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Sugar Maple Ecology and Health: Proceedings of an International Symposium

June 2-4, 1998
Warren, Pennsylvania



Acer saccharum

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Sugar Maple Ecology and Health: Proceedings of an International Symposium

June 2-4, 1998
Warren, Pennsylvania

Edited by:
Stephen B. Horsley
Robert P. Long

Sponsored by:
USDA Forest Service, Northeastern Research Station
Pennsylvania State University, School of Forest Resources
State University of New York, College of Environmental Sciences and Forestry
Pennsylvania Department of Conservation and Natural Resources
New York Department of Environmental Conservation

Preface

Sugar maple (*Acer saccharum* Marsh.) is a signature species in the northern hardwood forest of the northeastern and north central United States and eastern Canada. The species has been sought for its hard wood, sweet sap, and flaming fall foliage. Sugar maple biology has been the subject of much scientific study, yet despite a tremendous collective effort, many aspects of its ecology and health are not well understood.

During the past four decades, declines of sugar maple have occurred throughout its range. Each decline event has been the subject of intense research. The declines were ephemeral, preventing a complete understanding of conditions and causes. The most recent decline in Pennsylvania was the impetus to organize an international symposium on sugar maple ecology and health.

Speakers from the United States and Canada were invited to share their research and explore a variety of topics concerning sugar maple history and ecology, recent sugar maple declines, nutrient and belowground dynamics in northeastern forests, and interactions of forest health with biotic and abiotic stressors. Posters also were contributed. Attending scientists, natural resource professionals, and land managers participated in two days of talks and discussions and a day-long field trip to sugar maple decline research sites in northwestern Pennsylvania and southwestern New York.

Conference speakers and poster presenters were invited to submit abstracts, popular summaries, or complete manuscripts on the work presented at the conference. Abstracts and popular summaries have been reviewed by the conference co-editors; complete manuscripts received additional peer review.

Stephen B. Horsley and Robert P. Long
Conference Co-editors
USDA Forest Service, Northeastern Research Station,
Warren, PA, and Delaware, OH, respectively

Acknowledgments

We thank the many people who helped make the conference successful. In addition to the conference co-editors, the organizing committee included Douglas Allen, State University of New York, College of Environmental Science and Forestry; David DeWalle, Environmental Resources Research Institute and School of Forest Resources, Pennsylvania State University; and Scott Bailey, Northeastern Research Station, Durham, New Hampshire. The conference organizers also acted as session moderators. Wendy Snaveley, Kathy Sweeney, Susan Stout, Harry Steele, Vonley Brown, Barbara McGuinness, Todd Ristau, David Saf, and Ernest Wiltsie Northeastern Research Station, Warren, Pennsylvania, helped with local arrangements. Carol Calvin, Northeastern Research Station, Delaware, Ohio, prepared the conference logo. Stephen Wingate, Allegheny National Forest, Michael Fay and Stephen Smith, New York Department of Environmental Conservation, Paul Lilja and Thomas Hall, Pennsylvania Department of Conservation and Natural Resources, and Scott Bailey and Richard Hallett, Northeastern Research Station, Durham, New Hampshire, helped with the field trip. Ann Oroszi, Northeastern Research Station, Delaware, Ohio, provided clerical support.

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Sugar Maple: Its Characteristics and Potentials

Ralph D. Nyland¹

Abstract

Sugar maple dominates the northern hardwood forest, but grows over a broader geographic area. Conditions of soil and climate largely limit its distribution, and account for its less continuous cover along fringes of the range. Sugar maple regenerates readily following a wide range of overstory treatments. Success depends upon its status as advance regeneration, particularly under strategies favorable to less shade-tolerant species. In even-aged stands, trees of upper canopy positions grow well following release by cutting. Those of lower canopy positions do not. In uneven-aged stands, both small and large trees respond well to release. Diameter-limit cutting removes the best trees, often leaving stands in poor condition for growth and health. Damage to trees by natural agents and logging commonly leads to discoloration and decay, and often to dieback. Within the range of northern hardwoods, sugar maple seems generally healthy. Exceptions include stands damaged by defoliation, logging, and similar agents.

Requirements for Ecologic Success

To persist over ecologic time, a species must become established at available sites; survive, grow and develop successfully under prevailing edaphic, climatic, and biologic conditions; produce viable seed in quantity and frequency for establishment at critical times; and endure. Its range expands when seed moves to favorable sites in new areas.

In this context, *site* means the interacting biotic and abiotic factors that determine the potential for a species or tree to become established and develop. Important factors include:

1. the periodicity of extended shortages or excesses of moisture;
2. deficiencies or excesses of nutrients due to the parent material, with uptake influenced by available moisture;
3. mechanical damage by wind, ice and snow, and vertebrate animals (including people);
4. defoliation and other activities by insects and other invertebrates, and effects of fungi and disease organisms; and
5. physical and chemical interference and competition from existing or co-establishing vegetation.

These affect the form, vigor, and growth of individual trees and groups of trees. They also may influence the potential for flowering and pollination, seed development and dispersal, and embryo viability and germination.

¹Distinguished Service Professor, State University of New York, College of Environmental Science and Forestry, Syracuse, NY 13210.

Altogether, site factors influence tree success at three levels:

1. across the geographic range of a species, with the best sites likely toward the center of that area;
2. across environmental gradients within the geographic range, based upon soil, climate, and critical biota; and
3. across a single location, with variations of micro-site features that affect young trees before the root systems integrate soil across a larger local space

Generally, species and individual trees best adapted to the local site conditions and competitive effects have the highest vigor, grow the best, and occur in the upper crown positions within a cohort. Further, these trees may suffer fewer environmental stresses over time, live longer, and develop to larger sizes. Sugar maple (*Acer saccharum* Marsh.) exemplifies these principles within its range.

Ecologic Characteristics of Sugar Maple

Sugar maple is a major component of the northern hardwoods forest type group, including six distinct hardwood forest cover types and one mixed hardwood-conifer type (Eyre 1980). It occurs in lesser amounts or occasionally in two other eastern hardwood cover types, three oak-dominated forest cover types, five central hardwoods forest cover types, two boreal hardwood cover types, and six eastern conifer cover types. The current geographic range extends from the Maritimes in Canada westward across the Great Lakes region to the prairie, and southward into Missouri, Tennessee, Virginia, Pennsylvania, northern Maryland and Delaware, and southern New England. Small outliers occur farther south, and in northeastern South Dakota (Figure 1).

Sugar maple accounts for 50% or more of the basal area in northern hardwood stands. The most contiguous area of this cover type currently runs from northern Ohio and Pennsylvania through southern Ontario and Quebec, and eastward through northwestern Massachusetts into western Maine. Northern hardwoods also grow extensively in southern Ohio and west-central Indiana, and along the Appalachians in eastern West Virginia. More dispersed major blocks intermix with other forest cover types around the Great Lakes in Michigan, Wisconsin, Minnesota, and western Ontario; and from central Maine eastward through the Maritimes (Figure 1). This broad region has a generally cool and moist climate, a growing season of 80-260 days, and well-distributed precipitation throughout that period (Godman 1965; Eyre 1980; Godman *et al.* 1990).

Since the early 1900's, northern hardwoods have naturally reforested many former agricultural sites within their natural range, and probably in fringe areas as well. As a consequence, many areas formerly supporting only widely dispersed and disconnected remnant woodland patches now have large tracts of unbroken northern hardwood forest

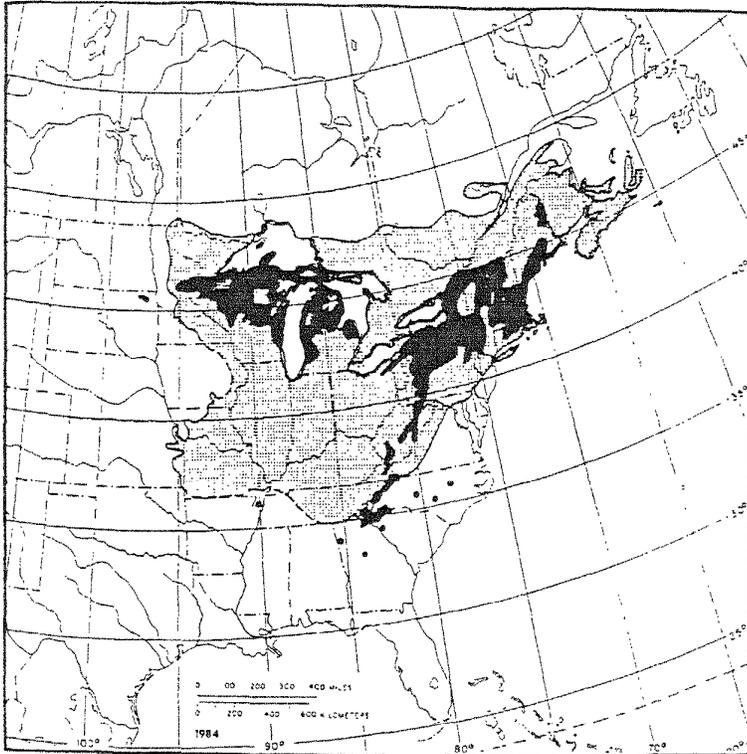


Figure 1.—The geographic range of northern hardwoods (black) in the United States, in comparison to the distribution of sugar maple (stippled) (after Shantz and Zon 1924; Godman *et al.* 1990).

(Nyland *et al.* 1986; Zipperer *et al.* 1988, 1990). Overall, from 1963 to 1992 northern hardwoods increased from approximately 13 to 19 million ha (32 to 46 million ac) (Quigley and Morgan 1969; Powell *et al.* 1993). At upland sites, the naturally reforested stands often contain pure sugar maple, or sugar maple mixed with some white ash (*Fraxinus americana* L.) or another common associate. On more poorly drained soils, red maple (*Acer rubrum* L.) has become dominant, along with white ash and American elm (*Ulmus americana* L.). The reforested stands generally have an even-aged character. Other woodlands commonly contain a broader array of species, and many have an uneven-aged character. (e.g., Nyland *et al.* 1986; Zipperer *et al.* 1990).

The range of northern hardwoods overlaps that of Spodosol and Inceptisol soils (Figure 2). Sugar maple also extends across a major area of Alfisols lying south of the Great Lakes, but primarily on fertile, mesic sites (Smith 1995). It grows in sands through silt loams, but develops best in fairly deep, moist, fertile, well-drained loam soils having ample growing season soil moisture. These conditions enhance leaf litter decomposition, helping to enrich the soil. Sugar maple does poorly in dry soils, and will not occur on wet sites (Godman 1965; Leak 1978; Godman *et al.* 1990). The fine feeding roots develop mainly within or near the organic horizons. They, and the mycorrhizal associations on them, react to variations in soil moisture and texture, and events that sharply reduce overstory shading can affect their development and survival (Fayle 1965; Kessler 1966; Allen 1987).

In the southern portion of its range, sugar maple is important on the highest quality oak sites, moist (but not wet) flats, and in ravines or coves. To the north it dominates mesic ridges between poorly drained areas, the warm upper slopes with good drainage and a middle or better range of pH, and enriched benches and coves. Along with the importance of bedrock and till sources on current soil, best growth occurs at sites with organic material incorporated into the mineral horizons. American beech (*Fagus grandifolia* Ehrh.) often replaces sugar maple on the drier sites, especially at the more northern latitudes. Red maple dominates the poorly drained soils throughout much of the natural range for sugar maple. At high elevations and toward the northern part of their range, northern hardwoods converge with boreal forests. Aside from soil, climate largely limits the distribution of sugar maple in elevation, as well as longitude and latitude. Conditions become too cold to the north, too warm to the south, and too dry to the west (Godman 1965; Post 1969; Hosie 1973; Leak 1978, 1980; Godman *et al.* 1990; Farrar 1995; Heisey 1995).

Biologic Attributes of Sugar Maple

Sugar maple produces some seed by age 50. Amounts increase thereafter, with production related to tree size and stand density (e.g., tree vigor). Large diameter (past 100 years) trees often produce vast quantities. In sawtimber stands, production varies from some seed annually, to medium or better crops in slightly more than one-half of the years within the range of northern hardwoods. Good crops

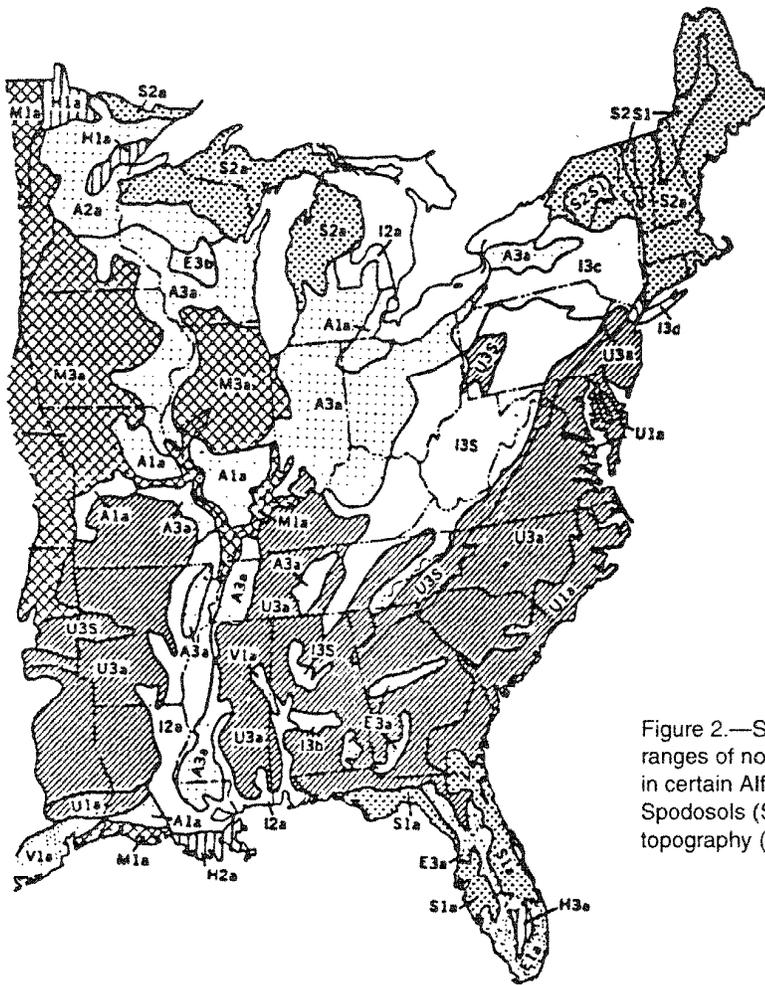


Figure 2.—Soil orders of northeastern United States. The ranges of northern hardwoods and sugar maple largely occur in certain Alfisols (A2a and A3a), Inceptisols (I3a and I2a), and Spodosols (S2a and S2S1) on gentle to steeply sloping topography (after US Soil Conserv. Soc. 1975).

often occur in successive years, with only occasional failures (Godman 1965; Tubbs 1969; Godman and Mattson 1976; Godman *et al.* 1990; Garrett and Graber 1995). At least among developing even-aged stands of seed-bearing ages in Pennsylvania at the fringe of northern hardwoods, annual seed production varies widely, with good seed years only every 7-8 years (Grisez 1975, Long *et al.* 1997).

Seeds will glide up to 107 m (350 ft) down wind into openings, but most fall much closer in closed stands (Godman *et al.* 1990; Nyland 1996). They stratify naturally over winter within the leaf litter. Most germinate the first year under favorable conditions. The high germination capacity commonly results in a carpet of seedlings following good seed years, given favorable environmental conditions during the spring and early growing season. The strong radicle readily penetrates a heavy leaf litter, so that a high proportion of germinants survive if the forest floor remains reasonably moist. Even small and light overstory disturbances, or other events that brighten the understory, trigger regeneration underneath residual stands at mesic sites. Once established, advance seedlings and saplings may persist for many years. They develop rapidly following either partial or complete overstory removal, especially at

sites with good moisture and available nitrogen. In addition, young trees, small saplings, and large seedlings readily sprout. These sources, coupled with well-developed advance regeneration, often maintain sugar maple as an important component of new stands where more rapidly growing species also regenerate (Godman 1965; Trimble *et al.* 1986; Godman *et al.* 1990; Tryon *et al.* 1992; Wang and Nyland 1993; Walters and Reich 1997).

Sugar maple shows considerable genetic variability. Sources from warm, dry portions of the range have greater drought resistance than seedlings from cooler and moister sites. Local and individual genetic variation also affects height growth and degree of apical dominance (Kriebel 1969). Also, tests suggest significant genetic effects on individual tree diameter and height growth, and survival. Early responses provide a good indicator of long-term height development (Schuler 1994).

Repeated browsing by ungulates, hare, and rabbits may destroy sugar maple seedlings, making regeneration difficult by any silvicultural method. Also, stands subjected to protracted intense browsing may develop understories of interfering plants that can prevent successful regeneration of

sugar maple in both even- and uneven-aged stands. These include ferns and grasses (Tubbs 1973; Marquis 1987), or a dense beech understory (Richards and Farnsworth 1971; Kelty and Nyland 1981; Marquis *et al.* 1984, 1992; Marquis 1987) or striped maple. Failure to control these plants will lead to a failure of sugar maple and other desirable species following cutting to a wide range of densities, and after clearcutting (Richards and Farnsworth 1971; Kelty and Nyland 1981; Marquis *et al.* 1984, 1992). The reproduction method must reduce these obstacles (site preparation and reduction of animal density) to insure success (Kelty and Nyland 1981; Sage 1987; Marquis *et al.* 1992; Horsley 1994; Nyland 1997). For large areas, applications using a skidder-mounted mist blower prove most efficient for controlling an interfering understory (Sage 1987; Horsley 1994).

Growth and Development

On suitable sites, sugar maple lives for 300-400 years, reaching more than 30 m (100 ft) tall and 89-102 cm (35-40 in) dbh (Westveld 1933; Eyre and Zillgitt 1953; Blum 1961; Leak 1975). It annually increases about 0.3 m (1 ft) in height for the first 30-40 years, but little after 140-150 years (Godman *et al.* 1990). Frequent breakage by ice, snow, wind, and logging often limits useable length to about 8-12 m (25-40 ft) at many high elevation and northern latitude sites (Nyland 1989). These injuries commonly lead to discoloration of wood present at the time of injury, and decay may develop in some cases (Shigo 1966).

Large trees add about 2.54 cm (1 in) of diameter per decade in unmanaged stands. Increment even of old trees will increase following release by cutting. In managed uneven-aged stands and even-aged ones of intermediate ages, radial increment of good-vigor trees will increase in proportion to the degree of release (intensity of cutting), and may average 5-8 cm (2-3 in) per 10 years (Nyland 1989). Mortality will decrease inversely with residual density (Eyre and Zillgitt 1953; Gilbert *et al.* 1955; von Althen *et al.* 1994; Majcen 1995; Pothier 1996). Yet net stand-wide production increases in stands thinned down to 60% relative density, due in part to the reduction of mortality losses (Nowak 1996). Also, individual residual tree diameter growth increases following thinning in even-aged stands. But the degree generally correlates with tree size and crown canopy position (Stone 1986; Marquis 1991; Nyland *et al.* 1993). Low vigor trees of intermediate and overtopped positions continue to grow at relatively slow rates, even following fairly heavy release (Figure 3a). By contrast, small (young) trees in managed uneven-aged communities have well developed crowns and good vigor (Kenefic and Nyland 1998). Their radial growth (Figure 3b) and height will increase appreciably if cutting regulates the spacing and density across size classes (Eyre and Zillgitt 1953; Gilbert *et al.* 1955; Mader and Nyland 1984; Donoso *et al.* 1998).

Some Factors Affecting the Health and Condition of Sugar Maple

Several insects, fungi, diseases, and environmental phenomena affect sugar maple. Few actually kill the trees. They may reduce the vigor, decrease the value for products, or structurally weaken the bole. Sugar maple borer has this effect. Some fungi like *Armillaria* kill sugar maple, and heavy defoliation over successive years may result in mortality. But defoliation mostly kills low-vigor trees, and root diseases and

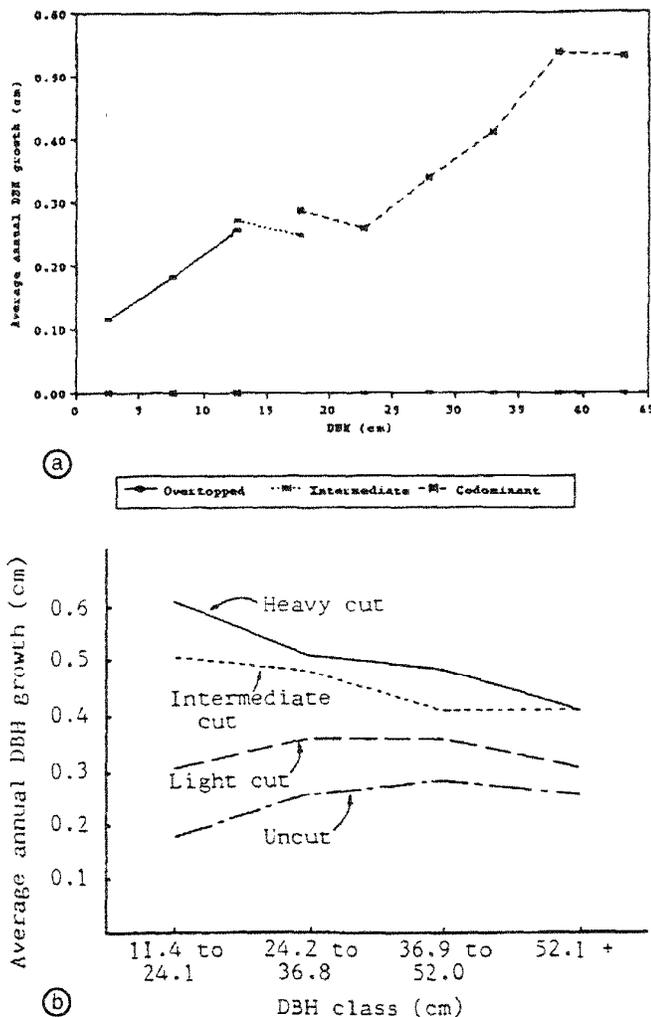


Figure 3.—Growth of sugar maple trees following release. a. After thinning in even-aged stands, radial increment correlates with crown position and tree diameter, with best increment among trees that initially grew in upper-canopy positions (after Lareau 1985; Nyland *et al.* 1993). b. After selection system treatments that cut across the diameter classes in uneven-aged stands, the growth of small trees increases in proportion to the intensity of cutting, and dramatically so at relatively low residual density (after Eyre and Zillgitt 1953).

other fungi commonly enter through wounds to a tree (Allen 1987; Shigo 1966; Shortle 1987). Breaking branches >8 cm (>3 in) diameter and removal of bark from >970 cm² (>150 in²) of the bole triggers discoloration of the wood present and may lead to decay if wood-rotting fungi colonize through the wounds (e.g., see Shigo 1966). Such large wounds appear to increase the chance of measurable decay within 20-25 years (Hesterberg 1957; Silverborg 1959; Ohman 1970; Nyland and Gabriel 1971; Nyland *et al.* 1976).

Landowners cannot prevent damage during storms and actions of fungi. They can spray to protect against defoliation. And they can control injuries from logging and other stand uses to some degree (Nyland 1989). Precluding skidding on saturated soils prevents root wounds that serve as entry courts for diseases and also reduce the size of a root system and its moisture absorption and carbohydrate storage capacities. These injuries can lead to dieback during periods of stress (Shigo 1985; Manion 1991; Cote and Ouimet 1996).

Several assessments suggest either a recent increase of diebacks and declines in sugar maple (Lachance *et al.* 1995; Cote and Ouimet 1996; Auclair *et al.* 1996; Auclair *et al.* 1997), a pattern of periodic growth depressions and recoveries over long time periods (Payette *et al.* 1996), or no anomalies (Lane *et al.* 1993; Hopkin and Dumond 1994; Heisey 1995). Reported problems commonly occur along outer portions of the range for northern hardwoods (e.g., northern Pennsylvania, Quebec, and the Maritimes). Evaluations implicate factors like drought, heat, insect attacks, stand maturation, freezing, freezing-thawing cycles, injuries, soil nutrients, other natural stresses, tree social status within the community, and forest management practices. As with other species, most likely a complex of site factors influence the success of sugar maple, and multiple factors determine its vigor and condition (Houston 1981; Stolte 1997).

Forest health specialists commonly suggest that trees of high vigor better withstand a variety of harmful agents. Appropriate tending to reduce inter-tree crowding and maintaining large and full crowns may help to make sugar maple more resistant, and more resilient in recovery (Boyce 1948; Hawley and Stickel 1948; Graham 1952). Silviculture will not prevent damage during widespread outbreaks of insects or major disease incidents (Baskerville 1975; Wood 1988). Yet a variety of health maintenance measures should become routinely incorporated into the silvicultural system for a stand. These include (after Belanger and Malac 1980; Belanger 1981; Nyland 1996):

1. use of an appropriate reproduction method and the requisite site preparation to insure an abundance of species suited to the site;
2. timely tending to control stand density and insure high tree vigor;
3. selection of sound, vigorous, and well-developed trees as residual growing stock;

4. timely salvage and sanitation cutting to remove weakened and badly injured trees, and to reduce risks to damaging insects and fungi;
5. setting an appropriate life span for an age class;
6. appropriately siting and designing skid trails to minimize affects on soil and residual trees;
7. scheduling skidding and other machine operations for seasons when the soil will support the equipment without rutting and root damage;
8. careful practice in logging to minimize injuries to residual trees; and
9. continual monitoring of potential health problems and their causes to allow prompt response as needs arise

These measures represent part of a landowner's integrated health management program.

Silviculture for Sugar Maple Dominated Stands

Silviculture either regenerates mature age classes, or tends those of intermediate ages. Foresters use both activities to establish and maintain some particular set of ecologically desirable plant community attributes. Uses that serve economic interests derive from those conditions. In this context, foresters use timber harvesting to implement the planned silvicultural treatments. When removals allow a commercial sale, landowners can manage the habitat for indigenous plants and animals, maintain essential hydrologic and other important ecologic functions, influence visual qualities, and serve many other purposes without major investments (Nyland 1996).

Several biologic and ecologic characteristics facilitate the regeneration of sugar maple throughout much of its range, and make it responsive to later management. Important ones include (after Bourdo 1969):

1. consistent and abundant seed production;
2. good dispersion from the parent tree once seeds mature;
3. ready germination and establishment of seedlings;
4. sprouting from stumps of both small and larger trees;
5. a high tolerance to shading;
6. good rates of diameter and height growth at high light levels;
7. strong growth response following release from competition;
8. high resistance to many harmful agents; and
9. good recovery following crown breakage by ice, snow, wind, and logging

Since sugar maple dominates northern hardwood stands, its silviculture parallels that for the forest type as a whole.

Considerations for Regeneration

The extent that sugar maple reforested former agriculture sites and cut-over forest stands attests to the ease of securing natural regeneration under a wide variety of seedbed and residual stand conditions. Yet in forested areas, regeneration often fails on skid trail surfaces devoid of an organic cover and humus, even if seeds fall on them and germinate (Walters and Nyland 1989; Wang and Nyland 1996). A leaf litter does not impede penetration of the radicle following germination (Godman *et al* 1990). Favorable moisture and nutrient supplies in the humus sustain the seedlings until their root systems develop.

Sugar maple seedlings develop best at about 13-45% of full sunlight. Once well established, they persist for many years under even heavy shade (Logan 1965; Tubbs 1969), and respond to release by overstory cutting. If well developed, advance seedlings survive and grow better following complete or heavy overstory removal. For stands lacking such seedlings, clearcutting may delay establishment and development of a new cohort, and shelterwood method commonly proves more effective (Tubbs 1977a, 1977b). Having seedlings greater than 0.3 m (1 ft) tall also speeds cohort development following partial overstory disturbance (Leak and Wilson 1958; Metzger and Tubbs 1971; Mader and Nyland 1984).

Advance seedlings of good vigor grow in proportion to the degree of release, reaching about 1.8 m (6 ft) in 12 years and 3.0 m (10 ft) in 20 years on good sites with full sunlight. Less shade-tolerant associates may grow twice as rapidly, making the advance status of sugar maple critical to insuring its place in the main canopy of even-aged stands (Wang 1990; Wang and Nyland 1996). Depending on how long they grew under shade prior to release, sugar maple saplings reached 3.0 m (10 ft) in 18-23 years after selection system cutting to 17 m²/ha (75 ft²/ac). Low light levels under this and higher stocking make conditions unfavorable for faster-growing less shade-tolerant species, so sugar maple commonly dominates the new age class (Tubbs 1969; Nyland 1997; Donoso *et al.* 1998). However, dense interfering plants (e.g., American beech) or intensive and protracted browsing (e.g., white-tailed deer) can preclude success following any cutting strategy.

Uneven-aged Silviculture

Selection system controls the density within different size (age) classes to sustain stand conditions and volume production over successive cutting cycles, the patterns of regeneration across a stand, and the growth and quality of residual trees. At regular intervals, landowners remove excess immature trees to maintain a specified residual number per size (age) class, and harvest the economically or ecologically mature ones to regenerate a new cohort across a fixed proportion of the stand area. Failure to incorporate regeneration, tending, and harvest simultaneously makes the result unpredictable, the residual conditions less consistent over time, and the yields less regular (Nyland 1987; Nyland *et al.* 1993; Nyland 1996).

Research and experience provided guidelines (Table 1) for selection system based upon an 8-12 yr cutting cycle (Eyre and Zillgitt 1953; Arbogast 1957; Gilbert and Jensen 1958; Leak *et al.* 1969). Simulation methods suggest other alternatives for longer treatment intervals, different stand conditions, and various landowner objectives (Hansen and Nyland 1987; Hansen 1987; Nyland 1996). Appropriately structured stands grow between 0.6 and 0.7 m³/ha/yr (2.5 and 3.0 sq ft/ac/yr) for basal area (Eyre and Zillgitt 1953; Blum and Filip 1963; Leak *et al.* 1969; Mader and Nyland 1984), and 2.2 and 3.2 m³/ha/yr (200-300 bd ft/ac/yr) of sawtimber volume (Eyre and Zillgitt 1953; Leak *et al.* 1969; Mader and Nyland 1984). Differences in production largely reflect the variation in tree heights across regions and sites. Generally, growth provides sufficient yields for another operable cut at the intended interval.

Partial cutting in uneven-aged stands commonly causes broken branches and basal wounds, and may destroy some trees. The incidence will be proportional to the numbers of trees in a size class, and ones with major injuries may comprise about one-fifth of the residual basal area. Repeated partial cutting might maintain a base level of physical defect in a stand managed with any type of partial cutting strategy (Nyland and Gabriel 1971; Nyland *et al.* 1976; and Nyland 1989).

Even-aged Silviculture

Treatments to regenerate a new age class and tend older ones never occur simultaneously in even-aged communities. So landowners often treat conditions found at a given time, rather than following a pre-planned management strategy for an entire rotation. Most landowners consider pre-commercial treatments financially unacceptable, and delay the first entry for 50-60 years, when they can do a commercial thinning. For this, foresters use an appropriate relative density guide to plan the residual stocking and method for thinning based upon the numbers of trees, their sizes, the basal area, and the species composition (Leak *et al.* 1969; Roach 1977; Tubbs 1977b; Marquis *et al.* 1984). Most guides recommend leaving increased levels of residual basal area as a stand matures, generally targeted at 60-70% relative density. This threshold insures full site utilization and high net volume production over a thinning cycle, while inhibiting epicormic branching and promoting natural pruning due to inter-tree shading. Stands become ready for another thinning when relative density regrows to about 80% (Leak *et al.* 1969; Roach 1977; Marquis 1986; Stout 1987; Nowak 1996).

Taking about two-thirds of the basal area from below the mean stand diameter, and the remainder from larger trees (crown thinning), concentrates the growth potential onto trees of upper canopy positions (Roach 1977; Marquis *et al.* 1984). Conversely, cutting the largest trees removes the best growing and volume-producing ones (Marquis 1986; Nyland *et al.* 1993). In fact, simulation work indicates that best sawtimber production will accrue in thinned stands having about 60% of the residual basal area in sawtimber-sized trees, and reduced to B-line relative density as represented on the appropriate stocking guide (Solomon 1977). Such

Table 1.—Alternate residual diameter distributions for selection system under different length cutting cycles (After Eyre and Zillgitt 1953; Arbogast 1957; Gilbert and Jensen 1958; Leak *et al.* 1969; Hansen and Nyland 1987; Hansen 1987 and Nyland 1996).

Diameter class Cm	Cutting cycle length			
	8-12 yrs	15 yrs	20 yrs	25 yrs
	M ² /ha	M ² /ha	M ² /ha	M ² /ha
5-13	2.5	2.3	2.3	2.3
14-28	4.5	5.7	4.5	6.8
29-43	6.8	8.0	6.8	5.7
44+	6.8	3.4	2.3	-
Total	20.6	19.4	15.9	14.8

thinnings increase the sawtimber yields by 50-100% for rotations of 90-125 years (Solomon and Leak 1986). Thinnings that favor trees of upper canopy positions should not cause extensive logging damage if the contractor carefully controls the skidding and uses appropriate machinery (Nyland 1986, 1989).

Both clearcutting and shelterwood methods effectively regenerate new even-aged communities of northern hardwoods when applied appropriately. Sugar maple will arise largely from advance seedlings and small saplings (Jensen 1943; Wendel and Trimble 1968; Grisez and Peace 1973; Marquis *et al.* 1984, 1992; Tubbs 1977a). Consequently, for stands lacking adequate advance regeneration, managers should use the shelterwood method. Some regeneration guides (e.g., Tubbs 1977a) recommend leaving some mature trees in place until each hectare averages at least 2025 (5000/ac) desirable trees >0.9 m (>3 ft) tall. If landowners find these already in place, they can remove the complete overstory in a single operation (Marquis 1967; 1987; Roberge 1977; Walters and Nyland 1989).

Shelterwood method seed cutting can leave from 11.5 m²/ha (50 ft²/ac) or less (Curtis and Rushmore 1958; Richards and Farnsworth 1971; Leak and Solomon 1975; Kelty and Nyland 1981), to as much as 21 m²/ha (90 ft²/ac) (Metzger and Tubbs 1971). Generally, 7 to 18 m²/ha (30 to 80 ft²/ac) gives acceptable stocking of desirable species, although sugar maple grows best under 7-9 m²/ha (30-40 ft²/ac) (Kelty 1987). *Rubus* will dominate most sites where cutting removes one-half or more of the basal area. That poses no problems in eastern regions, where the tree regeneration emerges from the berry bushes by the 6th or 7th year (Kelty and Nyland 1981; Kelty 1987; Walters and Nyland 1989). In the upper Lake States, dense *Rubus* and herbaceous plants may delay the development of sugar maple regeneration (Metzger and Tubbs 1971; Tubbs 1977a), so guides suggest leaving a 60% crown cover (Tubbs 1977b). Time to a removal cutting depends on the stocking of residual seed

trees and the rate that regeneration develops. Strip and patch clearcutting may provide acceptable alternatives. Patch size, strip width, and the orientation of either will influence shading patterns and seed dispersal (Marquis 1965a, 1965b; Lees 1987; Nyland 1996)).

Diameter-limit Cutting

Deliberate silviculture controls the growth, composition, and character of forest stands. It also leaves the best trees as growing stock and future sources of seed. Yet many landowners routinely do diameter-limit cutting that removes the salable products with little regard for the nature, density, or distribution of residual trees or the regeneration that follows. Because sugar maple regenerates so readily, at least some seedlings become established even after these exploitive cuts, given a seed source and no interference from browsing or existing vegetation. And while the inconsistent responses and reduced long-term economic value should make diameter-limit cutting undesirable, it remains popular (Nyland 1992; Nyland *et al.* 1993).

Actual effects differ between even- and uneven-aged stands. In the latter, diameter-limit cutting removes the older age classes, and does not necessarily degrade the younger ones. In even-aged communities it leaves low vigor trees of poor growth potential (Marquis 1991; Nyland *et al.* 1993). These often develop extensive epicormic branching after exposure by heavy cutting, and many die back as well. In most cases, diameter-limit cutting leaves an unevenly distributed or patchy residual stand with both high-density patches and areas having little stocking (Nyland 1996).

Often, contractors who do diameter-limit cutting also use little care with the skid trails, and continue to operate on saturated soils. This causes deep rutting, and damage to the root systems of adjacent residual trees. The combination of low-vigor trees and root damage may lead to later dieback in times of environmental stress (e.g., Cote and Quimet 1996; Manion 1991).

Some Other Important Considerations

Sugar maple has regenerated and then developed to at least moderate ages under a wide range of environmental conditions and management strategies. In fact, since the early 1900's, it has reforested extensive area within the original range, primarily on lands once cleared for agriculture. This resulted in a major consolidation of forests in areas earlier supporting primarily small and widely-scattered remnant stands (Nyland *et al.* 1986; Zipperer *et al.* 1988, 1990). Available records also suggest that during the same period, northern hardwoods spread into areas and sites where they occurred infrequently or not at all early in the 20th Century (Quigley and Morgan 1969). Further, in at least some areas of continuous forest cover and disturbed by only one of a few timber harvests (Whitney 1990; De Steven *et al.* 1991):

1. sugar maple's abundance, importance, and stature increased in stands where it occurred as a limited but noticeable part of the upper canopy in pre-settlement times;
2. sugar maple's distribution widened through regeneration onto sites where earlier it did not occur, or grew as a minor component; and
3. sugar maple's prominence as an overstory tree increased in stands where it persisted primarily in the understory in the absence of important natural or human stand-altering disturbances

As an illustration, in western portions of the Allegheny Plateau of Pennsylvania, sugar maple was a minor component of old-growth stands, and limited primarily to the understory except along upper slopes of the valleys (Hough 1936; Whitney 1990). Following cutting of the old-growth, sugar maple became a more important component of the replacement stands where it had originally occurred as a minor component of the overstory. The cutting also increased the areal extent of forest community types that have sugar maple as an important upper-canopy tree (Whitney 1990).

Recently, observers have reported declines of sugar maple, commonly in fringe portions of the range of northern hardwoods (Figure 2). This suggests that the current condition of sugar maple may reflect local or regional growing conditions, with incidents of poor health in localities with marginal soils and climate. This may include sites where sugar maple occurred only as a minor species in the earlier forests. On a broader range of sites, local diebacks may emanate from physical damage to trees by natural and human causes, and the poor social status of individual trees prior to release by heavy cutting and other modes of stand disturbance. Often the diebacks become apparent during later times of stress (U.S. For Serv. 1979; Houston 1981; Manion 1991; Cote and Ouimet 1996; Stolte 1997). At least in part, this sugar maple conference serves as a forum to examine such possibilities.

Markets for low value and small diameter trees often dictate the management strategy for sugar maple. Landowners can

easily sell large-diameter logs of good quality, and can profitably cut among the smaller diameter classes and in younger stands if they have outlets for fiber products (e.g., pulpwood and firewood) as well. Otherwise, they must usually invest in cull removal and small-tree tending, and most have historically opted not to spend the money. Instead, they often revert to diameter-limit cutting.

While diameter-limit cutting has become widespread, northeastern North America does have many examples of silviculture in stands dominated by sugar maple. New research will continue to illuminate the opportunities for influencing stand development and character through silvicultural practice. Still, the management of sugar-maple dominated stands appears at an important juncture. In the absence of better ways to promote deliberate silviculture, landowners seem destined to repeat the exploitive practices historically used across millions of hectares of northern hardwood forest. Under those circumstances, ecologic and economic outcomes may become increasingly less optimal, and forest health issues more common. Only time will tell.

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Sugar Maple: Abundance and Site Relationships in the Pre- and Post- Settlement Forest

Gordon G. Whitney¹

Abstract

A review of the available historical evidence provides a picture of sugar maple's site relationships in the presettlement forest and its changing status over the last 300 years. Sugar maple was widely distributed throughout the Northeast during the presettlement period. It was particularly abundant on the richer, better drained, silt-rich sites. A comparison of the early land survey records and more recent forest inventory data suggests that sugar maple has increased its abundance on a variety of sites, including a number of more marginal sites. The resulting off-site conditions may partially explain sugar maple's recent decline and its inability to exploit some old field sites.

Introduction

There is an increasing recognition that humans are an integral part of many ecosystems (Grumbine 1997). This has generated an interest in quantifying the degree to which humans have altered those ecosystems. The cutting and forest clearance accompanying European settlement entailed a major reorganization of North America's forests (Whitney 1994). Sugar maple *Acer saccharum* Marsh., was and is a dominant of the beech-sugar maple forest region and the hemlock-white pine-northern hardwood forest region, which cover much of the northeastern United States (Braun 1950). The present paper represents a brief overview of sugar maple's occurrence in the presettlement forest, its relationship to various site factors and its response to European settlement. I will start by summarizing our knowledge of existing sugar-maple site relationships and presettlement site relationships. I will then compare the early land survey records with more recent twentieth century forest inventory data to gain an idea of sugar maple's changing abundance. I will close with a brief discussion of some of the management implications of sugar maple's exacting site requirements and its postsettlement increase.

Existing Soil-site Relationships

Although sugar maple occupies a variety of sites, it makes its best growth on moderately fertile soils that are deep and well-drained (Godman 1957). Brand (1985) noted that sugar maple was associated with the more nutrient rich sites across a wide variety of U.S. Forest Service plots in Michigan and Minnesota. It dominates the melanized silt-rich, loamy, often gentle or moderately sloping soils of the Midwest and New England (Archambault and others 1989; Leak 1978; Lindsey 1998; Pregitzer and Barnes 1984; Wilde 1976). It is particularly abundant on lower slope positions or coves that are enriched by leaf litter, colluvium, or nutrient rich water moving from upslope (Leak 1982; Pregitzer and

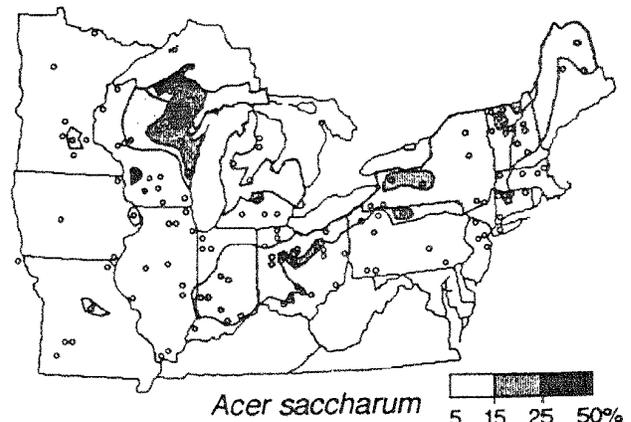


Figure 1.—Map showing abundance of sugar maple in presettlement forest as percent of trees noted in early land survey records. Each circle represents a land survey record, generally encompassing a township or a county. Slightly modified from Whitney (1994).

others 1983; Smith 1995). Foresters have recognized it as an overstory dominant of the fertile *Acer/Arisaema*, *Acer/Osmorhiza-Hydrophyllum*, *Acer/Viola*, and *Quercus rubra-Acer saccharum/Caulophyllum* site types (Archambault and others 1989; Pregitzer and Barnes 1984; Smith 1995).

Most weathered soils in the unglaciated portion of sugar maple's range are low in extractable nutrient base cations. As a result it is not surprising that south of the glacial border, sugar maple reaches its best development on soils that are influenced by base cations in the bedrock (Bailey and others 1999; Nigh and others 1985; Pearson 1962), the addition of silt on terraces and floodplains or nutrient enriched seep water from upslope (Jennings 1936).

Presettlement Abundance And Site Relationships

Counts of witness or corner trees in the early land survey records have frequently been employed to assess the abundance of various tree species in the presettlement forest (Whitney 1994). Although they are subject to surveyor and sampling biases, most investigators believe that they provide a fairly reliable quantitative estimate of the species composition of the forest (Bourdo 1955; Whitney 1994). A compilation of these records in the Northeast (Figure 1) indicates that although sugar maple was well distributed throughout the region, it infrequently accounted for more than 15 percent of the witness trees even in the glaciated portion of its range. Here again it was associated with more fertile site conditions. Sugar maple probably reached its greatest abundance in the hemlock-northern hardwood forest region of northern Wisconsin and the Upper Peninsula

¹Department of Biology, Allegheny College, Meadville, PA.

Table 1.—Relative density or percent representation of all trees reported in pre- and post- settlement (twentieth century) forests.

Location	Presettlement	Postsettlement	Source
N. Maine	5.4	6.5	Lorimer 1977
N. Vermont (Chittenden Co.)	15.8*	23.5	Siccama 1971
Catskill Mts., NY	12.8	23.2	McIntosh 1962 McIntosh 1972
N. Pennsylvania (Allegheny Natl. Forest)	5.3	13.3	Whitney 1990
N. lower Michigan (Crawford Co.)	2.1	6.0	Whitney 1987
N. Wisconsin (T35N, R14E)	29.3	43.6	Stearns 1949
S. Wisconsin (Cadiz Twp.)	3.4	28.2	Sharpe and others 1987
Northeastern Ohio (Wayne Co.)	4.2	6.0	Whitney and Sommerlot 1985
Northwestern Ohio	8.9	9.5	Gysel 1944

*Upper estimate of percentage as includes some red maple as well as sugar maple.

of Michigan directly to the west of beech's range limit. On the richer, loamy soils of the region (Albert 1995; Barrett and others 1995), it occasionally accounted for over 50 percent of the trees reported (Bourdo 1955). Sugar maple was also abundant (15 to 20 percent of the trees) in the more calcareous till derived soils of upstate New York south of Lake Ontario (Marks and others 1992). Braun (1950) stated that the boundary between the mixed mesophytic forest region and the beech-maple forest region coincides with the Wisconsin glacial boundary. In northeastern Ohio, however, sugar maple was fairly common (18% of the trees present) on the alkaline (10-15% carbonate) late Wisconsinian Hiram till. Its abundance dropped precipitously to 3.5 percent on the older more deeply leached (no natural lime within 5 feet) late Wisconsinian Hayesville and Navarre tills (Bureau and others 1984; White 1967; Whitney 1982). On the more acidic, residual soil south of the glacial border, sugar maple represented only 2.6 percent of the trees. Here it was confined to lower slope positions and the richer alluvial soils of floodplains (Whitney 1982). Sugar maple was likewise rare (<2 percent of the trees) and confined to the richer, more calcareous soils of the valley floors in the unglaciated Ridge and Valley Province of central Pennsylvania (Abrams and Ruffner 1995).

Soil texture and nutrients appear to have been major determinants of sugar maple's abundance in the Midwest. Sugar maple was positively associated with the richer loams and sandy loams of the morainal areas of northern lower Michigan (Harman and Nutter 1973; Whitney 1986) and the Upper Peninsula of Michigan (Barrett and others 1995). Sugar maple was a sure sign of rich, fertile soils to the early

settlers (Whitney 1994). In southern Michigan, Indiana and northern Ohio, sugar maple exhibited a preference for the richer, somewhat finer textured (silt and clay rich) loams of the till plains and the end moraines (Crankshaw and others 1965; Dodge 1987; Kapp 1978; Medley and Harman 1987; Whitney 1982). Sugar maple is a fairly drought-sensitive species (Bahari and others 1985). Its shift to the finer textured loam in the lower Midwest may have compensated for the greater evaporative stress to the south.

Drainage and landscape position also influenced sugar maple's occurrence on the beech and sugar maple dominated till plains. As it requires an adequate air supply for the growth of its roots, it reached its greatest abundance on the better drained soils of the swells and the slopes of the till plains. Beech was more a species of the poorly drained swales (Gilbert and Riemenschneider 1980; Lindsey 1998; Shanks 1953).

Changing Status

Comparisons of sugar maple's abundance in the early land survey records with more recent forest surveys suggests that sugar maple has at least maintained and in many cases increased its relative density in the postsettlement forest (Table 1). It showed major gains relative to other species in northern Vermont, in the Catskills, in northwestern Pennsylvania, in Michigan, and in Wisconsin. Significant increases were also noted in the relative importance value (another measure of abundance (Ward 1956)) of sugar maple in the Gogebic Iron Range of northern Wisconsin (Mladenoff and Howell 1980), and in a variety of soils in

northern lower Michigan (Harmon and Nutter 1973). The increase has variously been attributed to the cessation of fire (Sharpe and others 1987), to sugar maple's ability to resprout when cut and its prolific seed production (White and Mladenoff 1994) and to sugar maple's plasticity and its ability to reproduce and grow successfully in the understory as well as large and small gaps in the canopy (Canham 1988; Frellich and Lorimer 1991; Stearns 1949). Although sugar maple is very sensitive to crown and ground fires (Simpson and others 1990), other disturbances in the form of blowdowns or the death of a canopy tree favored sugar maple in the presettlement forest (Frellich and Lorimer 1991; Hough and Forbes 1943). Likewise sugar maple's shade tolerance and its vigorous seed and sprout reproduction made it "the most aggressive reproducer" of the cutover northern hardwood forest (Illick and Frontz 1928).

Management Implications

Sugar maple's high site requirements (Hornbeck and Leak 1992) and its significant postsettlement increase on a variety of soils and sites (Harman and Nutter 1973) suggests that sugar maple may now occupy a number of marginal sites, i.e., sandy nutrient poor soils, shallow acidic soils on ridges, and soils with impeded drainage. Sugar maple typically has slow growth, deteriorates at an early age, or succumbs to fungi and cankers on these sites (Nowak 1996; Ward and others 1966; Wilde 1976). "Off-site" conditions may partially explain the recent decline of sugar maple on a number of acidic shallow, nutrient poor sites across the Northeast (Horsley and others, this volume; Kolb and McCormick 1993; Wargo and Auclair 1999).

Sugar maple is a fairly nitrophilous species. Sugar maple reached its greatest abundance in Indiana's presettlement forests on soils with a high total (Kjeldahl) soil nitrogen level (Crankshaw and others 1965). Nitrogen availability and nitrogen mineralization rates are high in most woodland ecosystems dominated by sugar maple (Pastor and others 1982; Zak and Pregitzer 1990). Several investigators have suggested a deficiency of nitrogen could limit sugar maple's establishment on many old field sites, where plowing and erosion reduced the organic matter and nitrogen content of the soil (Ellis 1974; Lennon and others 1985). Much of the marginal farmland of the northeastern United States has been abandoned over the last 100 years (Whitney 1994). Sugar maple's exacting site requirements could explain its inability to capture many of these old field sites relative to its more successful but less nitrogen demanding congener, red maple.

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History of Sugar Maple Decline

David R. Houston¹

Abstract

Only a few episodes of sugar maple dieback or decline were recorded during the first half of the 20th Century. In contrast, the last 50 years have provided numerous reports of both urban and forest dieback/decline. In the late 1950s, a defoliation-triggered decline, termed maple blight, that occurred in Wisconsin prompted the first comprehensive, multidisciplinary study of a sugar maple decline. That research, and other investigations since, provided the conceptual framework for a model of sequential, stress-initiated cause and effect for dieback/decline disease. Many cases of urban maple dieback/decline have been attributed to soil compaction, drought, impeded soil water availability, or toxic effects of road deicing salt. Most cases of forest or sugarbush decline have been associated with the initiating stresses of insect defoliation or drought, singly or in concert. Mortality of stressed trees is often caused or hastened when roots or twigs are invaded by opportunistic, secondary organisms, especially the root rot fungi *Armillaria* spp. (and probably *Xylaria* sp.). In the past two decades, freezing of roots associated with periods of thaw-freeze and of deep cold, especially when snow cover was minimal or lacking, have been correlated with major decline episodes in eastern Canada and northern New England and New York. An hypothesis that dieback results when death of roots leads to transpiration-stress and vessel cavitation is supported by observations that dieback/decline episodes attributed to droughts appear correlated temporally with prior root-freeze events. Such events are now believed responsible for the serious maple dieback/decline problems in southern Quebec in the 1980-1990s that at first were hypothesized to result from atmospheric deposition. While atmospheric deposition has been discounted as a direct cause of maple declines, the long-term and perhaps complex effects on tree health of deposition-hastened changes in soil chemistry, especially in areas with soils susceptible to acidification, are the primary subjects of current investigations.

Introduction

Sugar maple (*Acer saccharum* Marsh.) has many highly valued qualities. Its long life, pleasing form, and brilliant fall color have made it a favored tree for gracing dooryards and roadsides from New England to the Lake States. Its hard, but easily-worked, light-colored wood is widely used for flooring, furniture, and many specialty products. Wood with uniquely figured patterns, including "bird's eye", "curley", or "fiddleback" is highly prized for fine woodworking. Further, the romanticism and economic values associated with spring sapflows and maple sugaring are as strong today as in colonial times.

¹Research Plant Pathologist (Retired), USDA Forest Service, 51 Mill Pond Road, Hamden, CT 06514

Certain ecophysiological characteristics of sugar maple have made it easy to exploit these values. Sugar maples fruit prolifically; seeds, which mature in the fall, are readily dispersed by wind and germinate the following spring. Well over 5,000,000 seeds per acre are common in good seed years and, establishment is often highly successful. Carpets of young seedlings are common, and the ability of shade-suppressed seedlings and saplings to respond when released has enabled the species to become a predominant component of many forest types. Sugar maple does best on deep soils that are moderately coarse-textured, moist and well-drained (Godman et al. 1990).

Sugar Maple Declines

Although records are lacking, it is highly probable that sugar maple has long experienced serious episodes of dieback/decline. Many of the environmental stresses affecting today's forests occurred in pre-European settlement times; droughts, insect defoliation, fire, damaging winds, and ice storms were no strangers to those early forests. Although opinions vary, the effects of these disturbances, especially, perhaps, fire and windstorms, created mosaics of both uneven-aged and even-aged forests of differing successional stages (Clawson 1983, Loucks 1983). Old, uneven-aged stands contained a high proportion of mature and overmature trees—those considered most susceptible to many of the stress factors that trigger declines. As colonization ensued, activities such as logging, clearing, burning, pasturing, and sugaring intensified dramatically. Areas best suited for tree growth were often those most desired for agricultural uses. Much of the old growth forest was removed, especially during the latter half of the 19th century. Reestablishment of forests on land withdrawn from agriculture has resulted in large areas of relatively even-aged forests that, during the latter half of the 20th century purportedly began reaching an age of increased susceptibility to stress events.

While a few reports of maple dieback/declines appeared in the first half of the 20th century (Hartley and Merrill 1915; Marsden 1950; McKenzie 1943), it was not until after 1950 that accounts of such problems become numerous. Several reviews present the chronologies and presumed causes of sugar maple dieback/decline episodes (e.g. Allen et al. 1992; Houston 1985, 1987; McIlveen et al. 1986; Millers et al. 1989; Sinclair 1964; Westing 1966). The purpose of this brief paper is not to restate what was presented in those reviews, but, rather, to discuss the main themes that seem most pertinent to the present situation.

The Nature of Sugar Maple Dieback/decline

One conceptual model of sugar maple dieback/declines in forest situations was structured around the premise that disease manifestation (progressive crown dieback sometimes leading to continued tree decline and death) results when one or more predisposing (*sensu stricto*) stress

factors reduces resistance to invasion by opportunistic, secondary-action organisms that result in death of tissues—sometimes of trees (e.g. Houston 1981, 1992). This model evolved initially from research on “maple blight”, a dieback/decline of sugar maple in northeastern Wisconsin, triggered by insect defoliation (Anonymous 1964, Giese et al. 1964). A complex of insects including several species of leafrollers and the maple webworm, *Tetralopha asperatella* (Clem.) caused severe defoliation on about 10,000 acres in the mid-late 1950s (Giese and Benjamin 1964). Dead and dying trees and saplings usually were attacked aggressively by *Armillaria* sp. (Houston and Kuntz 1964). Severely damaged stands, prior to being defoliated, had low basal area and density, and a high proportion (> 50%) of sugar maple. During the 10 months prior to the onset of mortality, the region had below-normal precipitation (-8.3 inches) (Skilling 1964).

Later studies elsewhere confirmed the defoliation stress/*Armillaria* association and clarified the biochemical basis for the lowered resistance of defoliation-affected tissues to attack by this opportunist (Parker and Houston 1971, Wargo 1972; Wargo et al. 1972; Wargo and Houston 1974). Another opportunist, *Steganosporium ovatum* (Pers.) S.J. Hughes, appeared to hasten the death of defoliation or drought-stressed twigs and branches (Hibben 1959, Wargo and Houston 1974). Research on several other stress-initiated problems (e.g., Appel and Stipes 1984, Ehrlich 1934, Houston 1994a, Schoeneweiss 1981a, b, Wargo 1977, 1983) has validated the chronological and spatial premises of the following simple, general model for dieback/decline diseases:

1. Healthy trees + stress → Altered trees (tissues) (dieback begins)
2. Altered trees + more stress → Trees (tissues) altered further (dieback continues)
 -
 -
 -
- n. Severely altered trees (tissues) + organisms of secondary action → Trees (tissues) invaded. (Trees lose ability to respond to improved conditions, decline, and perhaps die.)

For the defoliation-triggered sugar maple dieback/declines just described, the model would be:

1. Healthy sugar maple trees + defoliation → Sugar maples altered (dieback begins)
 -
 -
 -
- n. Altered trees + *Steganosporium ovatum* → Twig dieback accelerated + *Armillaria* sp. → Roots, root collars invaded, trees decline, die.

In these statements, the numbers refer to sequential episodes of stress events and host response: “n” indicates that at some point or degree of host change, organisms of secondary

action are able to invade altered tissues successfully. The model above indicates that although host changes sufficient to allow organism attack can occur after a single severe stress event, such changes usually follow multiple or repeated events. Arrows are to be read as “leads to”.

The statements of this model can be construed as summaries of several important relationships:

i) Dieback of trees or tissues often results from the effects of the stress factor(s) alone. With abatement of stress, and in the absence of significant colonization by saproogens or secondary insects, dieback often ceases and trees recover. The dieback phase can be viewed as a survival mechanism whereby the tree adjusts to its recently encountered adverse environment.

ii) Stress alone, if sufficiently severe, prolonged, or repeated, can cause continued or repeated dieback and even death. Numerous reports exist of tree mortality following either unusually severe and prolonged drought or episodes of severe defoliation, especially if repeated, perhaps even in the same growing season. Even one severe defoliation occurring concomitantly or sequentially with drought can result in high tree mortality.

iii) Usually, however, the decline phase, wherein vitality lessens and trees succumb, is the consequence of organism invasion of stress-altered tissues. Recovery from this phase depends on many factors including the vitality of the tree, the particular tissues invaded, the relative aggressiveness of the organism(s), and the degree of invasion.

iv) Where and when the dieback phase occurs is closely related to where and when the triggering stress(es) occurs. The decline and mortality phase is related, in addition, to the temporal and spatial distributions of the organisms of secondary action.

These summary statements point out the inherent difficulty in separating “dieback” from “decline”. Such a separation seems difficult and arbitrary—for most dieback/declines reflect complex continuums of host responses to successive and/or multiple events.

Temporal-spatial Patterns of Sugar Maple Dieback/declines

Comparisons of reported major episodes of sugar maple dieback/decline provide a picture of when and where trees have been affected and the stress factors or events that triggered them. For example, sorting the reports listed by Millers et al. (1989) by place, i.e., by urban or roadside (Table 1) vs. forest or sugarbush (Table 2), reveals that in eastern U.S., the few early (pre-1950) episodes were limited to urban/roadside problems that were triggered (as have subsequent problems in these arenas) by the effects of such stresses as drought, road deicing salt, soil compaction, and occasionally by *Verticillium* wilt, *Phytophthora* and *Fusarium* cankers, and *Armillaria* root disease (Table 1).

Table 1.—Chronology of dieback, decline, mortality problems of sugar maple reported for roadside or urban situations (adapted from Millers et al. 1989).

Dates	Location	Cause
1912-13	Washington DC - New England	drought
1939-49	Massachusetts	drought, defoliation
1956-58	Lake States	drought, <i>Verticillium</i> , <i>Phytophthora</i> , <i>Armillaria</i>
1950-60	Northeast	drought, salt, defoliation
mid-60's	Michigan	drought, salt
1968-70	Northeast	salt, pollution (?)
1975-78	Maine	mech., soil comp., pollution (?)
1976	Lake States, Northeast	drought, salt, compaction
1977-82	Wisconsin	<i>Fusarium</i> , <i>Phytophthora</i>
1978-81	Minnesota	drought, <i>Verticillium</i> wilt
1982	Missouri	?
1984-86	Iowa	?

Table 2.—Chronology of dieback, decline, mortality problems of sugar maple reported for forest trees and sugarbushes (adapted from Millers et al. 1989).

Dates	Location	Cause
1951-54	NY, VT	defoliation (Forest tent)
1956-58	MA	drought
1958-62	WI	defoliation/ <i>Armillaria</i> (leaf rollers, webworm)
1958-62	Lake States	high water tables
1950-60's	Northeastern US	drought, etc.
1957-67	CT	defoliation, (gypsy moth, spanworm)
1968-71	NY, ME	defoliation (saddled prominent)
1973	PA	defoliation (forest tent caterpillar)
1977	MI	defoliation (forest tent caterpillar, saddled prominent)
1978-81	MN	drought
1980-82	NY	defoliation (forest tent caterpillar)
1981-85	NH	defoliators
1984	MN, MI	drought, <i>Agrilus</i>
1984	NY	defoliation
1984-85	PA	defoliation, poor sites, thrips, anthracnose
1985	MA	?
1984-86	VT	defoliation (forest tent caterpillar)
1988-89	WI, MN	drought
1980-90	Quebec, NY	thaw-freeze, root-freeze

In contrast, the principal stress factors reported as triggers of major dieback/decline problems of forest and sugarbush, (noted only since 1951 in U.S.), are insect defoliation and drought, singly or in concert. Saprogens involved in forest decline situations have included *Armillaria* spp., *Agrius* spp. and anthracnose fungi (Table 2).

Accounts of maple dieback/decline from Canada generally have paralleled those from the U.S. Thus, except for episodes of dieback in the Beauce region of southern Quebec in 1932 (Pomerleau 1944) and elsewhere from 1937 to 1949 (especially from 1946 to 1949) (Pomerleau 1953), and in Ontario in 1947 (McIlveen et al. 1986), few accounts appeared prior to 1950. Most of the early episodes were triggered by insect defoliation, but a few were associated with the drought periods of the 1930s and later.

Since 1950, episodes of maple dieback/decline associated with insect defoliation, drought, logging, and more recently, with root freezing have increased in number. The relationship between root freezing (associated with deep soil freezing during times of low or absent snow cover) and the onset of dieback has received increasing attention in Canada and northeastern U.S. (e.g. Lachance 1985, Bauce and Allen 1991), has been replicated experimentally (Pomerleau 1991, Robitaille et al. 1995), and has been proposed as a major factor triggering maple decline in eastern Canada (e.g. Auclair et al. 1992). Drought and root freezing have been proposed as causes of irreversible cavitation in sapwood vessels that, in turn, prevents water movement (Auclair 1993, Auclair et al. 1992, Sperry et al. 1988, Tyree and Sperry 1989). Impairment of water conduction is believed to be responsible for crown dieback.

Usually, close examination of dieback/decline problems, even in remote areas, has revealed evidence for the prior occurrence of stress factors that singly, or in combination, are known to initiate dieback and also to render tissues susceptible to opportunists whose attacks can prevent recovery and hasten tree decline. Prior management practices (e.g., thinning) (Kelley 1988) and climatic episodes (e.g. drought) (Allen 1987, Bauce and Allen 1991) have been correlated with increased mortality following defoliation. It is probable that variations in trees' response to stress can occur locally due to differences in genotypes, local differences in tree vigor, patterns of stress occurrence, presence or absence or vigor of opportunistic organisms, or variations in site quality.

Sometimes imbedded within the maple decline complexes are two diseases caused by primary pathogens: *Verticillium* wilt, a vascular disease caused by *Verticillium dahliae* Kleb. which has been noted only in urban situations, and sapstreak, also a vascular disease, caused by *Ceratocystis virescens* (Davidson) C. Moreau, which rarely has been observed other than in forests and sugarbushes. Although caused by a primary pathogen, sapstreak should be considered part of the decline complex based on symptomatology and the facts that (1) injuries to roots or root collars are necessary as infection courts for *C. virescens*, and (2) tree mortality is almost always associated with

attacks by *Armillaria* sp. or *Xylaria* sp. (Houston 1993, 1994b). The importance of injuries for sapstreak infection creates a close temporal-spatial relationship between human activities and disease development. Thus, most diseased trees are located adjacent to skid trails or woods roads, and they develop symptoms within 1 to 4 years after infection. Recognized in North Carolina and Tennessee in the late 1930s and early 1940s (Hepting 1944), sapstreak was not reported from the Lake States until 1960 (Kessler and Anderson 1960) or from the northeast until 1964 (Houston and Fisher 1964). Whether recent increases in reported cases of sapstreak represent increases in disease incidence or in disease recognition is not known.

The ability of sugar maple to dominate favorable forest sites was noted earlier. Sometimes, however, this species colonizes sites unfavorable for later growth and development. For example, stands of sugar maple have developed on many abandoned fields in New England and New York. It is on these sites, often too wet, too dry, or nutrient impoverished, and along roadsides, that many sugar maple decline problems have occurred. Favoring sugar maple on wet, cool, bottom lands can create an unstable situation, as the species is neither long-lived nor vigorous on wet or dry soils and is extremely sensitive to abiotic or biotic stresses under such conditions. Widening and paving roads certainly have affected roadside maples adversely, and the added insult of road salt has created an intolerable environment for this mesically adapted, nutrient demanding species (LaCasse and Rich 1964). Trees along roadsides are prone to damage from drought events not sufficiently severe to affect forest trees.

Ironically, it was the dieback and deterioration of roadside trees that prompted a major research program on maple decline in Massachusetts in the early-mid 1960s (Westing 1966). Forest researchers were put in the position of trying to characterize a problem that at that time did not exist in the forests of Massachusetts. From this effort, however, came the initial thrust to understand soil nutrient - maple tree condition relationships (Mader and Thompson 1969).

The Stresses

Defoliation.—Effects of defoliation are addressed elsewhere in this symposium. Comments here are limited to pointing out that the consequences of defoliation stress were intensively investigated in studies of maple blight in Wisconsin (Anonymous 1964, Giese et al. 1964). Research on this problem comprised the first truly multidisciplinary investigation of a sugar maple decline. Those investigations, together with several since (Bauce and Allen 1991, Parker and Houston 1971, Wargo 1972, Wargo and Houston 1974) revealed the complex nature of host response and secondary organism attacks that characterize a dieback/decline disease and as described earlier, provided the model used as a framework for study of dieback/decline diseases of many tree species (Houston 1981, 1992).

Defoliation can affect all age classes, and even young trees exhibit twig and branch dieback that can progress with

repeated defoliations. Death of young defoliated trees is usually the consequence of root invasions by opportunists, especially *Armillaria* sp. Such killing attacks of young trees may occur in forest situations, even after a single defoliation, where abundant and vigorous opportunist populations occur. Where such populations are absent, tree mortality may not occur, even after repeated defoliations (e.g., Gregory and Wargo 1986, Parker and Houston 1971).

Drought.—Throughout this century, drought has been cited as a cause or a possible contributing factor of maple dieback/decline (Bauce and Allen 1991, Griffin 1965, Hartley and Merrill 1987, Hibben 1962, 1964, Marsden 1950, Ohman 1969, Sinclair 1964, Skelly and Wood 1966, Skilling 1964, Westing 1966). Beginning in the 1950s, notable episodes of maple dieback/decline occurred during or following periods of severe water shortage (e.g., Table 2). Observations that defoliation episodes, that are coincident or closely followed by drought are especially devastating (e.g. Allen 1987), are paralleled by the recent analyses by Auclair et al. (1996) suggesting that the effects of root freezing are especially damaging if followed by drought. Dieback/decline appears to result when desiccation of branches and re-leafing tissues (following defoliation), or of the first spring flush of leaves (following winter root freeze), is enhanced when conducting tissues are injured or killed by cavitation. The biochemical changes in sugar maple caused by drought and defoliation are similar (Parker 1970), and these changes favor growth and invasion by *Armillaria* spp. (Wargo 1972, Wargo and Houston 1974). Thus, because of their effects on host-defense systems, combinations of stress factors render trees exceptionally vulnerable to lethal attacks by opportunistic organisms.

Extremes of Temperature.—In northern Wisconsin, fall frosts killed immature leaves and terminal buds that formed after a midsummer defoliation and thus contributed to branch and twig dieback (Houston and Kuntz 1964). Other cold events also have been associated with maple dieback and decline. Episodes of thaw-freeze and of deep cold during snow-free winter periods were associated with diebacks of sugar maple and other species (e.g. Pomerleau 1944, 1991). These events apparently occurred commonly in the first half of this century yet, major diebacks did not occur during that time, presumably because tree populations were relatively young (Auclair et al. 1992, Auclair et al. 1996). Thus, forest maturation is postulated as a key factor preconditioning trees to climatic injury and dieback (Auclair et al. 1996, 1997). The recent re-recognition that root freezing is an important factor in northern forests stems largely from the work by Auclair and coworkers (e.g., Auclair et al. 1992, 1996) in Quebec, and by Bauce and Allen (1991) in New York. Auclair et al.'s (1996) analysis of climate data suggests that episodes of forest dieback are correlated with heat and drought stress but only after forests have been affected by root-freezing events. According to Auclair et al. (1996), crown dieback reflects drought effects in trees injured previously by freezing.

Acidic Deposition.—In the 1980s concern arose that atmospheric deposition, especially acidic deposition, was

causing sugar maple decline in Ontario, Quebec, and Vermont (Carrier 1986, McLaughlin et al. 1985, Vogelmann 1982, Vogelmann et al. 1985). Surveys and studies showed damage to sugar maple on a number of sites with soils deemed highly susceptible to acidification (e.g., the Muskoka area in southern Ontario, the Beauce region of southern Quebec and Camel's Hump in Vermont). Observers promoting acid-deposition hypotheses tended to dismiss such factors as defoliator outbreaks, climatic events such as early thaws or droughts, or disturbances caused by harvesting or tapping as the primary or sole cause. Attention was focused narrowly on atmospheric deposition. Subsequently, it was realized that the rather sudden appearance of dieback and decline in the Canadian forests was not the result of a direct effect of acid deposition, but rather a consequence of one or a combination of several factors previously associated with dieback/declines, especially the winter freeze-thaw events during periods of little snow cover (e.g., Pitelka and Raynal 1989, Auclair et al. 1992). Concern remains that acidic deposition may play a role in certain cases of sugar maple decline, especially as it may influence the chemistry of soils susceptible to acidification over the long term. That concern is strongly demonstrated by the emphasis placed on soil chemistry relationships at this symposium.

Synthesis

The fact that few major episodes of maple dieback/decline occurred during the first half of the 20th Century suggests that either there were fewer or less severe predisposing stresses, or that the forests then were more resistant or resilient to such stress. Arguments for the latter seem most plausible if, as Auclair et al. (1996, 1997) suggest, younger trees are less susceptible than mature ones to cavitation-inducing climatic events. Correlations of dieback episodes and a number of weather/climate indices, both local and global, support that hypothesis (Auclair et al. 1996, 1997). The paucity of reported sugar maple dieback episodes early in this century, even though there were frequent and severe winter-thaw-freeze and root-freeze events, as well as significant drought periods, presumably stems from the fact that in most northern hardwood forests, maple had not reached its susceptible age (= commercial maturity) of 100 years (Auclair et al. 1996) or 150 years (Millers et al. 1989) following the massive harvesting that occurred between 1860 and 1890. Under this scenario, forest (species) maturation would seem critical.

On the other hand, old-age may be less critical when stresses other than climate extremes are involved. Defoliation was the initiator of maple blight, but fall frosts, drought, and root pathogens, especially *Armillaria* sp. were all involved in the dieback, decline, and mortality of defoliated trees. Outbreaks of a unique suite of defoliators began in "young" stands soon after unusually heavy harvesting of older trees had opened up the forest and stimulated sapling growth. As the insect populations increased and spread, all ages were defoliated—and all ages suffered heavy mortality. Perhaps forest stand "maturation" is not only a matter of physiological

predisposition to cavitation of individual trees, but also of the abundance and condition of secondary-organism populations within "mature" stands.

Whether, or how, outbreaks of defoliating insects are associated with the climate measures utilized by Auclair et al. (1996) needs to be determined. Populations of some defoliators are favored by hot, dry summers, and the concomitant or successive occurrence of defoliation and drought has proven disastrous to sugar maple (Allen 1987). Finally, it is clear that natural changes in soil chemistry, especially acidification, when augmented by acidic deposition, may significantly affect growth and tree resistance to stresses and opportunistic organisms. How such edaphic factors influence or are influenced by the stress factors known to severely affect sugar maple remains unclear.

Conclusion

Most of the maple dieback/declines that have been studied intensively were initiated by severe, acute stress factors, such as defoliation, drought, or winter root freezing. The concomitant or sequential occurrence of these in various combinations contributes strongly to the acuteness and severity of host responses.

Understanding of cause-effect relationships and underlying mechanisms is increasing. For example, the emerging hypothesis that dieback following certain stresses is a consequence of vessel column cavitation is balanced by climate models which suggest that cavitation may not be especially serious unless followed by severe drought. These concepts must be evaluated in light of current understanding of the role of secondary-action organisms as agents that impair recovery and cause mortality of stressed trees.

The focus now and for the immediate future, and which is emphasized in this symposium, is on soil relationships. It is clear, however, that knowledge gained from the past needs to be carefully interpreted in light of what already is known here about histories of management, drought, defoliation, and root pathogens. All of these factors are part of the picture. From the point-of-view of a forest dieback/decline researcher, it does not get any better than this!

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A Ten-Year Regional Assessment of Sugar Maple Mortality

Douglas C. Allen, Andrew W. Molloy, Robert R. Cooke, and Bruce A. Pendrel¹

Abstract

The North American Maple Project (NAMP) monitored annual sugar maple mortality from 1988 through 1997 in Maine, Massachusetts, New Brunswick/Nova Scotia, New Hampshire, New York, Ontario, Quebec, Vermont, and Wisconsin. Annual mortality in Minnesota, Ohio and Pennsylvania was evaluated for 1992 through 1997. When data from the dominant/codominant and intermediate/suppressed crown levels were combined, average annual mortality (% trees) ranged from 1.9% (New York) to 0.3% (New Brunswick/Nova Scotia) in sugarbushes (SBs) and 1.9% (New Hampshire) to 0.4% (Wisconsin) in maple stands not managed for syrup production (NSBs). In general, mortality of dominant/codominant sugar maple was lower than in the intermediate/suppressed crown position. Average annual mortality was not significantly different among each of three elevational categories or among each of three deposition levels for wet sulfate or wet nitrate. Mortality in plot-clusters located >300 m elevation and exposed to high levels of wet nitrate (>20 kg/ha/yr) or wet sulfate (>27.5 kg/ha/yr) deposition was significantly greater in both SBs and NSBs compared to mortality in plot-clusters exposed to high levels of deposition but located <300 m elevation (SB: >300 m 2.2%, <300 m 0.6%; NSB: >300 m 1.1%, <300 m 0.3%). A number of small, but statistically significant ($p \leq 0.05$), differences in mortality occurred among three ecological Divisions, three Provinces and three Sections in the U.S., and three Ecozones and four Ecoregions in Canada. Within 13 geographic regions (states and provinces), two crown positions, two management categories, three levels of elevation, three deposition levels for both wet nitrate and wet sulfate, and 18 biophysical regions, annual sugar maple mortality documented by the NAMP was similar to mortality reported in the literature for typical northern hardwood stands. Mortality in SBs was similar to that in NSBs.

Introduction

The North American Maple Project (NAMP) was initiated in 1988 in response to public concern for the condition and sustainability of the sugar maple (*Acer saccharum* Marsh) resource. An earlier paper (Allen et al. 1992) reported on the crown condition of overstory sugar maple monitored during the first three years (1988-1991) of the project. More recently, Allen et al. (1995) summarized changes in crown condition for 1988 through 1995 and presented an overview of mortality. Here we examine nine years of sugar maple mortality (1989 through 1997) in the context of geographic regions (states and provinces), crown position, management

¹Professor of Forest Entomology and Senior Research Support Specialist, State University College of Environmental Science and Forestry, Syracuse, NY.; Forest Health Protection, Northeastern Area, USDA Forest Service, Durham, New Hampshire; and Acting Director, Forest Resources, Atlantic Forestry Centre, Canadian Forest Service, Fredericton, New Brunswick, respectively.

category, levels of atmospheric deposition, elevation, and ecological unit. We address the hypothesis that sugar maple mortality which occurred in the NAMP plots during this period is within the range expected for the stand and site conditions included in the study.

Methods

The general methods used to select, establish and measure plot-clusters (Millers et al. 1991) changed little during the ten-year history of the NAMP (Allen et al. 1995). Stands were selected systematically to facilitate frequent visits, to cover a variety of sugar maple sites, to encompass a range of atmospheric deposition levels, and to assure long-term integrity. A cluster of five 20 x 20 m permanent plots was established in each stand. To qualify, a stand had to have an overstory that contained 50% or more sugar maple, 50-150 years old. All trees ≥ 10 cm diameter at breast height (1.4 m) were evaluated annually for crown condition and survival. Analyses of sugar maple mortality are presented as annual percent tree loss resulting from "natural" mortality. That is, we did not include loss of trees that were deemed healthy but died or were removed as a direct result of some forest management related activity, such as road building or thinning. Natural mortality constitutes a baseline for determining losses ostensibly due to natural stresses. The occurrence and extent of natural disturbances (e.g., insect defoliation, drought, wind damage, etc.) were incorporated into the database for each plot-cluster and used to establish the temporal occurrence and extent of stresses.

Annual mortality was determined by monitoring the number of trees surviving from one year to the next:

Annual Plot-Cluster Mortality=

$$\frac{[(\text{number of live trees in year } t-1) - (\text{number of live trees in year } t)] \times 100}{\text{number of live trees in year } t-1}$$

Plot-cluster mortalities were then averaged within each year to obtain annual mortalities for the various strata. The strata were based on region (state, province, country), elevation, deposition level, and ecotype (Table 1). Estimates of wet sulfate and wet nitrate deposition for each plot-cluster were interpolated using deposition maps (5 kg/ha isopleths) provided by Environment Canada and the U.S. National Atmospheric Deposition Program/National Trends Network Coordination Office. UTM coordinates located each site relative to the nearest isopleth or monitoring station. Mortality figures are based on 7,569 dominant/codominant (D/C) and 3,885 intermediate/suppressed (I/S) sugar maples ($N = 11,454$) monitored annually between 1988 and 1997 (Table 2). Two-way comparisons were made with the t-test, and analysis of variance (ANOVA) in conjunction with Tukey's test for multiple comparisons. Prior to analysis all data were tested for homoscedasticity. Alpha was set at 0.05 as a nominal indicator of significance for all comparisons.

Table 1.—Ecological variables used to stratify NAMP data on sugar maple mortality

VARIABLE	CATEGORIES	NUMBER OF PLOT-CLUSTERS
Elevation	High >450 M	39
	Medium 300-450 m	71
	Low < 300 m	53
Biophysical Units United States (McNab and Avers 1994)	Divisions	
	Warm Continental	25
	Warm Continental Regime Mts.	60
	Hot Continental	21
	Provinces	
	Eastern Broadleaf Forest (Continental)	17
	Laurentian Mixed Forest	25
	Adirondack New England Mixed Forest	60
	Sections	
	White Mountains	17
	New England Piedmont	13
Green Taconic, Berkshire Mts.	23	
Canada (Ecological Stratification Working Group 1995)	Ecozones	
	Atlantic Maritime	24
	Boreal Shield	16
	Mixed Wood Plain	18
	Ecoregions	
	Algonquin-Lake Nipissing	6
	Appalachian	14
	Lake Erie Lowland	6
	Manitoulin-Lake Simcoe	8
	Northern New Brunswick Uplands	5
Southern Laurentians	8	
Wet Sulfate Deposition	High >27.5 kg/ha/yr	24
	Medium 17.6-27.5	192
	Low <17.6	49
Wet Nitrate Deposition	High >20 kg/ha/yr	37
	Medium 16-20	71
	Low <16	57
Forest Management	Sugarbush	
	U.S.	53
	Canada	31
	Nonsugarbush	
	U.S.	53
Canada	28	

Table 2.—Regional distribution of plot-clusters and number of sugar maples monitored by NAMP

REGION	NO. PLOT-CLUSTERS IN 1988	INITIAL AVE.(RANGES) BASAL AREA (m ² /ha)	NUMBER OF LIVE SUGAR MAPLES BY CROWN POSITION (1988)		
			DOMINANT/CODOMINANT	INTERMEDIATE/SUPPRESSED	INITIAL NO. LIVE SUGAR MAPLES
Maine	18	29.1 (20.2-40.8)	726	455	1,181
Massachusetts	10	27.9 (15.4-36.2)	453	175	628
Michigan	10	24.1 (17.8-31.0)	194	78	272
Minnesota *	8	24.4 (24.5-31.5)	221	238	459
New Brunswick/ Nova Scotia	11	22.7 (12.9-31.0)	856	116	972
New Hampshire	6	24.6 (15.2-36.5)	257	121	378
New York	18	24.8 (15.7-35.5)	645	438	1,083
Ohio *	6	33.7 (28.3-39.9)	141	120	261
Ontario	24	26.8 (15.4-40.3)	928	434	1,362
Pennsylvania *	6	29.1 (21.6-36.4)	173	112	285
Quebec	24	27.6 (17.4-35.6)	1,285	594	1,879
Vermont	26	27.6 (12.2-43.4)	1,054	588	1,642
Wisconsin	18	24.9 (15.7-32.4)	636	416	1,052
TOTAL	185		7,569	3,885	11,454

*Plot-clusters were not established in these regions until 1992, the remainder were initiated in 1988.

Results

Canada vs United States

Percent sugar maple mortality in the NAMP plot-clusters by crown position from 1989 through 1997 was similar in both Canada and the United States, except in a few cases. Generally, mortality of dominant/codominant (D/C) trees was similar in both sugarbushes (SB) and non-sugarbushes (NSB). However, in four of nine years (1989, 1990, 1992, 1997), mortality of intermediate/suppressed (I/S) sugar maples in Canada's sugarbush (SB) plot-clusters exceeded that of sugar maple in the dominant/codominant crown position. During the remaining five years, average mortality in both crown positions was approximately equal (Table 3).

Mortality of understory sugar maple in U.S. SBs exceeded that in the overstory in seven of nine years; mortality in the two crown positions was approximately the same in 1992

and 1997. Sugar maple mortality in the intermediate/suppressed crown class for NSBs always exceeded overstory mortality in both countries.

In 1989, mortality of intermediate/suppressed maples in U.S. SBs (4.0%) was more than four times that which occurred in the dominant/codominant crown class (0.8%). Comparative mortality for the two management categories was more dissimilar in the intermediate/suppressed crown position compared to the dominant/codominant trees. For Canadian SBs, annual mortality of dominant/codominant maple ranged from 0.4% (1993) to 0.9% (1995) and intermediate/suppressed losses varied from 0.4% (1994) to 2.4% (1990). Comparative figures for maple in U.S. SBs were, D/C: 0.3% (1990) to 1.3% (1995) and, I/S: 1.0% (1993) to 4.0% (1989).

Differences in the nine-year average annual tree mortality when SB and NSB data within each country were combined

Table 3.—Average annual mortality (% trees) of sugar maple for NAMP plot-clusters in Canada and the United States (1989-1997) by management category and crown position)

COUNTRY	MANAGEMENT CATEGORY ^a	CROWN POSITION ^b	YEAR								
			1989	1990	1991	1992	1993	1994	1995	1996	1997
CANADA	SB	D/C	0.5	0.5	0.8	0.6	0.4	0.5	0.9	0.9	1.1
		I/S	1.2	1.5	0.8	2.4	0.5	0.4	1.0	0.9	2.3
U.S.	NSB	D/C	0.4	0.4	0.6	0.6	0.3	0.3	0.8	0.3	0.3
		I/S	2.1	2.2	1.3	1.4	1.8	1.6	1.6	1.2	1.1
	SB	D/C	0.8	0.3	0.8	0.9	0.6	0.7	1.3	0.7	0.7
		I/S	4.0	1.6	1.5	1.0	1.0	1.1	2.7	1.6	0.8
NSB	D/C	0.8	0.3	0.6	0.5	0.8	0.4	0.7	0.5	0.3	
	I/S	2.7	1.7	2.3	1.3	1.0	0.8	1.8	1.6	2.4	

^aSB = sugarbush, NSB = non-sugarbush

^bD/C = dominant/codominant; I/S = intermediate/suppressed

were similar in both dominant/codominant (Can.: $0.6 \pm 0.1\%$, U.S.: $0.7 \pm 0.1\%$) and intermediate/suppressed (Can.: $1.4 \pm 0.1\%$, U.S.: $1.7 \pm 0.2\%$) crown positions and were significantly different between crown positions in each country.

Average annual mortality of dominant/codominant maples for the nine-year period was significantly lower than losses of intermediate/suppressed for both Canadian SBs (D/C: $0.7 \pm 0.1\%$, I/S: $1.3 \pm 0.2\%$, $p=0.046$) and NSBs (D/C: $0.5 \pm 0.1\%$, I/S: $1.6 \pm 0.1\%$, $p=0.0001$). Similarly, the average annual nine-year sugar maple mortality in U.S. dominant/codominant maples was significantly lower than that of intermediate/suppressed maples in both SBs (D/C: $0.8 \pm 0.1\%$, I/S: $1.7 \pm 0.3\%$, $p=0.0258$) and NSBs (D/C: $0.5 \pm 0.1\%$, I/S: $1.7 \pm 0.2\%$, $p=0.0004$).

Regional Mortality

Mortality data from the 10 states and four provinces included in the NAMP represent sugarbushes and nonsugarbushes which exist under a variety of geographic locations and site conditions. Cooperators are interested in viewing the condition of their stands relative to those in other jurisdictions. Examining regional differences is the first step in identifying unusual levels of mortality that may be linked to local disturbances.

Total average annual sugar maple mortality (i.e., all crown positions combined) for SBs within regions ranged from 0.3% in New Brunswick/Nova Scotia to 1.9% in New York (Table 4). Mortality in NSBs was lowest in Michigan (0.2%) and highest in New Hampshire (1.9%). Mortality in the understory of SBs was significantly higher than that in the overstory only in Massachusetts, New Hampshire and Vermont. In 9 of 12 regions, mortality in the understory of NSBs was significantly higher than overstory mortality (Table 4).

Overstory mortality for SBs in New York and Quebec was significantly higher than mortality in their respective NSBs

(Table 5). In Massachusetts, mortality of dominant/codominant sugar maple was significantly lower in SBs compared to NSBs. For all other regions, there were no statistically significant differences in mortality of overstory sugar maples between management categories (Table 5). Similarly, in only three regions was mortality of intermediate/suppressed trees significantly different when comparing NSBs with SBs; Massachusetts, New Brunswick and New Hampshire (Table 5).

Mortality of dominant/codominant maples in SBs was higher in New York (1.8 ± 0.3) compared to mortality of overstory maple in all other regions and significantly higher than mortality in 8 of 12 regions (the eight regions: MA, NB/NS, PA, ON, WI, VT, NH, and ME). Overstory mortality in Massachusetts (0.1 ± 0.1) was significantly lower than this mortality in New York and Quebec. Average annual mortality levels for dominant/codominant trees in NSBs were statistically similar between management categories for all regions and varied from zero to 0.8% (Table 5).

There were no statistical differences in average annual mortality of understory sugar maple in SBs among the 13 regions. In NSBs, mortality in this crown position was significantly higher in New Hampshire (4.6 ± 1.1) compared to seven regions (MI, WI, ON, NY, ME, VT, QU) but not statistically different from mortality in Pennsylvania, Massachusetts, NB/NS, and Minnesota (Table 5).

Influence of Elevation

When data from SB and NSB management categories were combined, beginning with the original sample in 1988 (Table 1), average annual sugar maple mortality was significantly lower in the dominant/codominant crown level compared to the intermediate/suppressed level for plot-clusters in all three elevation categories: high (D/C: $0.5 \pm 0.1\%$, I/S: $2.0 \pm 0.2\%$), medium (D/C: $0.8 \pm 0.1\%$, I/S: $1.8 \pm 0.3\%$) and low (D/C: $0.5 \pm 0.1\%$, I/S: $1.1 \pm 0.2\%$). Mortality of dominant/codominant trees at medium elevations ($0.8 \pm 0.1\%$) was

Table 4.—Average (\pm S.E.) annual mortality (% trees) of dominant/codominant and intermediate/suppressed sugar maples by management category (1988-1997)

REGION	SUGARBUSH			NON-SUGARBUSH		
	Dom./ Codom.	Inter./ Supp.	TOTAL	Dom./ Codom.	Inter./ Supp.	TOTAL
Maine	0.8 \pm 0.2	3.0 \pm 1.4	1.3 \pm 0.1	0.6 \pm 0.2	1.8 \pm 0.5	0.9 \pm 0.2
Massachusetts†	0.1 \pm 0.1a	1.4 \pm 0.4b	0.4 \pm 0.2	0.7 \pm 0.2a	2.9 \pm 0.5b	1.4 \pm 0.2
Michigan	0.8 \pm 0.3	1.2 \pm 0.5	1.0 \pm 0.3	0.2 \pm 0.1	0.1 \pm 0.1	0.2 \pm 0.1
Minnesota‡	0.8 \pm 0.3	1.0 \pm 0.1	0.9 \pm 0.2	0.0 \pm 0.0a	1.9 \pm 0.7b	1.0 \pm 0.3
New Brunswick/ Nova Scotia	0.2 \pm 0.1	0.6 \pm 0.3	0.3 \pm 0.1	0.5 \pm 0.2a	2.5 \pm 0.4b	0.7 \pm 0.2
New Hampshire	0.6 \pm 0.1a	1.8 \pm 0.4b	1.0 \pm 0.2	0.7 \pm 0.1a	4.7 \pm 1.1b	1.9 \pm 0.3
New York	1.8 \pm 0.3	2.0 \pm 0.7	1.9 \pm 0.3	0.5 \pm 0.1a	1.5 \pm 0.4b	0.9 \pm 0.2
Ohio‡	0.9 \pm 0.3	0.3 \pm 0.2	0.6 \pm 0.2	—	—	—
Ontario	0.4 \pm 0.1	1.7 \pm 0.6	0.6 \pm 0.1	0.4 \pm 0.1a	1.1 \pm 0.2b	0.7 \pm 0.1
Pennsylvania‡	0.3 \pm 0.3	0.6 \pm 0.2	0.5 \pm 0.3	0.4 \pm 0.2	3.1 \pm 1.2	1.2 \pm 0.4
Quebec	1.2 \pm 0.2	1.3 \pm 0.2	1.3 \pm 0.1	0.5 \pm 0.2a	1.9 \pm 0.3b	0.9 \pm 0.1
Vermont	0.5 \pm 0.2a	1.4 \pm 0.2b	0.9 \pm 0.1	0.8 \pm 0.3a	1.9 \pm 0.3b	1.2 \pm 0.2
Wisconsin	0.4 \pm 0.1	0.8 \pm 0.2	0.6 \pm 0.1	0.2 \pm 0.1a	0.9 \pm 0.2b	0.4 \pm 0.1

† different letters in the same row signify a statistically significant difference at $\alpha=0.05$ between the dominant/codominant and intermediate/suppressed comparisons within a region and management category.

‡ plot-clusters were not established in these regions until 1992; average mortality is for 1993-1997.

Table 5.—Average (\pm S.E.) annual sugar maple mortality (% trees) for management categories within sugar maple crown positions (1988-1997)

REGION	DOMINANT/CODOMINANT		INTERMEDIATE/SUPPRESSED	
	SB \pm SE	NSB \pm SE	SB \pm SE	NSB \pm SE
Maine	0.8 \pm 0.2	0.6 \pm 0.2	3.0 \pm 1.4	1.8 \pm 0.5
Massachusetts†	0.1 \pm 0.1a	0.7 \pm 0.2b	1.4 \pm 0.4a	2.9 \pm 0.5b
Michigan	0.8 \pm 0.3	0.2 \pm 0.1	1.2 \pm 0.5	0.1 \pm 0.1
Minnesota‡	0.8 \pm 0.3	0.0 \pm 0.0	1.0 \pm 0.1	1.9 \pm 0.7
New Brunswick/ Nova Scotia	0.2 \pm 0.1	0.5 \pm 0.2	0.6 \pm 0.3a	2.5 \pm 0.4b
New Hampshire	0.6 \pm 0.1	0.7 \pm 0.1	1.8 \pm 0.4a	4.7 \pm 1.1b
New York†	1.8 \pm 0.3a	0.5 \pm 0.1b	2.0 \pm 0.7	1.5 \pm 0.4
Ohio‡	0.9 \pm 0.3	—	0.3 \pm 0.2	—
Ontario	0.4 \pm 0.1	0.4 \pm 0.1	1.7 \pm 0.6	1.1 \pm 0.2
Pennsylvania‡	0.3 \pm 0.3	0.4 \pm 0.2	0.6 \pm 0.2	3.1 \pm 1.2
Quebec†	1.2 \pm 0.2a	0.5 \pm 0.2b	1.3 \pm 0.2	1.9 \pm 0.3
Vermont	0.5 \pm 0.2	0.8 \pm 0.3	1.4 \pm 0.2	1.9 \pm 0.3
Wisconsin	0.4 \pm 0.1	0.2 \pm 0.1	0.8 \pm 0.2	0.9 \pm 0.2

† different letters signify a statistically significant difference at $\alpha=0.05$ between the sugarbush/non-sugarbush comparisons within a region and mortality type.

‡ plot-clusters were not established in these regions until 1992; annual average mortality is for 1993-1997.

SB=sugarbush, NSB=non-sugarbush.

significantly higher than dominant/codominant mortality at both high ($0.5 \pm 0.1\%$) and low ($0.5 \pm 0.1\%$) elevations. Mortality of intermediate/suppressed maples was significantly higher at high elevations ($2.0 \pm 0.2\%$) than mortality in this crown position at low elevations ($1.1 \pm 0.2\%$). When data from all crown positions were combined, mortality for both SBs and NSBs was similar at high, medium and low elevations (Fig. 1).

Nitrate Deposition

There were no significant differences in average annual percent mortality of sugar maple in SBs compared to NSBs from 1989 through 1997 when D/C and I/S crown positions were combined in areas of high (SB: $1.3 \pm 0.3\%$, NSB: $0.8 \pm 0.1\%$), medium (SB: $1.0 \pm 0.1\%$, NSB: $1.0 \pm 0.1\%$) and low (SB: $0.8 \pm 0.1\%$, NSB: $0.8 \pm 0.1\%$) levels of nitrate deposition. Mortality of intermediate/suppressed sugar maples was significantly higher than mortality in the dominant/codominant crown position at all deposition levels; high (SB: $1.6 \pm 0.3\%$, NSB: $0.8 \pm 0.2\%$), medium (SB: $1.6 \pm 0.2\%$, NSB: $0.6 \pm 0.1\%$) and low (SB: $1.7 \pm 0.1\%$, NSB: $0.4 \pm 0.1\%$). There were no statistically significant differences in total (D/C and I/S combined) average annual mortality of sugar maple when compared among the three deposition categories for wet nitrate in either SBs or NSBs.

Sulfate Deposition

There were no significant differences in average annual percent mortality of sugar maples in SBs compared to NSBs from 1989 through 1997 when D/C and I/S crown positions were combined for plot-clusters in areas of either high (SB: $1.3 \pm 0.3\%$, NSB: $0.7 \pm 0.1\%$), medium (SB: $1.0 \pm 0.1\%$, NSB: $1.0 \pm 0.1\%$) or low (SB: $0.7 \pm 0.1\%$, NSB: $0.7 \pm 0.1\%$) wet sulfate deposition. In plot-clusters ostensibly exposed to high levels of sulfate deposition, there was no statistically significant difference in mortality of dominant/codominant maples ($0.8 \pm 0.2\%$) compared to maples in the intermediate/suppressed crown position ($1.4 \pm 0.4\%$). However, percent mortality of intermediate/suppressed maples was significantly higher than mortality of dominant/codominant trees in areas exposed to medium (SB: $1.7 \pm 0.2\%$, NSB: $0.7 \pm 0.1\%$) and low (SB: $1.6 \pm 0.4\%$, NSB: $0.5 \pm 0.1\%$) deposition levels. There were no statistically significant differences in total (D/C and I/S combined) average annual mortality of sugar maple when compared among the three wet sulfate deposition categories in either SBs or NSBs.

Interaction Between Elevation and High Levels of Deposition

To further examine the possibility that elevation may have influenced the association between atmospheric deposition and maple mortality, sugar maples in plot-clusters exposed to high levels of both wet nitrate and wet sulfate deposition were reclassified into one of two categories; those at $>300\text{m}$ elev. (viz., high and medium elevation classes combined), and those at $<300\text{m}$ elev. For high sulfate deposition, 12 plot-clusters occurred at elevations $>300\text{m}$, 11 plot-clusters were $<300\text{m}$. Twenty plot-clusters located at $>300\text{m}$ and 16 at $<300\text{m}$ were subjected to high levels of nitrate deposition.

There were no significant differences in average annual percent tree mortality between SBs and NSBs in either the high+med (SB: $2.2 \pm 0.6\%$, NSB: $1.1 \pm 0.1\%$) or low (SB: $0.6 \pm 0.1\%$, NSB: $0.3 \pm 0.1\%$) elevation categories for areas receiving high levels of wet nitrate deposition ($>20\text{ kg/ha/yr}$). Similarly, when SB and NSB management categories were combined, there were no significant differences in mortality between crown positions at either elevation: high+med – D/C: $1.2 \pm 0.3\%$, I/S: $2.2 \pm 0.5\%$; Low – D/C: $0.4 \pm 0.1\%$, I/S: $0.7 \pm 0.2\%$. Within SBs when crown positions were combined, average annual mortality was significantly greater at elevations $>300\text{m}$ (2.2%) compared to that of stands occurring at $<300\text{m}$ (0.6%) (Fig. 2). Similarly, in NSBs there was significantly greater mortality at high+med elevations (1.1%) compared to low elevations (0.3%) (Fig. 2). Mortality of intermediate/suppressed sugar maples when data from SBs and NSBs were combined was significantly greater in the high+med (2.2%) category compared to low elevations (0.7%), and there was significantly more mortality in the dominant/codominant crown position at high+med elevations (1.2%) than at low elevations (0.4%).

In like manner, mortality from plot-clusters exposed to high levels of wet sulfate deposition ($>27.5\text{ kg/ha/yr}$) were stratified by combining data from high and medium elevations (i.e., $>300\text{m}$) and comparing it to sugar maple mortality in plot-clusters at low elevations ($<300\text{m}$). When data from both D/C and I/S crown positions were combined, there was no statistical difference in average annual tree mortality of sugar maple when comparing SBs and NSBs at either high+med. (SB: $2.2 \pm 0.7\%$, NSB: $1.0 \pm 0.2\%$) or low elevations (SB: $0.5 \pm 0.1\%$, NSB: $0.3 \pm 0.1\%$). Mortality in the dominant/codominant and intermediate/suppressed crown positions were statistically similar for both high+med (D/C: $1.2 \pm 0.3\%$, I/S: $2.2 \pm 0.8\%$) and low (D/C: $0.4 \pm 0.1\%$, I/S: $0.6 \pm 0.3\%$) elevations. Maple mortality within SBs and NSBs when crown positions were combined was significantly higher at high+med elevations compared to mortality at $<300\text{m}$ (Fig. 3). This can be attributed mainly to the fact that when management categories were combined mortality of dominant/codominant trees (1.2%) was significantly higher at the higher elevations compared to maples in this crown position below 300m (0.4%).

Ecological Units (U. S.)

NAMP plot-clusters in the United States are distributed over 46 Ecological Sections, five Provinces and four Divisions as mapped by Keys et al. (1995) and described by McNab and Avers (1994). The Canadian component of this project encompasses 13 Ecoregions and three Ecozones (Ecological Stratification Working Group 1995). For the purpose of examining sugar maple mortality, small sample sizes (i.e., few plot-clusters) in many ecological units limited comparative analyses in the U.S. to three Divisions and three Provinces in the Humid Temperate Domain and three Sections in the Adirondack New England Mixed Forest-Coniferous Forest-Alpine Meadow Province (Table 6). Sample size for the Canadian portion of NAMP permits mortality comparisons between three Ecozones and six Ecoregions (Table 7).

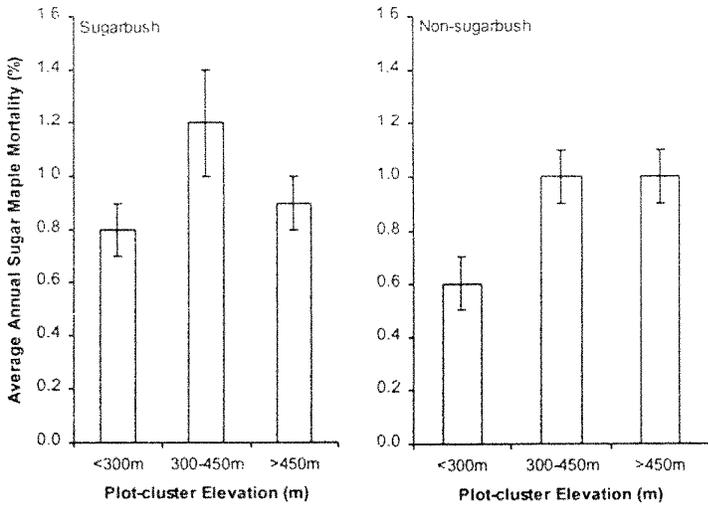


Fig. 1. Total (D/C and I/S crown positions combined) average (\pm SE) annual mortality (% trees) of sugar maple for SBs and NSBs in three elevational categories

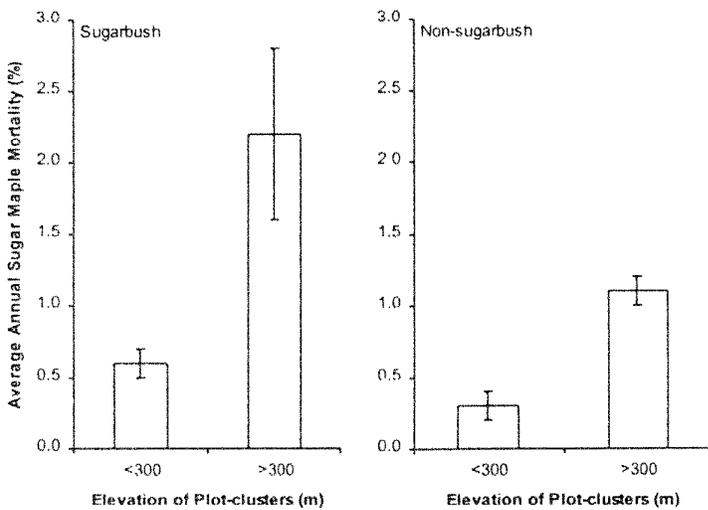


Fig. 2. Total (D/C and I/S crown positions combined) average (\pm SE) sugar maple mortality (% trees) for SBs and NSBs in plot-clusters occurring at high-medium (>300m) and Low (<300m) elevations in regions exposed to high (>20 kg/ha/yr) levels of wet nitrate deposition.

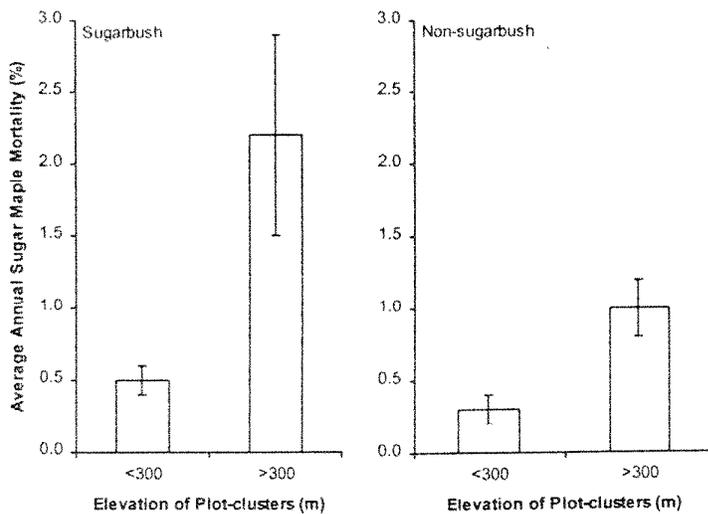


Fig. 3. Total (D/C and I/S crown positions combined) average (\pm SE) annual sugar maple mortality (% trees) for SBs and NSBs in plot-clusters occurring at high+medium (>300m) and low (<300m) elevations in regions exposed to high (>27.5 kg/ha/yr) levels of wet sulfate deposition.

Table 6.—Original (1988) number of live sugar maples monitored by NAMP in each of eight ecological regions, two management categories and two crown positions in the United States

Ecological Classification ^a	Management Category (No. Plot-Clusters) ^b	No. of Sugar Maples by Crown Position	
		Dom./Codom.	Interm./Supp.
Warm Continental Division (210)	SB (13)	818	550
	NSB (12)	885	591
Warm Continental Regime Mts (M210) Division	SB (29)	841	333
	NSB (31)	843	467
Hot Continental Division (220)	SB (12)	332	159
	NSB (9)	246	171
Laurentian Mixed Forest Province (212)	SB (13)	818	550
	NSB (12)	885	591
Adirondack New England Mixed Forest Province (212)	SB (29)	841	333
	NSB (31)	843	467
White Mts. Section (M212A)	SB (8)	337	251
	NSB(9)	322	182
East. Broadleaf Forest (Continental) Province (222)	SB (9)	210	114
	NSB (8)	213	155
New England Piedmont Section (M212B)	SB (7)	344	137
	NSB (6)	225	160
Green Taconic, Berkshire Mts. Section (M212C)	SB (11)	404	167
	NSB (12)	572	316

^aSource: McNab and Avers 1994. Numbers are codes for ecological units.

^bSB = sugarbush, NSB = nonsugarbush.

U.S. Ecological Divisions

Average annual percent tree mortality was similar for comparisons of SBs and NSBs when D/C and I/S crown positions were combined for plot-clusters located in the Warm Continental (WC) and Warm Continental Regime Mountain (WCRM) Divisions (Fig. 4). In the Hot Continental (HC) Division, annual mortality was significantly higher in SBs compared to NSBs (Fig. 4). Mortality of intermediate/suppressed sugar maples was significantly higher than that of dominant/codominant trees in both the WC (I/S: $0.9 \pm 0.1\%$, D/C: $0.4 \pm 0.1\%$) and WCRM (I/S: $2.3 \pm 0.4\%$, D/C: $0.8 \pm 0.1\%$), but did not differ statistically in HC (I/S: $1.1 \pm 0.3\%$, D/C: $0.7 \pm 0.1\%$). Combined mortality for SBs in WC (0.6%) was significantly lower than SB mortality in WCRM (1.3%). In NSBs, combined mortality was significantly higher in WCRM (1.1%) than in WC (0.7% and HC (0.6%) (Fig. 4).

U.S. Ecological Provinces

There were no significant differences in the overall (D/C and I/S crown categories combined) average annual percent tree mortality between SBs and NSBs in either the Laurentian Mixed Forest (LM, SB: $0.6 \pm 0.1\%$, NSB: $0.7 \pm 0.1\%$) or the Adirondack New England Mixed Forest (ANE, SB: $1.3 \pm 0.2\%$, NSB: $1.1 \pm 0.1\%$) Provinces. Mortality in the Eastern Broadleaf Forest (Continental) Province (EBFC), however, was significantly higher in SBs ($1.2 \pm 0.3\%$) compared to NSBs ($0.4 \pm 0.1\%$). Annual mortality of intermediate/suppressed maples was significantly higher than mortality of dominant/codominant trees in ANE and LM (data not shown). Mortality of sugar maple in the dominant/codominant crown position was statistically similar in all three regions (data not shown). Mortality of intermediate/suppressed sugar maples in ANE (2.3%) was significantly

Table 7.—Original (1988) number of live sugar maples monitored by NAMP in each of nine ecological regions, two management categories and two crown positions in Canada

Ecological Classification ^a	Management Category (No. Plot-Clusters) ^b	No. of Sugar Maples by Crown Position	
		Dom./Codom.	Interm./Supp.
Atlantic Maritime Ecozone (AM)	SB (14)	943	262
	NSB (10)	670	188
Boreal Shield Ecozone (BS)	SB (8)	398	201
	NSB (8)	397	218
Mixed Wood Plain Ecozone (MW)	SB (9)	286	136
	NSB (9)	361	137
Algonquin-Lake Nipissing Ecoregion (ALN)	SB (3)	142	68
	NSB (3)	136	80
Appalachian Ecoregion (APP)	SB (7)	401	191
	NSB (7)	370	145
Lake Erie Lowland Ecoregion (LEL)	SB (3)	68	51
	NSB (3)	110	29
Manitoulin-Lake Simcoe Ecoregion (MLS)	SB (4)	137	70
	NSB (4)	141	70
Northern New Brunswick Uplands Ecoregion (NNBU)	SB (4)	305	38
	NSB (1)	51	7
Southern Laurentians Ecoregion (SL)	SB (4)	187	118
	NSB (4)	213	112

^aEcological Stratification Working Group 1995.

^bSB = sugarbush, NSB = nonsugarbush.

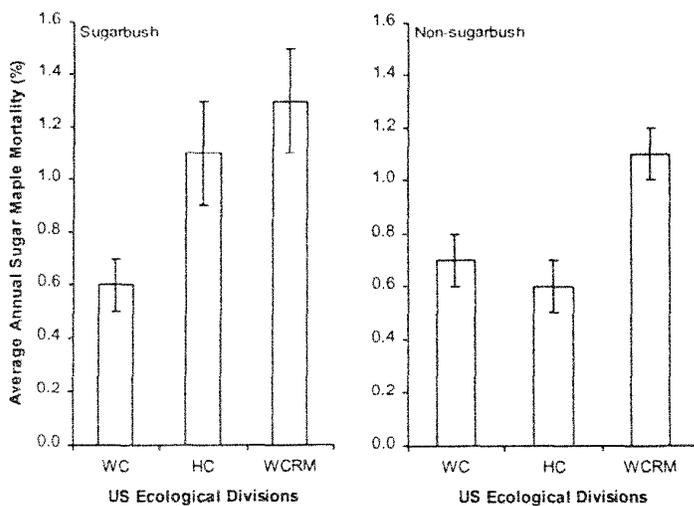


Fig. 4.—Total (D/C and I/S crown positions combined) average (\pm SE) annual sugar maple mortality (% trees) for SBs and NSBs in three ecological Divisions in the United States; WC = Warm Continental, HC = Hot Continental, WCRM = Warm Continental Regime Mountains.

higher than mortality at this crown position in either LM (0.9%) or EBFC (0.9%). Total average annual mortality (crown positions combined) among these Provinces was not significantly different for SBs (range 0.6 - 1.3%), but in NSBs overall mortality was significantly higher in ANE compared to LM and EBFC (Fig. 5).

U.S. Ecological Sections

The distribution of NAMP plot-clusters permits a comparison of three Sections within the Adirondack New England Mixed Forest-Conifer Forest-Alpine Meadow Province: White Mountains (WM); New England Piedmont (NEP); and Green, Taconic, Berkshire Mountains (GTBM). Sections are the smallest ecological units in the U.S National Hierarchical Framework for which NAMP sample sizes permit reasonable comparisons, and it is at this level that comparisons are most meaningful (McNab and Avers 1994).

There was no statistically significant difference between the 9-year average annual mortality of sugar maple in SBs compared to NSBs when both D/C and I/S crown positions were combined for WM, NEP or GTBM (Fig. 6). For SBs, combined mortality in both WM and NEP was significantly higher than combined mortality in GTBM. There were no significant differences in NSB mortality between Sections when crown levels were combined (Fig. 6). In all three Sections, mortality in the intermediate/suppressed crown position was significantly higher than that of overstory trees (Fig. 7). Mortality of trees within dominant/codominant and intermediate/suppressed crown positions was similar among the three Sections (Fig. 7).

Ecological Units (Canada)

Canadian Ecozones

Average annual mortality of sugar maple in Atlantic Maritime Ecozone (AM) SBs (0.6%) was significantly lower than

maple mortality in NSBs (0.8%). There were no significant differences between management categories for either the Boreal Shield or the Mixed Wood Plains Ecozones (data not shown). When SB D/C and I/S crown positions were combined, mortality in BS (1.2%) was significantly higher than comparable mortality in either AM (0.6%) or MW (0.8%) (Fig. 8). Similarly, total mortality in NSBs was significantly higher for the BS Ecozone (1.1%) compared to AM (0.8%) or MW (0.5%) (Fig. 8). Mortality of intermediate/suppressed sugar maple was significantly higher than that of dominant/codominant maple in AM (I/S: $1.4 \pm 0.2\%$, D/C: $0.4 \pm 0.1\%$) and BS (I/S: $2.3 \pm 0.5\%$, D/C: $0.7 \pm 0.4\%$) but not in MW (I/S: $0.7 \pm 0.1\%$, D/C: $0.6 \pm 0.1\%$). There were no statistically significant differences among Ecozones in mortality of dominant/codominant sugar maples (data not shown). However, mortality of intermediate/suppressed trees was significantly higher in BS (2.3%) compared to mortality at this crown level in either AM (1.4%) or MW (0.7%).

Canadian Ecoregions

Total (D/C and I/S crown positions combined) sugar maple mortality in SBs and NSBs was similar within all six Ecoregions (data not shown). When SB D/C and I/S crown positions were combined, average annual mortality of sugar maple in the Southern Laurentians (SL) Ecoregion was significantly higher than mortality in the Northern New Brunswick Uplands (NNBU) region (Fig. 9). Likewise, in NSBs the only statistically significant difference in total mortality among Ecoregions occurred between SL and NNBU (Fig. 9). In three regions (ALN, APP, MLS), mortality of overstory D/C maple was significantly lower than understory I/S mortality (Fig. 10). Mortality of dominant/codominant trees in SL was significantly higher than mortality at this crown level in MLS or NNBU (Fig. 10). Intermediate/suppressed mortality in SL was significantly higher than understory I/S mortality in either the LEL or NNBU Ecoregions (Fig. 10).

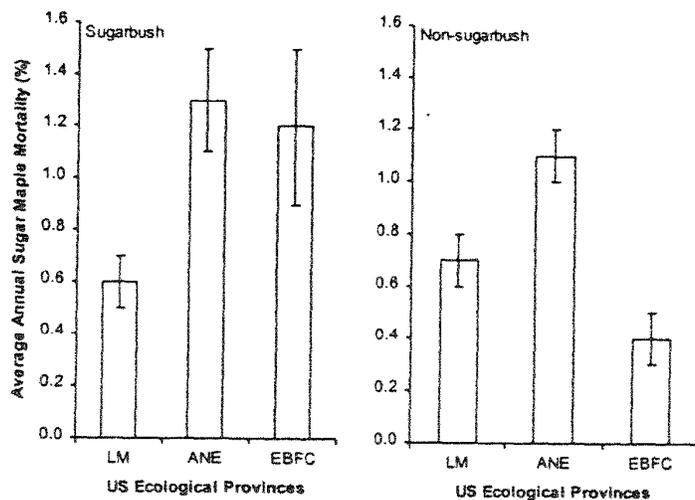


Fig. 5.—Total (D/C and I/S crown positions combined) average (\pm SE) annual sugar maple mortality (% trees) for SBs and NSBs in three ecological Provinces in the United States; LM = Laurentian Mixed Forest, ANE = Adirondack New England and Mixed Forest, EBFC = Eastern Broadleaf Forest (Continental).

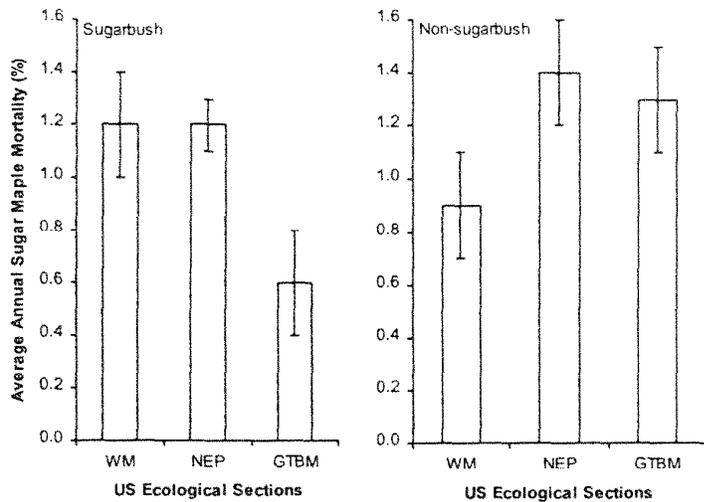


Fig. 6.—Total (D/C and I/S crown positions combined) average (\pm S.E.) annual sugar maple mortality (% trees) for SBs and NSBs in three ecological Sections in the United States; WM = White Mountains, NEP = New England Piedmont, GTBM = Green, Taconic, Berkshire Mountains.

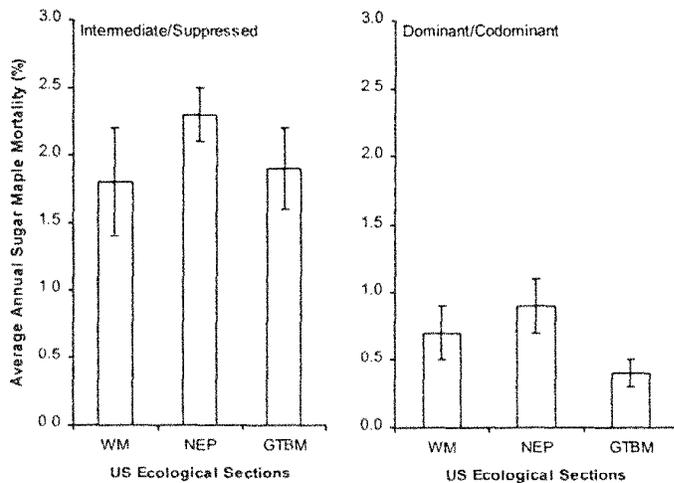


Fig. 7.—Average (\pm SE) sugar maple mortality (% trees) for intermediate/suppressed and dominant/codominant trees in three ecological Sections in the United States; WM = White Mountains, NEP = New England Piedmont, GTBM = Green, Taconic, Berkshire Mountains.

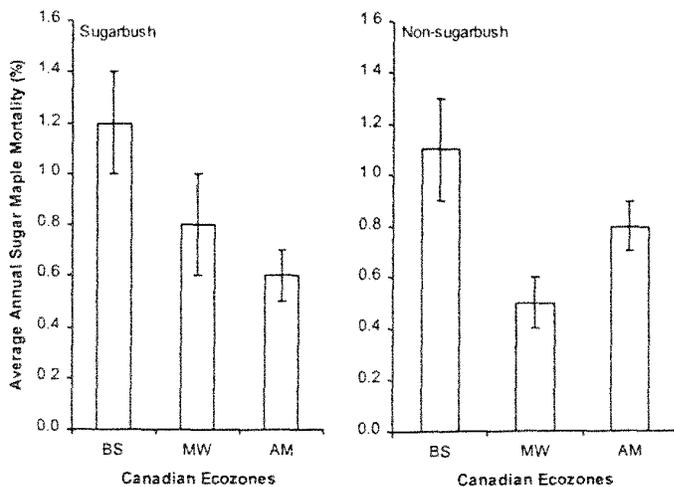


Fig. 8.—Total (D/C and I/S crown positions combined) average (\pm SE) annual sugar maple mortality (% trees) in three Canadian Ecozones: Boreal Shield (BS), Mixed Wood Plains (MW) and Atlantic Maritime (AM).

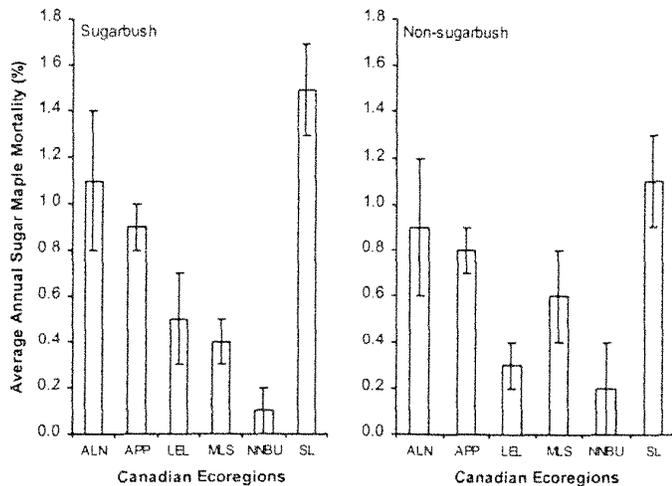


Fig. 9.—Total (D/C and I/S crown positions combined) average (\pm S.E.) annual percent sugar maple mortality (% trees) for SBs and NSBs in six Canadian Ecoregions; Algonquin-Lake Nipissing (ALN), Appalachians (APP), Lake Erie Lowland (LEL), Manitoulin-Lake Simcoe (MLS), Northern New Brunswick Uplands (NNBU) and Southern Laurentians (SL).

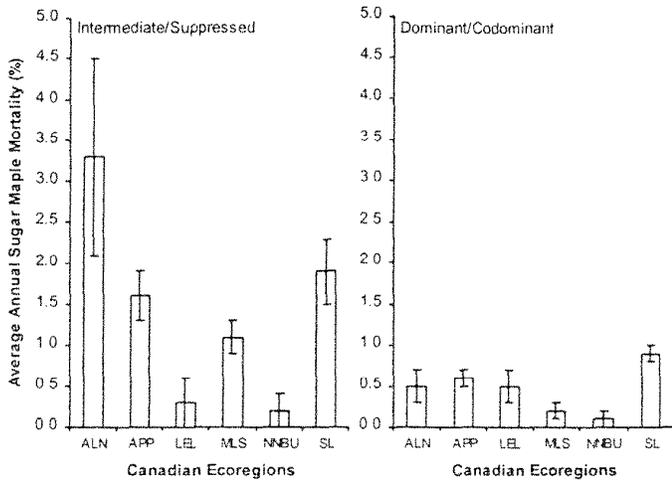


Fig. 10.—Average (\pm SE) annual sugar maple mortality (% trees) for intermediate/suppressed and dominant/codominant trees in six Canadian Ecoregions; Algonquin-Lake Nipissing (ALN), Appalachians (APP), Lake Erie Lowland (LEL), Manitoulin-Lake Simcoe (MLS), Northern New Brunswick Uplands (NNBU), and Southern Laurentian (SL).

Discussion

Results of monitoring and evaluating sugar maple mortality in the NAMP plot-clusters should be viewed with the understanding that stands were selected on the basis of regional location, accessibility, condition (age, species mix), and security (assurance of long-term use). In other words, sites were not picked at random and, in a statistical sense, results may be biased and not generally applicable to the maple resource. In our view, this does not detract from the ability to identify a normal or expected threshold of mortality in the absence of disturbance. Neither does it hinder evaluation of the immediate and long-term consequences of natural disturbances in terms of annual mortality or changes in crown condition of sugar maple, nor does it disallow comparison of ecological conditions included within the study. Long-term, quality controlled monitoring and subsequent evaluation is requisite to developing a baseline with which to compare changes following stress. Similarly, this type of monitoring is necessary to identify causes of

unusual mortality and to facilitate early detection of potentially harmful effects (Spellerberg 1991).

The results, analyses and discussion are specific to sugar maple even though other species occur in all plot-clusters. Therefore, total tree mortality (i.e., all species combined) for each stand may be slightly higher than the values given for each crown level and when crown levels are combined. For example, at nine of the ten sites where monitoring was initiated in 1988 (Table 2), sugar maple comprises 75% to 92% of the dominant/codominant trees in SBs and 63% to 80% in NSBs. In Wisconsin, sugar maple constitutes only 56% of the overstory in SBs and 38% in NSBs.

When sugar maple mortality from NAMP plot-clusters in the United States and Canada are combined (Fig. 11), a clear pattern emerges in both SBs and NSBs. Average annual percent mortality of intermediate/suppressed trees consistently exceeds or approximates that of dominant/

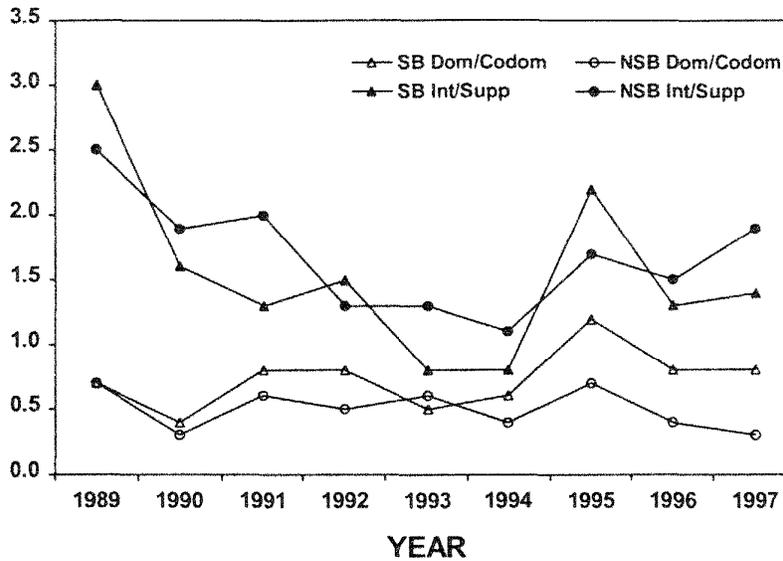


Fig. 11.—Annual natural mortality (% trees) of sugar maple (1988-1997) in Canadian and U.S. plot-clusters combined according to management category (SB = sugarbush, NSB = non-sugarbush) and crown position.

codominant trees; in SBs the difference in annual average mortality between crown positions was as much as 1% to 3%. The pattern of mortality within each crown position is very similar for both countries. With two exceptions (Ohio - SBs, Michigan - NSBs), this pattern of higher mortality in the intermediate/suppressed crown position is a consistent, though not always statistically significant, pattern when viewed at the regional level (Table 4).

Differential mortality between crown levels is expected given the more intense competition for light, moisture and soil nutrients typically experienced by trees in the understory (Peet and Christensen 1987). In all likelihood, this discrepancy is enhanced because the dominant/codominant trees are at a competitive advantage for resources disproportionate to their size (Weiner and Thomas 1986). The variation in crown level mortality within each country and within each state and province results from many factors, the most important of which are variation in stocking (Leak 1961, 1970; Solomon 1977), uneven moisture conditions (Stephens and Waggoner 1980, Hopkin and Dumond 1994), species characteristics (Westoby 1984), stage of stand development (Franklin et al. 1987), and nutrition and stress conditions (Long et al. 1997; Horsley et al. this volume). In a five-year study of mortality in a *Fagus-Magnolia* forest, Harcombe and Marks (1983) were able to demonstrate only a weak relation between death rate and stand density, suggesting that between-tree competition was not merely related to density. Indeed, in only three NAMP regions was the nine-year average annual percent sugar maple mortality positively and significantly correlated with stand basal area: New Brunswick/Nova Scotia ($r = .750$, $p = 0.012$), New York ($r = 0.604$, $p = 0.008$) and Quebec ($r = 0.520$, $p = 0.009$). The correlation coefficients indicate that even in these three examples, site and species characteristics are important, because only 27% to 56% of the variation in the dependent variable is explained by stand density alone.

One of the major questions of concern to NAMP is how total sugar maple mortality (i.e., the average annual mortality when crown positions are combined) compares with mortality of northern hardwoods reported in the literature in the absence of disturbance. A look at comparative differences or similarities is especially meaningful because the NAMP sites cover a broad geographic range for sugar maple. Total mortality in SBs (col. 4, Table 4) ranged from a high of 1.9%/yr in New York to 0.3%/yr in NB/NS. NSB mortality was highest in New Hampshire (1.9%/yr) and lowest (0.2%/yr) in Michigan (col. 7, Table 4). There are several reports of annual mortality for different broadleaved species and combinations of species in the eastern U.S. and Canada (Table 8). Two, dealing specifically with sugar maple, indicate that mortalities of <1% (Hall 1995) to 1.2% (McLaughlin et al. 1996) are typical. Kelley and Eav (1987) reported 0.5% mortality for dominant/codominant sugar maple in Vermont. Mortality in this crown position varied from 0.1% (Massachusetts) to 1.8% (New York) in NAMP SBs and 0% (Minnesota) to 0.8% (Vermont) in NSBs (Table 4). Levels of total mortality reported for eastern hardwoods range from <1% to 3.2% (Table 8). The annual mortality reported in this paper refers solely to sugar maple; therefore, mortality for the NAMP sites might be slightly higher if all species were included. Also of interest is the comparative mortality of sugar maple in SBs compared to NSBs. The hypothesis of interest here is that stands subjected to management and tapping activities associated with the maple syrup industry are subjected to repeated physical stresses which may increase annual mortality compared to less intensively managed forests. Mortality of dominant/codominant sugar maple in only two regions was significantly higher in SBs compared to NSBs: New York (1.8% vs 0.5%) and Quebec (1.2% vs 0.5%). In Massachusetts, mortality in NSBs (0.7%) was significantly higher than in SBs (0.1%). Mortality in the lower crown position was significantly higher for NSBs in Massachusetts (I/S: 2.9%, D/C: 1.4%), New Brunswick/Nova Scotia (I/S:

Table 8.—Examples of normal or expected annual mortality (% trees) for eastern hardwoods

Source	Mortality
Frelich and Lorimer (1991)	So. Appalachian, old growth mixed mesophytic, 0.6-1.0%; Lake States, old growth sugar maple/hemlock, 0.6-0.7%
Hall (1995)	Canada, sugar maple, <1%
Hall (1996)	Canada, mixed woodland plains, 0-3.2%
Hall et al. (1996)	Canada, temperate broadleaved forests and woodlands, 1-3%
McLaughlin et al. (1996)	Ontario, sugar maple, 1.2%
Buchman (1983)	Lake States, major tree species, 2.6%/yr for saplings and 0.3%/yr for poles and small sawtimber
Kelley et al. (1992)	VT, northern hardwoods, upper canopy <1%
Stephens and Waggoner (1980)	CT, mixed hardwood forests; moist site, 1.2-1.4%; medium site 1.2-2.0%; dry site 0.8-2.0%
Waring and Schlesinger (1985 ref. therein)	Generally 1-2%
Leak (1970)	NH, second growth northern hardwoods, high stocking-1.4%; med. Stocking-0.3%; low stocking-0%
Kelley and Eav (1987)	VT, dominant/codominant maple mortality, 0.5
Abrell and Jackson (1977)	IN, old growth beech-maple, 1.2%

2.5%, D/C: 0.6%) and New Hampshire (I/S: 4.7%, D/C: 1.8%) (Table 4). The relatively high average annual mortality of sugar maples in New York's SBs, and overall mortality in this region compared to other regions when data from management categories and crown levels were combined, can be attributed to an unusually severe windstorm (Pendrick 1996) that eliminated a majority of the trees in one plot-cluster in 1995. At this site, approximately 65% of the understory and 35% of the overstory maples were lost due to this one disturbance (Fig. 12). Eliminating this plot-cluster from the analysis reduces New York's annual average mortality to approximately 1.1%. Total mortality in New Hampshire (1.4%) was the second highest of the 13 regions and can be attributed mainly to relatively high losses in the intermediate/suppressed crown position in NSBs (4.6%, Table 5).

Currently, there is growing interest in the effects of atmospheric pollution on sugar maple growth and mortality. The evidence presented to date is equivocal because underlying mechanisms are poorly understood (Foster 1989). Contradictory results also confuse the issue. Bernier and Brazeau (1988), for example, speculated that a combination of P and K deficiency play a major role in maple decline. However, reports from Quebec (Payette et al. (1996), Pennsylvania (Brooks 1994) and Ontario (Hart 1991) suggest the impact of atmospheric deposition is minor, and the key factors are a combination of insect defoliation and drought (Kolb and McCormick 1993). Other evidence suggests winter weather conditions that promote deep soil frost reduce sugar maple growth (Bauce and Allen 1991),

may initiate maple decline (see Auclair this volume) or alter soil solution chemistry in ways that are detrimental to maple condition (Boutin and Robitaille 1995).

We do not have on-site measures of wet sulfate or wet nitrate deposition for the NAMP plot-clusters and had to classify stands according to deposition levels determined at the nearest monitoring site (Allen et al. 1995). It seems reasonable, however, that if atmospheric conditions relative to these two elements had a major influence on maple crown condition or mortality, detectable changes in both would appear in regions receiving relatively high levels of sulfate or nitrate deposition compared to regions receiving relatively low exposure.

To examine this hypothesis, plot-clusters were first stratified by elevation, under the assumption that due to orographic uplift atmospheric deposition in eastern North America tends to increase with elevation (Lovett and Kinsman 1990, Garner et al. 1989). Differences in annual percent sugar maple mortality between the three elevation categories were significantly greater for dominant/codominant maples in plot-clusters located at mid-elevations compared to mortality in this crown position at either high or low elevations, and for intermediate/suppressed maples mortality was significantly greater at high compared to low elevations. When total (D/C and I/S crown levels combined) plot-cluster mortality was examined by deposition level regardless of elevation, there were no significant differences between deposition categories for either nitrate or sulfate. Only in SBs was

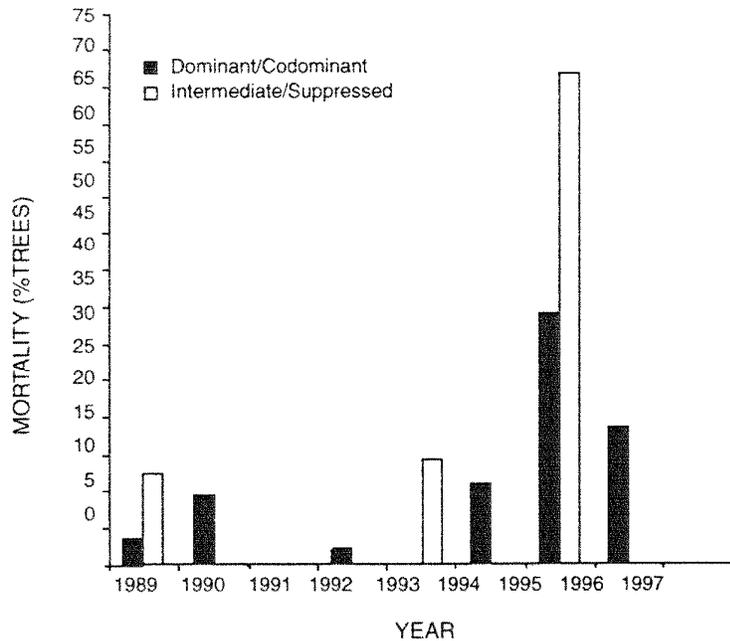


Fig. 12.—Annual mortality (% trees) of sugar maple for the Altire Bros. Sugarbush in New York (1989-1997).

mortality above 300m (1.1%) significantly higher than mortality below 300m (0.3%). Whether differences described above are biologically significant can not be determined. These subtle differences may become more obvious when plot-clusters experience severe disturbances (Horsley et al. this volume). However, since the beginning of the NAMP several plot-clusters have experienced severe drought and heavy defoliation, yet unusual levels of mortality have not materialized. Studies in states that do not have significant sources of pollution (e.g., Vermont, Tennessee and North Carolina) may not show strong trends in precipitation chemistry with elevation (Scherbatskoy and Bliss 1984). Neither Mielke et al. (1991) working along a pH gradient in Wisconsin nor Linzon's (1987) studies of maple decline on acidic compared to calcareous soils in Ontario demonstrated significant differences in the condition of sugar maple under these ranges of conditions.

Assessment of sugar maple mortality across the range of ecological units examined by NAMP revealed no differences that appear biologically significant. These regions are described on the basis of predominant biotic and abiotic features that control or modify inputs of solar energy, precipitation and nutrients; for example, climate, geology, soils, water and vegetation. Different units are identified or described through spatial differences in a combination of these characters (Smith and Carpenter 1996, Ecological Stratification Working Group 1995). The generally similar condition of sugar maple throughout such a broad range of soils, parent geology and climate suggests that if atmospheric deposition is affecting maple or the sites on which it exists, the effect or effects are subtle and not reflected in crown condition (Allen et al. 1995) or differential

mortality. Only long-term monitoring that documents the occurrence and extent of stresses and provides well-structured, chronologically collected data (Stout 1993) will determine whether what appear to be negligible affects are exacerbated by stress complexes.

Results from the 233 stands that have been monitored by NAMP for the past six to nine years indicate that in these northern hardwood stands maple crowns are in good condition (Allen et al. 1995) and mortality occurs at levels generally associated with normal stand development. Similarly, independent studies in Canada (Hall 1996, Hopkin and Dumond 1994), Vermont (Kelley and Eav 1987), and Wisconsin (Mielke et al. 1991) have been unable to document unusual levels of sugar maple mortality. However, studies in northwestern and north central Pennsylvania outside the area monitored by the NAMP plot clusters show unusual levels of sugar maple mortality (Kolb and McCormick 1993; Lauder Milch 1995; McWilliams et al. 1996; Horsley et al. this volume).

Nevertheless, we recognize that in some regions extensive sugar maple mortality has occurred during the past four decades (Table 9). It is important to examine these events in order to identify the factor or factors that precipitated unusual levels of mortality and, more importantly, to distinguish causes related to human activities from those which are not directly related to human intervention. Since the classic study of maple blight in Wisconsin during the early 1960s (Giese et al. 1964), very few maple declines have been investigated with scientific rigor involving a structured look at cause and effect. However, anecdotal information is available for many episodes, provided by

Table 9.—Examples of physical and biological stresses associated with sugar maple decline

Source	Example
NH Dept. Res. And Econ. Develop. 1998 ^a	Central NH, Cardigan Mt.; 1,013 ha; cutting history; maple now on sites not previously occupied; 640-670 m elev.; <i>Heterocampa guttivitta</i> ; frequent ice damage; shallow soils
Payette et al. 1996	So. Quebec; drought in combination with <i>Malacosoma disstria</i>
Rhodes 1997	Northeastern PA; 15-30% mort. On 44,145 ha >30% mort. On 27,540 ha; <i>M. disstria</i> , <i>Alsophila pomataria</i> , <i>Ennomos subsignarius</i> , anthracnose
Penn. Dept. Environ. Res. 1985	Northwestern PA; 1,215 ha; >640 m elev., <i>A. pomataria</i> ; history of heavy logging
NYS Dept. Environ. Cons. 1982 ^a	SE NY; 81,000 ha; <i>M. disstria</i> ; drought; mort. 95% in many stands
Gross 1981a	So. Ontario; 16% mort.; <i>M. disstria</i> , site conditions, weather
Can. For. Serv. 1980	So. Ontario; >50% mort.; 8,500 ha; <i>M. disstria</i>
Giese et al. 1964. U.S. Dept. Of Agric. 1964.	NE Wisc.; 4,050 ha; 2-33% mort. Overstory. 1-56% mort. Understory; cutting hist. favored intolerants; drought killed hemlock; hem./hdwd. stand converted to maple; defoliator complex
Wink 1998 ^a	North. NY, Tug Hill Plateau; 48,600 ha; 17-20% mort.; <i>M. disstria</i> ; highgrading

^aData on file, unpublished.

professionals with knowledge of local forest types, past land use practices and disturbance histories for the areas involved. We should pay attention to these observations, because several common threads connect past episodes of sugar maple mortality.

Several recent reviews of sugar maple decline and mortality cataloged these events (e.g., Barnard et al. 1990, McIlveen et al. 1986, Millers et al. 1989). The examples chosen here (Table 9) are some of the best documented incidents of true maple declines and not merely examples of temporary crown dieback resulting from a single, short-term stress. The two predisposing factors mentioned most frequently relate to stand composition and site condition. In most instances, affected stands are predominantly sugar maple as a consequence of selective cutting, which often allows maple and other shade tolerant species to dominate sites (Nyland 1986) where historically it may have constituted a relatively small percentage of the stand. Of course, under favorable site and stand conditions sugar maple naturally attains dominance, largely due to its long life, prolific seed production, extreme shade tolerance, and persistence in the understory. These characteristics account for its ability to quickly exploit gaps in the overstory and sustain this position (Abrell and Jackson 1977). Site seems to become

particularly critical when, as a consequence of either selective cutting or natural events, northern hardwood stands that are predominantly sugar maple occur at elevations where soils are thin and trees are exposed repeatedly to adverse weather events.

The most common inciting event is insect defoliation, occasionally exacerbated by drought (Kolb and McCormick 1993). Forest tent caterpillar, *Malacosoma disstria* Hubner, has been most frequently associated with maple decline and mortality, but the literature also indicates that saddled prominent, *Heterocampa guttivitta* (Walker); fall cankerworm, *Alsophila pomataria* (Harris); and elm spanworm, *Ennomos subsignarius* (Hubner) have played inciting roles as well.

Acknowledging and addressing factors that have been consistently associated with maple decline and mortality is important, because they are manageable and predictable. That is, in most situations applying appropriate silvicultural methods to alter stand conditions (encourage sugar maple on appropriate sites, maintain species diversity, optimize stand density) and maintaining conscientious pest management strategies (annual monitoring and evaluation, appropriate controls) will lower the susceptibility of northern hardwood forests to sugar maple decline.

Conclusions

During the mid- to late 1980s, the general public was inundated by sensational press describing maple decline as "a catastrophe in the making" (Jones 1986), a "mysterious plague destroying a way of life" (Pawlick 1985) and that, in general, we were "losing our forests to acid rain" (Kappel-Smith 1985). These claims were made without the benefit of long-term observations and adequate scientific investigation. After monitoring the condition of sugar maple from a variety of site conditions and geographic locations, we conclude that levels of mortality observed in plots maintained by the North American Maple Project are within normal bounds reported for a variety of broadleaved forests, including those dominated by sugar maple.

Mortality of dominant/codominant sugar maple in stands actively managed for sap production (sugarbushes) is similar to that of stands that have not been as intensively managed.

Unusual levels of mortality associated with forest declines in the past have been associated generally with a combination of nonanthropogenic biotic and abiotic stresses, and forest management activities that decrease tree diversity, or damage residual trees during stand intervention. Most forest declines can be explained by documenting the extent, timing and nature of on-site disturbances combined with a knowledge of land use history. Continued quality controlled monitoring is necessary to reveal what, if any, long-term effects may result from changes in soil chemistry and to determine whether these changes magnify the impact of other stresses.

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