Potential Impacts of Climate Change on Forest Resources in New England

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Forest resources in New England are intensively utilized for many different purposes. Population density is high, and because New England also has the highest proportion of forested land in the Nation, there is an intimate association of people and forests. Both large and small municipalities rely on forested watersheds for water supplies. Local economies are strongly tied to forest resources for uses such as outdoor recreation, hunting, maple syrup production, wood and fiber production, and aesthetic values.

Increasing atmospheric CO_2 (and other trace gases) causes enhanced greenhouse warming and has a direct effect on tree physiology and growth. Along with these changes, air pollution and acidic deposition exert strong influences on forest ecosystems in New England. Climate and pollution stresses, and their interactions with pests and intensive land uses, are likely to cause unprecedented and unanticipated changes in forest productivity and composition. The fragmentation of Northern forests due to urbanization, recreation, and agricultural use affects species habitats and the ability of some species to adapt to climatic change.

Research in New England has begun to unravel some key questions about how environmental changes will impact the productivity and health of forest ecosystems, species distributions and abundance, and associations of people and forests. However, just as we cannot predict with much certainty how climate in New England will change, we cannot yet predict how a given climate change scenario might impact different forest types or species. Nevertheless, some interesting information is becoming available and we should be aware of the possible consequences of climate change, and how climate change may interact with other factors to shape our future forests. Because of these potential changes, there is a need to develop adaptive management practices to protect forest health and productivity on both public and private lands.

New England Forests in a National and Global Context

The dense forests of New England and New York contain 4.2 billion metric tons of carbon in forest ecosystems, and this amount is increasing at a rate of about 20 million metric tons per year. Annual CO_2 emissions in the United States, primarily from burning fossil fuels for energy, are equivalent to 1.5 billion metric tons of carbon. In the international negotiating arena, the President is seeking ways to reduce or offset CO_2 emissions by 100 million metric tons, of which about 10 million would come from additional carbon storage in forests. The maturing forests of New York and New England are contributing in a very positive way to offset CO_2 emissions from other sources.

The rate of increase in forest carbon will not last. Growth is slowing as the forests mature, and harvest levels remain steady. Thus the inventory of forest carbon will level off in future years, and the U.S. will have to seek other ways besides forest offsets to control CO_2 emissions. Threats to the forests could reverse the trend and reduce the amount of carbon storage by causing declines and diebacks. On the other hand, increasing atmospheric CO_2 and nitrogen deposition may increase growth rates for many species, which would increase the amount of carbon in forest ecosystems. We are monitoring the exchange of CO_2 between forests and the atmosphere at research sites in Maine and Massachusetts so that we may understand better how forests are changing now and prospectively.

Which Forests and Species are Vulnerable to Climate Change?

Although we cannot yet identify which specific forest ecosystems and resources are most vulnerable to rapid climate change, some general characteristics of vulnerable forest ecosystems have been identified. These include: (1) forests and trees growing at or near their ecological limits of survival; (2) forests and trees already undergoing stress of some kind; (3) isolated populations or populations growing where barriers would pre-

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vent successful migration; and (4) forests and trees with limited adaptive capability.

In general, forests at climatic extremes, ecotones or transition areas, and forest areas limited by a barrier such as a mountain top or unfavorable site condition are often considered at greatest risk. Forests that are already stressed by other biotic or abiotic factors are also at high risk.

Some examples of vulnerable forests in New England include:

1) High-elevation red spruce, which is already stressed by acid deposition and winter injury.
2) Aging hardwood forests, which may be limited in adaptive capability.
3) Aspen-birch, which reaches its southern limit in Northern New England.

Some Tree Species May Adapt Quickly to Environmental Stress

Some tree species are well adapted to extreme environmental conditions. Under a changing environment, adaptation may be a significant alternative survival strategy to migration for some species. Successful adaptation or migration, or both, of a species may depend on how rapidly environmental conditions change.

Investigations on larch show how rapidly conifers can change their genetic makeup in response to changes in the environment. Genetic maps of the DNA from larch seeds grown under two temperature conditions show a strong segregation in certain marker locations, and show different growth responses, indicating selection for alternative traits under differing growth environments. The environment induces selection of different alleles in genetically identical populations of trees.

Eventually, identified genetic markers can be correlated with tree stress responses. This correlation would allow managers to select and propagate trees with adaptive traits for changing climatic conditions. A better understanding of the effect of breeding environment on plant performance may allow managers to select seed sources tailored to the expected environment in which a tree will grow over a long rotation.

Acid Deposition is Linked to Increased Winter Injury in Red Spruce

Damage to the foliage of red spruce during the winter is observed periodically in New England. Reports of winter injury have increased since 1960. Several studies have shown that exposure to acid mist, common at high elevations in New England, reduces the cold tolerance of red spruce foliage, predisposing it to winter injury. In experiments with simulated acid cloud water, exposing plants to acid mist at pH 5.6 and pH 3.2 reduced their cold tolerance by 3 to 5^{o}C.

Midwinter dehardening followed by extreme cold or rapid freezing (rather than reduced tolerance to cold temperature) may also cause winter injury. In laboratory experiments and field studies, rapid freezing causes the same damage symptoms as observed in the field after winter injury events. There were strong elevation and aspect patterns to damaged trees after severe injury during the winter of 1992-93, suggesting that solar radiation plays a role in rapid temperature changes.

Foliage exposed to acid mist has lower amounts of calcium (Ca) in the tissue. There is some disagreement concerning the role of Ca in the sensitivity of tissue to cold. Attempts to mediate reductions in cold tolerance by adding Ca to the soil in short-term experiments have not been successful. There is some uncertainty regarding the role of older, weathered soils that have depleted levels of Ca vs. newer glaciated soils that have abundant available Ca.

Although the link between acid deposition and increased winter injury has been demonstrated in experiments, the impact on red spruce at different field sites is still under study. Effective management practices have yet to be identified.

Warmer Temperatures Affect C and N Dynamics in New England Forest Soils

Climate—particularly temperature and precipitation—affects the rate at which organic matter decays and is broken down into its mineral components. This has led to much debate about the potential effects of global warming on northern temperate and boreal forest soils, especially since soils are major reservoirs for C, N, and other nutrients necessary for forest growth and productivity. Air pollution, particularly acid deposition, may also affect the availability of certain nutrients such as calcium and magnesium.

The response of a commercial spruce-fir forest soil to a warmer climate was investigated by increasing the forest floor thermal regime by 5^{o}C with the use of buried heating cables. This experiment has shown that fine root growth, litter decay, and CO_2 emissions are greater in the heated plots than the unheated plots. It is likely that increased microbial decomposition and root respiration caused these changes. A similar soil heating study in a northern hardwood forest produced similar results: increases in CO_2 flux, litter decomposition, and N mineralization. Germination of white pine seeds increased but there was no change in germination of eastern hemlock seeds in response to heating. In another study using sample plots along a series of short climate gradients in Maine, investigators concluded that temperature is a strong predictor of soil respiration and net N mineralization, though there are regional differences in the derived relationships.

These studies suggest that global warming would affect forest productivity, species composition, and carbon sequestration in forests of New England. Such experiments help answer some key questions about CO_2 flux and nutrient availability under a changing climate, and provide data to use in predictive models of the effects of regional climate change.

Nitrogen Deposition Is Retained and Sulphur Deposition Exported in Northeastern Study Sites

Continuous, long-term measurements of climate variables, atmospheric deposition, throughfall chemistry, and soil solution chemistry provide a basis for evaluating changes in chemical deposition and effects on forest processes. Nitrogen deposition is of particular importance in the Northeast. Although most temperate forests are considered N limited, there is a growing concern that chronic N deposition can lead to the contrasting condition of excess N or N saturation. Excess N interferes with normal soil processes and can reduce productivity, and may also be exported from the forest in streams and rivers, with undesirable effects on water quality. Sulphur (S) affects vegetation in the Northeast primarily as sulfuric acid, a major component of acid deposition.

At a commercial spruce-fir forest site in Howland, Maine, S deposition has decreased over a 6-year period while N deposition has remained relatively steady. There was a net retention of N in the soils, attributable to N-deficiency in the ecosystem. Outputs of S in streamwater decreased in proportion to decreasing atmospheric inputs.

The effects of elevation on deposition and nutrient cycling were studied over an 8-year period at a high-elevation spruce-fir forest on Whiteface Mountain, New York. There are large (four- to fivefold) differences in deposition of S and N over an elevational range of 600 to 1275 m. The differences are attributed to higher levels of cloud water deposition at higher elevations. Most of the N is retained in the ecosystem, except a small amount is exported in streamwater. This may signal the early stages of N saturation. Sulphur output varies with the level of S input, similar to observations at Howland.

These long-term observations of chemical inputs, transformations, and outputs in forest ecosystems allow us to analyze changes that result from the recent revision of the Clean Air Act. They also facilitate understanding of the critical role of N in ecosystem productivity, interactions with other stresses such as increasing CO_2 and O_3, and the role of N fertilization in the global C cycle. Of particular importance are prospects for N saturation and eventual export of nitrate, a significant pollutant of drinking water and marine systems, from northeastern watersheds.

Nutrient Concentrations Are Declining in Areas Sensitive to Acid Deposition

Several long-term studies in the Adirondack Mountains of New York and the White Mountains of New Hampshire documented a substantial decline since 1950 in Ca and Mg in the organic soil layers of red spruce forests. Evidence of changing Ca and Mg availability is also present in wood. Chemical analysis of wood cores from the northeastern United States has documented trends in Ca and Mg concentrations that are consistent with changes measured in the soil. There is a strong correlation between these changes in the forest and historical changes in acid deposition, which increased substantially about 1950.

It has been suggested that reduced availability of Ca and Mg could cause decreased productivity and decline/dieback of red spruce in the Northeast, especially on calcium-deficient soils. Chemical analyses from the 12 research sites in New England and New York have documented increased leaching of Ca and Mg from the soil, a decreased amount of Ca and Mg available to tree roots, and corresponding changes in Ca in wood. These changes are initiated by acid deposition. Acid deposition leaches Ca from the soil, and can cause aluminum (Al) to become soluble. Soluble Al may be brought to the surface soil and the rooting zone of red spruce by upward water movement. Elevated concentrations of Al inhibit the uptake of Ca and Mg by the roots, and can be toxic if concentration becomes too high.

Decreased availability of Ca and Mg and increased availability of Al cause stress in red spruce and make the trees more vulnerable to winter injury, defoliators, and root rot. High elevation spruce-fir sites have shown the greatest impact, and although lowland spruce-fir forests have been less obviously impacted, the same chemical processes are occurring and there is reason to expect that impacts may become more apparent over time.

Scientists are seeking to discover early indicators of stress in red spruce trees so that managers have an early warning of impending decline/dieback. They are also evaluating possible mitigating effects of additions of Ca. Results of this research will assist land managers in maintaining healthy forests over a large area of red spruce forest in the Northeast.

Can We Predict or Detect Species Migrations?

Predictions of the effects of global warming on the ranges of individual tree species indicate northward shifts of up to 800 km. Estimates of the maximum rate of tree migration from historical records (15-50 km per century) suggest that most species could not keep pace with the predicted rate of climate change. Keeping pace would require a migration rate of more than 10 times the past rates. Following this logic, many have speculated that rapid climate change could cause tree species to grow under environmental conditions that are not optimal for growth during transition to a new climate (a transient response), which could cause growth reductions, declines in tree health, or abnormal rates of tree mortality.

Historical rates of distribution shifts may be misleading because human land use has fragmented most landscapes, making it even more difficult for many species to move into new areas. On the other hand, humans have unprecedented capability to assist in the process of species establishment and so could substantially increase the natural rate of seed dispersal.

We have remeasured long-term, permanent sample plots with the objective of detecting changes in species composition associated with disturbance, acid deposition, and climate change. Establishment of sample plots along an elevation gradient in New Hampshire, and remeasurment of forest inventory plots over a 24-year period in Maine, show that species composition changes are strongly associated with past land use changes, obscuring any signal of changing composition associated with climate. A separate study covering a 60-year period on the Bartlett Experimental Forest in New Hampshire showed that the primary factor affecting species composition was natural succession, followed by management activities and wind damage.

These and other studies highlight the difficulty of attributing observed changes in forest composition to specific causes when there are many factors simultaneously influencing the systems. Natural succession, disturbance and drought, and past and present human activities seem to be dominant factors affecting forests in the Northeast. Detection of changes in species composition as a consequence of warming or other environmental change would require intensive monitoring of sites that would be most sensitive to small perturbations.

Ozone May Reduce Regional Ecosystem Productivity

We are synthesizing, on a regional basis, the different responses of trees, stands, and landscapes to multiple environmental stresses. We developed or studied a number of models with the goal of integrating a cluster of biological models operating at various spatial and temporal scales with models of physical and social systems.

In one study we adapted a well-known ecosystem process model, PnET-II, to estimate the effects of O_3 on forest productivity over the northeastern United States. The productivity model is applied to regional data bases within a geographic information system. The model simulates physiological processes at the ecosystem scale and applies the predicted changes to landscapes composed of a grid of cells classified by vegetation attributes, climate parameters, pollution exposure, and so on.

We assumed that the only effect of elevated O_3 was a reduction in photosynthesis. Using average O_3 exposures from 1987-92, we estimated that annual Net Primary Productivity (NPP) was reduced from 2 to17 percent, with the greatest reductions in southern New York and New England where O_3 levels and potential photosynthesis were greatest.

No Evidence of Decline in Productivity of Sugar Maple

Since the 1980's, some stands of sugar maple have declined in New England and Canada. Extensive monitoring has failed to substantiate reports of widespread decline, yet the issue continues to surface because maple is so important in many ways: wood, maple syrup, aesthetics, and wildlife.

In 1991 we recovered records of research plots measured in the late 1950's in northern hardwood stands of Vermont's Green Mountains. The purpose of the original study was to examine relationships between site index and site characteristics. It was hypothesized that remeasurement of these same plots and replication of the original analyses would uncover any significant changes in productivity that might have occurred over the 33-year period. About half of the plots had been harvested, allowing tests of additional hypotheses about the effects of disturbance.

The investigators found current growth to be equal to or better than growth 33 years ago, with shade tolerant species such as sugar maple increasing to a greater degree than shade intolerant species. This is consistent with expected stand dynamics. In the undisturbed plots, stands grew essentially as predicted from the 1957-59 data. For a given d.b.h., sugar maple was slightly (but not significantly) taller in 1990-92 than in 1957-59 (Figure 11). For maple stands that were harvested, there was apparently no effect on total carbon stored in the soil.

Conclusions Prospective Effects of Global Change On New England Forests

While we cannot predict the future with great certainty, research and monitoring are highlighting some important trends in forest ecosystems of New England and New York:

1) Carbon storage in Northeastern forests is increasing at a decreasing rate. The rate of change is affected by maturing forests and harvesting activity, increasing atmospheric CO_2, air pollution, and acid deposition.
2) High-elevation red spruce, aging hardwood forests, and aspen-birch forests are examples of forest types at risk from climate change.
3) Species composition is likely to change due to variability in adaptation and migration between species.
4) Increased winter injury of red spruce is likely as a consequence of acid deposition and extreme weather events.
5) Warmer temperatures have strong effects on soil processes. Nutrient availability and CO_2 flux will be affected, as will productivity and forest growth.
6) Nitrogen deposition remains high and sulphur deposition is declining. These chemical inputs affect productivity and forest growth.
7) Calcium and magnesium, important forest nutrients, are declining in calcium-deficient soils and may cause decreased productivity and decline/dieback of red spruce.
8) Because of the many factors affecting forests in New England and New York, it will be very difficult to identify the effect of climate change alone. Natural succession, disturbance, and drought seem to be the dominant factors affecting forests at the current time.
9) There is evidence that ground-level ozone may reduce ecosystem productivity in New England and New York, in areas where exposure is highest.
10) There is no evidence of widespread decline of sugar maple in New England and New York. In Vermont, sugar maple is growing as good or better than 3 decades ago.