds) Proceedings of the 3rd symposium on Hemlock Woolly Adelgid. USDA forest service, Ashville, NC, USA, pp 169–172
Dale VH, Lugo AE, MacMahon JA et al (1998) Ecosystem management in the context of large, infrequent disturbances. Ecosystems 1(5):546–557
Dale VH, Joyce LA, McNulty S et al (2001) Climate change and forest disturbances. Bioscience 51(9):723–734
Danby RK, Hik DS (2007) Variability, contingency and rapid change in recent subarctic alpine tree line dynamics. J Ecol 95(2):352–363
Dankers R, Christensen OB (2005) Climate change impact on snow coverage, evaporation and river discharge in the Sub-Arctic Tana Basin, Northern Fennoscandia. Clim Change 69(2):367–392
Davis MB (1981) Quaternary history and the stability of forest communities. In: West DC, Shugart HH, Botkin DB (eds) Forest succession: concepts and application. Springer, New York, pp 132–153
Davis AJ (2000) Does reduced-impact logging help preserve biodiversity in tropical rainforests? A case study from Borneo using dung beetles (Coleoptera: Scarabaeoidea) as indicators. Environ Entomol 29(3):467–475

DeGaetano A (1996) Recent trends in maximum and minimum temperature threshold exceedences in the Northeastern United States. J Climate 9:1646–1657
Dwyer JP, Kabrick JM, Wetteroff J (2007) Do improvement harvests mitigate oak decline in Missouri Ozark forests? Northern J Appl For 24(2):123–128
Easterling DR (2002) Recent changes in frost days and the frost-free season in the United States. Bull Am Meteorol Soc 83(9):1327–1332
Egan A, Taggart D, Annis I (2007) Effects of population pressures on wood procurement and logging opportunities in northern New England. Northern J Appl For 24(2):85–90
Environmental Protection Agency (2006) Inventory of U.S. greenhouse gas emissions and sinks: 1990–2004. EPA430-R-06–002, Washington, DC
Eriksson E, Gillespie AR, Gustavsson L et al (2007) Integrated carbon analysis of forest management practices and wood substitution. Can J For Res 37(3):671–681
Evans AM, Gregoire TG (2007) A geographically variable model of Hemlock Woolly Adelgid spread. Biol Invasions 9(4):369–382
Evans AM, Camp AE, Tyrrell ML et al (2007) Biotic and abiotic influences on wind disturbance in forests of NW Pennsylvania, USA. For Ecol Manag 245(1–3):44–53
Eyre FH (1980) Forest cover types of the United States and Canada. Society of American Foresters, Bethesda
Fajvan MA, Knipling KE, Tift BD (2002) Damage to Appalachian hardwoods from diameter-limit harvesting and shelterwood establishment cutting. Northern J Appl For 19(2):80–87
Finkral AJ, Evans AM (2008) The effect of a restoration thinning on carbon stocks in a ponderosa pine forest. For Ecol Manag 255(7):2743–2750
Flannigan MD, Amiro BD, Logan KA et al (2006) Forest fires and climate change in the 21st century. Mitig Adapt Strategies Glob Chang 11(4):847–859
Foley JA, DeFries R, Asner GP et al (2005) Global consequences of land use. Science 309(5734): 570–574
Foster DR, Clayden S, Orwig DA et al (2002) Oak, chestnut and fire: climatic and cultural controls of long-term forest dynamics in New England, USA. J Biogeogr 29(10–11):1359–1379
Franklin JF, Swanson FJ, Harmon ME et al (1992) Effects of global climate change on forests in northwestern North America. In: Peters RL, Lovejoy TE (eds) Gobal warming and biological diversity. Yale University Press, New Haven, pp 244–257
Frumhoff PC, McCarthy JJ, Melillo JM et al (2007) Confronting climate change in the U.S northeast: science, impacts and solutions. In: Northeast climate impacts assessment. Union of Concerned Scientists, Cambridge
Gilbert B, Lechowicz MJ (2005) Invasibility and abiotic gradients: the positive correlation between native and exotic plant diversity. Ecology 86(7):1848–1855
Gottschalk KW (1993) Silvicultural guidelines for forest stands threatened by the gypsy moth. NE-GTR-171. USDA Forest Service, Northeastern Forest Experiment Station, Radnor, PA
Gower ST (2003) Patterns and mechanisms of the forest carbon cycle. Annu Rev Environ Resour 28:169–204
Gray DR (2008) The relationship between climate and outbreak characteristics of the spruce budworm in eastern Canada. Clim Change 87:361–383
Groffman PM, Driscoll CT, Fahey TJ et al (2001) Colder soils in a warmer world: a snow manipulation study in a northern hardwood forest ecosystem. Biogeochemistry 56(2):135–150
Gustavsson L, Madlener R, Hoen H-F et al (2006) The role of wood material for greenhouse gas mitigation. Mitig Adapt Strategies Glob Chang 11(5–6):1097–1127
Hadley JL, Schedlbauer JL (2002) Carbon exchange of an old-growth eastern hemlock (Tsuga canadensis) forest in central New England. Tree Physiol 22(15–16):1079–1092
Hallett RA, Hornbeck JW (2000) Managing oak and pine stands on outwash sands: protecting plant nutrients. Northern J Appl For 17(2):57–61
Halpin PN (1997) Global climate change and natural-area protection: management responses and research directions. Ecol Appl 7(3):828–843
Hansen AJ, Neilson RP, Dale VH et al (2001) Global change in forests: responses of species, communities, and biomes. Bioscience 51(9):765–779
Hanson PJ, Wullschleger SD, Norby RJ et al (2005) Importance of changing CO2, temperature, precipitation, and ozone on carbon and water cycles of an upland-oak forest: incorporating experimental results into model simulations. Glob Chang Biol 11(9):1402–1423
Harmon ME, Marks B (2002) Effects of silvicultural practices on carbon stores in Douglas-fir-western hemlock forests in the Pacific Northwest, USA: results from a simulation model. Can J For Res 5(32):863–877

Harmon ME, Ferrell WK, Franklin JF (1990) Effects on carbon storage of conversion of old-growth forests to young forests. Science 247:699–702
Hayhoe K, Wake CP, Huntington TG et al (2007) Past and future changes in climate and hydrological indicators in the US Northeast. Clim Dyn 28(4):381–407
Henry H (2008) Climate change and soil freezing dynamics: historical trends and projected changes. Clim Change 87(3):421–434
Hoover CM (2005) Carbon storage in northeastern US forest soils. In: Kenefic LS, Twery MJ (eds) Changing forests—challenging times. NE-GTR-325. USDA Forest Service, Northeastern Research Station, Newtown Square, p 17
Hoover C, Stout S (2007) The carbon consequences of thinning techniques: stand structure makes a difference. J For 105(5):266–270
Horn R, Vossbrink J, Peth S et al (2007) Impact of modern forest vehicles on soil physical properties. For Ecol Manag 248(1–2):56–63
Houghton RA, Hackler JL (2000) Changes in terrestrial carbon storage in the United States. 1: the roles of agriculture and forestry. Glob Ecol Biogeogr 9(2):125–144
Howard TG, Gurevitch J, Hyatt L et al (2004) Forest invasibility in communities in southeastern New York. Biol Invasions 6(4):393–410
Huebner CD, Tobin PC (2006) Invasibility of mature and 15-year-old deciduous forests by exotic plants. Plant Ecol 186:57–68
Huntington TG (2005) Assessment of calcium status in Maine forests: review and future projection. Can J For Res 35(5):1109–1121
Huntington TG, Hodgkins GA, Keim BD et al (2004) Changes in the proportion of precipitation occurring as snow in New England (1949–2000). J Climate 17(13):2626–2636
Intergovernmental Panel on Climate Change (2007) Summary for policymakers. In: Parry ML, Canziani OF, Palutikof JP et al (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 7–22
Irland LC (1999) The northeast's changing forests. Harvard Forest, Petersham
Iverson LR, Schwartz MW, Prasad AM (2004) How fast and far might tree species migrate in the eastern United States due to climate change? Glob Ecol Biogeogr 13:209–219
Iverson L, Prasad A, Matthews S (2008) Modeling potential climate change impacts on the trees of the northeastern United States. Mitig Adapt Strategies Glob Chang 13(5–6):487–516
Jactel H, Brockerhoff E, Duelli P (2005) A test of the biodiversity–stability theory: meta-analysis of tree species diversity effects on insect pest infestations, and re-examination of responsible factors. In: Scherer-Lorenzen M, Körner C, Schulze E-D (eds) Forest diversity and function. Temperate and boreal systems. Springer, Berlin, pp 235–262
Johnson D, Curtis P (2001) Effects of forest management on soil C and N storage: meta analysis. For Ecol Manag 140(2–3):227–238
Keeton WS (2006) Managing for late-successional/old-growth characteristics in northern hardwood-conifer forests. For Ecol Manag 235(1–3):129–142
Keeton W (2007) Silvicultural options for managing aboveground carbon storage in northern hardwood-conifer forests. In: New England chapter of the society of American foresters, 2007 meeting. Fairlee, VT
Krankina ON, Harmon M (2006) Forest management strategies for carbon storage. In: Matrazzo D (ed) Forests, carbon and climate change: a synthesis of science findings. Oregon Forest Resources Institute, Portland, pp 79–91
Kunkel KE, Easterling DR, Hubbard K, Redmond K (2004) Temporal variations in frost-free season in the United States: 1895–2000. Geophys Res Lett 31:L03201
Larsen JB, Nielsena AB (2007) Nature-based forest management—where are we going? Elaborating forest development types in and with practice. For Ecol Manag 238(1–3):107–117
Law BE, Sun OJ, Campbell JL et al (2003) Changes in carbon storage and fluxes in a chronosequence of ponderosa pine. Glob Chang Biol 9(4):510–524
Lee J, Morrison IK, Leblanc J-D et al (2002) Carbon sequestration in trees and regrowth vegetation as affected by clearcut and partial cut harvesting in a second-growth boreal mixedwood. For Ecol Manag 169(1–2):83–101
Li Q, Chen J, Moorhead DL et al (2007) Effects of timber harvest on carbon pools in Ozark forests. Can J For Res 37(11):2337–2348
Liebhold AM, MacDonald WL, Bergdahl D et al (1995) Invasion by exotic forest pests: a threat to forest ecosystems. For Sci Monogr 30(2):1–38

Lindner M (2000) Developing adaptive forest management strategies to cope with climate change. Tree Physiol 20(5–6):299–307
Liski J, Pussinen A, Pingoud K et al (2001) Which rotation length is favourable to carbon sequestration? Can J For Res 31(11):2004–2013
Logan JA, Régnière J, Powell JA (2003) Assessing the impacts of global warming on forest pest dynamics. Front Ecol Environ 1(3):130–137
Luyssaert S, Schulze E-D, Borner A et al (2008) Old-growth forests as global carbon sinks. Nature 455(7210):213–215
Magnani F, Mencuccini M, Borghetti M et al (2007) The human footprint in the carbon cycle of temperate and boreal forests. Nature 447(7146):848–850
Malcolm JR, Pitelka LF (2000) Ecosystems and global climate change: A review of potential impacts on US terrestrial ecosystems and biodiversity. Pew Center on Global Climate Change, Arlington
Malcolm JR, Markham A, Neilson RP et al (2002) Estimated migration rates under scenarios of global climate change. J Biogeogr 29(7):835–849
Mandryk AM, Wein RW (2006) Exotic vascular plant invasiveness and forest invasibility in urban boreal forest types. Biol Invasions 8(8):1651–1662
Markewitz D (2006) Fossil fuel carbon emissions from silviculture: impacts on net carbon sequestration in forests. For Ecol Manag 236(2–3):153–161
Marland G, Obersteiner M (2008) Large-scale biomass for energy, with considerations and cautions: an editorial comment. Clim Change 87(3):335–342
McCament CL, McCarthy BC (2005) Two-year response of American chestnut (Castanea dentata) seedlings to shelterwood harvesting and fire in a mixed-oak forest ecosystem. Can J For Res 35(3):740–749
McCarthy HR, Oren R, Kim H-S et al (2006) Interaction of ice storms and management practices on current carbon sequestration in forests with potential mitigation under future CO2 atmosphere. J Geophys Res 111(D15103)
McLachlan JS, Hellmann J, Schwartz M (2007) A framework for debate of assisted migration in an era of climate change. Conserv Biol 21(2):297–302
McNab WH, Cleland DT, Freeouf JA et al (2007) Description of ecological subregions: sections of the conterminous United States. GTR-WO-76B. U.S. Forest Service, Washington, DC
Millar C, Stephenson N, Stephens S (2007) Climate change and forests of the future: managing in the face of uncertainty. Ecol Appl 17(8):2145–2151
Moomaw W, Johnston L (2008) Emissions mitigation opportunities and practice in Northeastern United States. Mitig Adapt Strategies Glob Chang 13(5–6):615–642
Muller SD, Richard PJH (2001) Post-glacial vegetation migration in conterminous Montreal lowlands, southern Quebec. J Biogeogr 28(10):1169–1193
National Climate Data Center (2008) US climate at a glance. http://www.ncdc.noaa.gov/oa/climate/research/cag3/cag3.html . Accessed 1 Oct 2008
Nebeker TE, Leininger TD, Meadows JS et al (2005) Thinning southern bottomland hardwoods stands: insect and disease considerations. In: Ecology and management of bottomland hardwood systems: the state of our understanding. University of Missouri-Columbia, Puxico, MO, pp 467–477
Neilson ET, MacLean DA, Menga F-R et al (2007) Spatial distribution of carbon in natural and managed stands in an industrial forest in New Brunswick, Canada. For Ecol Manag 253 (1–3):148–160
New England Regional Assessment (1999) The New England regional assessment of the potential consequences of climate variability and change. U.S. Global Change Research Program, Durham
North East State Foresters Association (2002) Carbon sequestration and its impacts on forest management in the northeast. Concord, NH
Nowak RS, Ellsworth DS, Smith SD (2004) Functional responses of plants to elevated atmospheric CO2—do photosynthetic and productivity data from FACE experiments support early predictions? New Phytol 162:253–280
Ohman JH (1970) Value loss from skidding wounds in sugar maple and yellow birch. J For 68(4): 226–230
Ollinger SV, Aber JD, Reich PB et al (2002) Interactive effects of nitrogen deposition, tropospheric ozone, elevated CO2 and land use history on the carbon dynamics of northern hardwood forests. Glob Chang Biol 8(6):545–562

Ollinger SV, Goodale CL, Hayhoe K et al (2008) Potential effects of climate change and rising CO2 on ecosystem processes in northeastern U.S. forests. Mitig Adapt Strategies Glob Chang 13 (5–6):467–485

Ostrofsky WD (2005) Management of beech bark disease in aftermath forests. In: Evans CA, Lucas JA, Twery MJ (eds) Beech bark disease: proceedings of the beech bark disease symposium. NE-GTR-331. USDA Forest Service, Northeastern Research Station, Saranac Lake, pp 133–137

Overpeck JT, Bartlein PJ, Webb T III (1991) Potential magnitude of future vegetation change in eastern North America comparisons with the past. Science 254(5032):692–695

Park BB, Yanai RD, Germain RH (2005) Effects of silvicultural treatments on coarse woody debris in the catskill region. In: Kenefic LS, Twery MJ (eds) Changing forests—challenging times: proceedings of the New England society of American foresters 85th winter meeting. GTR-NE-325. USDA Forest Service, Northeastern Research Station, Newtown Square

Parmesan C, Yohe G (2003) A globally coherent fingerprint of climate change impacts across natural systems. Nature 421:37–42

Parmesan C, Galbraith H (2004) Observed impacts of global climate change in the U.S. Pew Center on Global Climate Change, Arlington

Penman J, Gytarsky M, Hiraishi T et al (eds) (2003) Good practice guidance for land use, land use change and forestry. Intergovernmental Panel on Climate Change, Kamiyamaguchi, Japan

Perschel R (2006) Ensuring sustainable forestry through working forest conservation easements in the northeast. Forest Guild, Santa Fe

Potter C, Gross P, Klooster S et al (2008) Storage of carbon in U.S. forests predicted from satellite data, ecosystem modeling, and inventory summaries. Clim Change 90(3):269–282

Prasad AM, Iverson LR, Matthews S et al (2007) Climate change tree atlas. In: USDA Forest Service. Northern Research Station, Delaware, Ohio

Putz P (1996) Retaining biomass by reducing logging damage. Biotropica 29(3):278–295

Rehfeldt GE, Wykoff WR, Ying CC (2001) Physiologic plasticity, evolution, and impacts of a changing climate on Pinus Contorta. Clim Change 50(3):355–376

Reinmann AB, Kenefic LS, Fernandez IJ et al (2005) Soil characteristics 30-years post-harvest on Maine spruce flats: preliminary results. In: Kenefic LS, Twery MJ (eds) Changing forests - challenging times: proceedings of the New England society of American foresters 85th winter meeting. GTR-NE-325. USDA Forest Service, Northeastern Research Station, Newtown Square, p 66

Rodenhouse NL, Matthews SN, McFarland KP et al (2008) Potential effects of climate change on birds of the Northeast. Mitig Adapt Strategies Glob Chang 13(5–6):517–540

Ruddell S, Sampson R, Smith M et al (2007) The role for sustainably managed forests in climate change mitigation. J For 105(6):314–319

Salonius P (2007) Silvicultural discipline to maintain Acadian forest resilience. Northern J Appl For 24(2):91–97

Sampson RN (2004) Potential for agricultural and forestry carbon sequestration in the RGGI region. The Sampson Group, Alexandria

Saxe H, Cannell MGR, Johnsen Ø et al (2001) Tree and forest functioning in response to global warming. New Phytol 149(3):369–399

Schmid S, Thürig E, Kaufmann E et al (2006) Effect of forest management on future carbon pools and fluxes: a model comparison. For Ecol Manag 237(1–3):65–82

Schulte LA, Mladenoff DJ, Crow TR et al (2007) Homogenization of northern U.S. Great Lakes forests due to land use. Landsc Ecol 22(7):1089–1103

Scott NA, Rodrigues CA, Hughes H et al (2004) Changes in carbon storage and net carbon exchange one year after an initial shelterwood harvest at Howland Forest, ME. Environ Manag 33(Supplement 1):S9–S22

Shepperd WD, Rogers PC, Burton D et al (2006) Ecology, biodiversity, management, and restoration of aspen in the Sierra Nevada. RMRS-GTR-178. USDA Forest Service, Rocky Mountain Research Station, Fort Collins

Simberloff D (2000) Global climate change and introduced species in United States forests. Sci Total Environ 262(3):253–261

Skog KE, Nicholson GA (1998) Carbon cycling through wood products: the role of wood and paper products in carbon sequestration. For Prod J 48(7/8):75–83

Smallidge PJ, Han Y, Leopold DJ et al (1991) Management implications of ash yellows in northeastern hardwood stands. Northern J Appl For 8(3):115–118

Sohngen B, Walker S, Brown S et al (2007) Terrestrial carbon sequestration in the Northeast quantities and costs: part 4 opportunities for improving carbon storage and management on forest lands. The Nature Conservancy Conservation Partnership Agreement, Arlington
Spiecker H (2003) Silvicultural management in maintaining biodiversity and resistance of forests in Europe-temperate zone. J Environ Manag 67(1):55–65
Spittlehouse DL (1997) Forest management and climate change. In: Taylor E, Taylor B (eds) Responding to global climate change in British Columbia and the Yukon. Environment Canada, Vancouver, pp 24–21 to 24–28
Springer CJ, Thomas RB (2007) Photosynthetic responses of forest understory tree species to long-term exposure to elevated carbon dioxide concentration at the Duke Forest FACE experiment. Tree Physiol 27(1):25–32
Stavins RN, Richards KR (2005) The cost of US forest-based carbon sequestration. Pew Center on Global Climate Change, Arlington
Strong TF (1997) Harvesting intensity influences the carbon distribution in a northern hardwood ecosystem. RP-NC-329. USDA Forest Service, North Central Research Station, St. Paul
Stupak I, Nordfjell T, Gundersen P (2008) Comparing biomass and nutrient removals of stems and fresh and predried whole trees in thinnings in two Norway spruce experiments. Can J For Res 38(10):2660–2673
Taylor AR, Wang JR, Chen HYH (2007) Carbon storage in a chronosequence of red spruce (Picea rubens) forests in central Nova Scotia, Canada. Can J For Res 37(11):2260–2269
Upton B, Miner R, Spinney M et al (2007) The greenhouse gas and energy impacts of using wood instead of alternatives in residential construction in the United States. Biomass Bioenergy 32(1):1–10
Uriarte M, Papaik M (2007) Hurricane impacts on dynamics, structure and carbon sequestration potential of forest ecosystems in Southern New England, USA. Tellus A 59(4):519–528
US Census Bureau (2000) Decennial census, summary file 1–4. Washington, DC
Venette RC, Cohen SD (2006) Potential climatic suitability for establishment of Phytophthora ramorum within the contiguous United States. For Ecol Manag 231(1–3):18–26
Wang F, Wall MM (2003) Incorporating parameter uncertainty into prediction intervals for spatial data modeled via parametric variogram. J Agric Biol Environ Stat 8(3):269–309
Wang J, Chameides B (2005) Global warming's increasingly visible impacts. Environmental Defense Fund, New York
Waring KM, O'Hara KL (2005) Silvicultural strategies in forest ecosystems affected by introduced pests. For Ecol Manag 209:27–41
Watson RT, Zinyowera MC, Moss RH (eds) (1998) The regional impacts of climate change: an assessment of vulnerability. Cambridge University Press, Cambridge, UK
Westerling AL, Hidalgo HG, Cayan DR et al (2006) Warming and earlier spring increases western U.S. forest wildfire activity. Sciencexpress. doi:10.1126/science.1128834
Westveld M (1956) Natural forest vegetation zones of New England. J For 54(5):332–338
Whitehead DR (1979) Late glacial and post glacial vegetational history of the Berkshires, Western Massachusetts, USA. Quat Res 12(3):333–357
Whitehead RJ, Safranyik L, Russo G et al (2003) Silviculture to reduce landscape and stand susceptibility to the mountain pine beetle. In: Shore TL, Brooks JE, and Stone JE (eds) Mountain pine beetle symposium: challenges and solutions. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Kelowna, pp 233–244
Williamson M, Fitter A (1996) The character of successful invaders. Biol Conserv 78:163–170
Woodbury PB, Smith JE, Heath LS (2007) Carbon sequestration in the U.S. forest sector from 1990 to 2010. For Ecol Manag 241(1–3):14–27
Yanai RD, Currie WS, Goodale CL (2003) Soil carbon dynamics after forest harvest: an ecosystem paradigm reconsidered. Ecosystems 6(3):197–212
Ziegler SS (2000) A comparison of structural characteristics between old-growth and postfire second-growth hemlock-hardwood forests in Adirondack Park, New York, USA. Glob Ecol Biogeogr 9(5):373–389